chapter 8

Perspectives on Bioenergy

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Highlights

- Holistic studies of the energy sector show that bioenergy is an essential component of GHG reduction technologies
- The development of biofuel industries in Brazil and the USA illustrate that biofuels can make significant contribution to the transportation sector
- Commercialization of cellulosic biofuels has begun
- Biogas is underutilized in most regions and could expand strongly in the future
- Biodiesel from plant oils has limited potential but new routes are opening up for conversion of sugar to diesel and jet fuel
- Restricting bioenergy and minimizing prices are not likely to increase food security
- The use of marginal land for production of cellulosic biofuels will reduce the use of food crops for biofuels and concerns about land use change

Summary

Our understanding of the challenges and opportunities associated with bioenergy production has strongly expanded since a previous SCOPE report on biofuels in 2009. Concerns about escalating food prices and negative environmental effects associated with indirect land use change have significantly abated; the promise of lignocellulosic fuels has begun to be realized with the startup of the first generation of commercial lignocellulosic biofuels biorefineries; bioenergy production has continued to expand under the implementation of more stringent sustainability criteria; and there has been technical progress on many fronts. The motivations for reducing greenhouse gas (GHG) emissions have become more compelling, as summarized in the recent IPCC reports, and holistic analyses of the options for GHG reduction have confirmed that bioenergy has an essential role to play in accomplishing such reductions.

8.1 Introduction

Biomass was the first energy resource used by mankind, the unique source of fuel for millennia. Even today, biomass accounts for nearly 10% of world total primary energy supply (IEA 2012c) and is the largest contribution to renewable energy – 52.2% of renewable energy is provided by biomass. Roughly 60% of biomass is used for primary energy production (residential heating and cooking via combustion), largely in non-OECD countries. This form of inefficient use has considerable negative impacts on human health (smoke pollution) and the environment (deforestation) (Chapter 16, this volume). This volume focuses primarily on technologies that move away from this form of bioenergy, which requires not only attention to technology but to social and economic factors including energy access and social equity.

The modern concept of bioenergy, based on advanced and efficient conversion processes, is largely motivated by energy security and sustainability concerns (Chapters 3 and 5, this volume). Worldwide bioenergy contributes 310 TWh of electricity (2% of world electricity generation in 2011), 8 EJ of industrial heat, and 110 billion liters of liquid biofuel (2.3% of transportation energy) (IEA 2012c). Bioenergy is expected to be an important contributor to reducing greenhouse gas (GHG) emissions required to address climate change, as well as meeting the increase in energy demand expected in the coming years (IPCC 2014). However, one of the main challenges in envisioning and implementing optimal paths for bioenergy deployment is the large diversity of feedstocks, processes and products that must be considered. In some cases, there are options that are compatible with both environmental benefits and economic feasibility, in other cases, bioenergy production scenarios need more assessment to avoid undesirable impacts. In this volume, several alternatives are put forward and discussed, recognizing that bioenergy can supply transport fuels and electricity, in different contexts and scales.

The developed economies of the world provide a vast array of goods and services that depend upon the consumption of large amounts of inexpensive energy. Less developed societies aspire to have similar goods and services, so energy demand is expected to continue to expand into the foreseeable future. According to the World Energy Council, the world fleet of 800 million LDV (Light Duty Vehicles) in 2010 is expected to reach the range of 1.7 to 2.1 billion cars in 2050 (WEO 2011). The International Energy Agency (IEA) predicts that world energy use will increase by more than a third between 2010 and 2035 (IEA 2012b). At present, approximately 87% of energy demand is satisfied by energy produced through consumption of fossil fuels. Although the IEA predicts that this share will fall to 75%, the total consumption of fossil fuels will continue to rise, adding another 6 Gt of carbon to the atmosphere by 2035. In view of the fact that current rates of carbon emissions are causing climate change, the prospect of increased emissions far into the future is disheartening.

Climate change is unwelcome for many reasons that are well documented in the recent

IPCC reports (IPCC 2014b) and many other thoughtful commentaries. However, in the context of this volume, perhaps the most important impacts of climate change are those that are expected to impact agriculture and natural ecosystems, including marine environments. The most fundamental implication is that in many regions of the world, agricultural production will decrease because of heat-induced damage or drought resulting from changes in rainfall patterns. Reduced agricultural productivity combined with increasing population may be expected to cause conversion of natural ecosystems to agriculture. Similarly, the altered temperature, ocean acidification and changing rainfall will also disrupt many ecosystems. Thus, it is imperative that we explore all possible means of reducing carbon emissions if we hope to preserve some vestige of the natural ecosystems that remain today and avert the social disruptions that may attend regional agricultural failures. A recent study of all options for reducing GHG emissions in California concluded that, even with massive commitment to efficiency and other sources of renewable energy, the use of bioenergy and biofuels, in particular, is essential (Box 8.1).

The utility and impact of liquid biofuels was the subject of a previous SCOPE study in 2009 (SCOPE 2009). Since that time there has been rapid progress on many aspects of bioenergy, including biofuels, which are described in chapters 9-21 of this volume. The implications of these advances in a forward-looking global context were discussed by many of the authors and other experts during a week-long meeting in Paris in December 2013. The conclusions from those discussions were captured in four crosscutting chapters (chapters 3-6, this volume) entitled Energy Security, Food Security, Environmental and Climate Security and Sustainable Development and Innovation. Thus, the crosscutting chapters represent a consensus view of the field of bioenergy that may be particularly helpful to policymakers and regulators who must confront the often confusing barrage of academic discourse in this field.

In this brief perspective, we have endeavored to highlight a few rapidly evolving topics, mainly focusing on liquid biofuels, where we have formed opinions, based on our experiences in two of the major regions of biofuel development, that are less nuanced than is possible in a consensus document.

8.2 The Upward Trajectory of Biofuels

The fossil fuel industry has, for more than a century, provided an abundant and relatively inexpensive source of liquid, solid and gaseous fuels and chemicals and, based on current estimates of reserves, can continue to do so for centuries (BP 2013). More fossil fuel remains in the earth than the total amount used in human history. Thus, in order to envision the future trajectory of biofuels, it seems worthwhile to reflect briefly on the progress made in several regions of the world in partially displacing liquid fossil fuels with biofuels. The feasibility of the use of biofuels in Diesel and Otto engines was recognized early last century in the automotive industry, but discoveries of abundant, cheap oil made biofuels uncompetitive and their contribution marginal.

Box 8.1. Bioenergy is essential

There are many conceivable ways to reduce carbon emissions. Thus, critics of bioenergy argue that biofuels and other forms of bioenergy are not necessary. The fallacy of this argument was recently exposed in a major study conducted by the California Council on Science and Technology (CCST) on behalf of the Government of California. In brief, in 2005, the governor of California issued an executive order that established a state mandate to reduce California's carbon emissions to 1990 levels by the year 2020 and by another 80% below 1990 levels in 2050 (Schwarzenegger 2005). The CCST was charged with evaluating the technical possibilities of meeting those goals. Approximately forty scientists representing all sectors of the energy system collaborated for more than two years on an analysis of how much energy demand could be reduced through efficiency and how much energy could be produced and distributed within the state by all known or pending low-carbon technologies. This analysis resulted in the conclusion that even though California is well-suited to production of solar, wind, wave and geothermal energy and even with efficiency measures, it was impossible to reach the GHG reduction goals without significant inclusion of bioenergy, particularly for liquid biofuels (Long et al. 2011). Furthermore, it was concluded that it would be necessary for the state to import large amounts of biofuels from other regions, such as Brazil, in order to satisfy the demand for low-carbon fuels for the heavy duty fleet and aviation (Youngs and Somerville 2013).

The necessity of biofuels was surprising to many participants in the study who previously held the opinion that vehicle electrification and solar or wind-based electricity generation could sufficiently decarbonize transportation. Indeed, the CCST study was based on the unrealistic assumption that a large percentage of the light-duty fleet, buses and rail in California would be electrified and fuelled by such means. However, there is no known or pending storage technology that would allow electrification of the aviation or heavy duty ground transportation fleets. Furthermore, because of inescapable use of natural gas for electrical grid load following, it was necessary to propose the phasing out of all fossil-based transportation fuels in order to reach the goal of reaching the goals of AB-32. Thus, as previously noted (Pacala and Socolow 2004), biofuels are an essential part of the suite of approaches needed to minimize climate change. Indeed, the main conclusion of the CCST study was that we need to use all known and pending low-carbon technologies in order to have any chance at a significant reduction in energy-based carbon emissions. A similar conclusion was reached in a large multidisciplinary study of America's energy future by the U.S. National Academy of Sciences (US NRC 2009).

The sudden rise of the price of petroleum during the oil crisis of the 1970s changed that. Particularly hit were the developing countries that depended heavily on oil imports. For some, the oil import bill reached 50% of all their export earnings. As a consequence, large sugar-producing countries, such as Brazil, started aggressive programs for producing ethanol from sugarcane as a replacement for gasoline (Box 8.2). Environmental considerations didn't play an important role in such decisions at that time.

Box 8.2. A Short History of Brazilian Ethanol

The production of sugar from sugarcane juice results in a byproduct called molasses that has long been used for alcoholic beverage production, among other things. Thus, in some sugarcane-producing countries there is a long tradition of ethanol production. In 1931, the Brazilian government implemented a compulsory blend of at least 5% anhydrous ethanol in gasoline, aimed at reducing the impact of total dependence on imported petroleum and absorbing the excess production of the sugar industry. The ethanol content in Brazilian gasoline varied over successive decades as indicated in Figure 8.1. Thus, for more than eighty years, all Brazilian cars have been using blends of ethanol and gasoline.

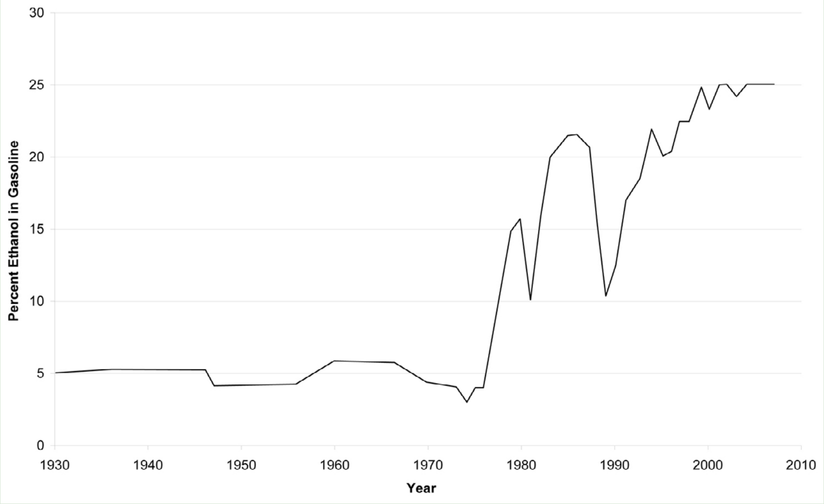

Figure 8.1. Evolution of ethanol content in Brazilian gasoline from 5% in 1930 to 25% in 1998.

In 1975, in response to the impacts of the oil shocks during the 1970s, the Brazilian government initiated the National Alcohol Program (Proálcool) which fostered the expansion of ethanol use as a replacement for gasoline, initially

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increasing the ethanol blending up to 25% in gasoline (E25) and also introducing pure hydrated ethanol (E100) for use in dedicated vehicles (reviewed in Nogueira 2008). The combination of incentives adopted by Proálcool at that time included the following measures: a) minimum levels of anhydrous ethanol in gasoline were established; b) lower consumer prices for hydrated ethanol than for gasoline were guaranteed (fuel prices were determined by the government at that time); c) competitive prices for ethanol producers were guaranteed, even when international prices for sugar were more advantageous than for ethanol; d) financing under favorable conditions for mills to increase their production capacity was offered; e) taxes on new cars were reduced and annual registration fees for vehicles capable of running on hydrated ethanol were reduced; f) the compulsory sale of hydrated ethanol at gas stations was mandated; and g) the creation of ethanol reserves to ensure supply throughout the year were mandated (Nogueira 2008). Given this favorable policy framework, the production of ethanol expanded significantly (Figure 8.1). This, in turn, stimulated the breeding and diffusion of better varieties of sugarcane, adoption of more efficient agroindustrial practices, such as vinasse use as fertilizer and improved cogeneration schemes. Additionally, the automotive industry improved significantly the pure ethanol motors, eliminating some problems initially observed with material compatibility and cold start, reaching performance similar to the gasoline motors. Almost all sales of new cars in this period were of models for hydrous ethanol use.

Around 1985, due to the decline in oil prices and strengthening of international sugar prices, that positive situation faltered. In 1986, the government revised the ethanol policies, thereby reducing the average financial returns to the sugarcane industry and stimulating the allocation of sugarcane to produce sugar for export, rather than for ethanol production. This led to a temporary end to expansion of the Proálcool initiative. The mechanisms for creating ethanol reserves failed, and policy changes that included reduced levels of ethanol in gasoline, ethanol imports, and the use of gasoline-methanol blends were implemented. The consumers grew wary of pure ethanol as fuel and moved towards gasoline cars, progressively reducing ethanol demand. Thus, the use of ethanol was gradually restricted to anhydrous ethanol blended with gasoline.

By the beginning of the 1990s, because of decades of strict government control, agricultural and industrial production was under the control of the sugar mills, there was limited utilization of byproducts, and the competitiveness of the Brazilian sugarcane industry was largely driven by low salaries and efficiencies of scale (CGEE 2007). Between 1991 and 1999, the Brazilian government initiated administrative reforms that included a shift

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» towards free-market pricing in the sugar and ethanol sectors, progressive removal of subsidies, and a reduction of the government's role in setting ethanol prices. Additionally, a new set of rules was implemented to organize the relationships between sugarcane producers, ethanol producers, and fuel distributors. The only feature of the original framework of legal and tax measures that remained, and was maintained until recently, was the differential tax on hydrated ethanol and gasoline, which was intended to maintain approximate parity of consumer choice between hydrated ethanol and gasoline. In this context, ethanol is freely traded between producers and distributors. Sugarcane is also traded freely, but its price is mainly determined according to a contractual voluntary model jointly coordinated by the sugarcane planters and ethanol and sugar producers.

The institutional restructuring of the ethanol industry continued with the creation in 1997 of two important institutions: the National Energy Policy Council (CNPE), and the National Oil Agency (ANP), later renamed the National Oil, Natural Gas and Biofuels Agency. The CNPE is responsible for establishing directives for specific programs for biofuels use. The ANP oversees the regulation, contracting, and inspection of biofuel-related economic activities and implements national biofuel policies, with an emphasis on ensuring supply throughout the country and protecting consumer interests with regard to product price, quality and supply.

In 2003, flex-fuel cars were launched and were well accepted by consumers. Flex-fuel cars offer owners the options of using gasoline (with 20–25% anhydrous ethanol), hydrated ethanol, or any blend of the two. Thus, the consumption of hydrated ethanol in the domestic market made a comeback, creating new opportunities for the expansion of the sugarcane industry in Brazil, as well as the possibility of meeting the demand of the international market for ethanol for use in gasoline blends.

During the period 2003–2008, the Brazilian sugarcane industry expanded rapidly, new and more efficient mills were commissioned, and a consolidation process was initiated, at the same time that positive indicators for the industry's environmental sustainability were demonstrated (Macedo 2005). Flex-fuel cars currently represent approximately 90% of sales of new cars, and pure ethanol can be used nowadays by 12.7 million Brazilian vehicles (mostly cars with flex-fuel engines), which represent approximately 47% of the national fleet of light road vehicles (ANFAVEA 2013).

However, since 2008 the Brazilian ethanol agroindustry has been facing hard times, essentially due to the increasing lack of competitiveness in relation to »

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gasoline. Officially motivated by inflation control, the Brazilian government (which controls Petrobras, the main oil products supplier) has held the gasoline price at the refinery gate (ex-taxes) at approximately 70 US$/barrel for the last 5 years, significantly below the international parity prices formerly adopted. Besides, although taxes have historically represented more than 40% of the final price of gasoline, the Federal government also has been gradually reducing taxes on this fuel and in June 2012, the main Federal tax on gasoline was set to zero. Thus, the current gasoline price (Nov 2014) at Brazilian gas stations is significantly below the value that would be expected if taxes were applied. Thus, as the Brazilian fleet is predominantly flex-fuel, ethanol demand has decreased as this biofuel has been substituted by gasoline, and ethanol production in 2010 was 30% less than in 2008. This situation has brought heavy economic losses to Petrobras, to the Brazilian trade balance and to the Treasury, highlighting the relevance of proper public policies to foster bioenergy.

At present, the word “biofuel” generally means ethanol from sugar or starch (e.g. corn or sugarcane), or biodiesel (fatty acid methyl esters) made from oils (e.g. soy, palm, rapeseed). Worldwide, consumption of ethanol is roughly three times that of biodiesel (Table 8.1). Brazil and the USA produce about 88% of the fuel ethanol used in the world and consume much of what they produce. Ethanol use elsewhere in the world is comparatively anemic, with China being the third largest producer and user of fuel ethanol. In some cases the low level of production may be related to the fact that few other regions have the land, climate, and experience required to scale-up production of highly productive starch or sugar crops to the extent possible in the USA and Brazil. However, just as most countries are not self-sufficient in petroleum, it is unrealistic to assume that all regions will produce their own biofuels. Thus, for instance, Germany and the UK import about half of the ethanol used whereas other countries such as France use approximately the same amount as they produce.

Brazil currently substitutes about a quarter of gasoline demand with ethanol as a result of a somewhat tumultuous eighty year development program (Box 8.2) and is a significant net exporter of ethanol (Table 8.1). The long-term commitment to ethanol by Brazil led to the development of flex-fuel vehicles that can operate using variable blends of ethanol and gasoline. The international auto manufacturers responded, which could facilitate the expansion of ethanol use around the world. Ethanol production in Brazil is projected to triple by 2040 because Brazil benefits in net international trade by exporting petroleum rather than using it domestically (US EIA 2013). The development of the ethanol industry in Brazil is due, in part, to the availability of large amounts of land that is suitable for sugarcane production. However, even under such favorable conditions, the development of the ethanol industry has required persistent

Table 8.1. Biofuel production and consumption in 2011 (thousands of barrels per day).

	Ethanol		**Biodiesel**	
	production	**consumption**	**production**	**consumption**
North America	938.9	883.4	65.9	62.9
United States	908.6	841.1	63.1	57.8
Central & South America	415.9	350.1	103.2	72.8
Brazil	392.0	332.4	46.1	45.0
Europe	72.8	104.3	177.7	239.5
France	17.4	16.0	34.0	40.5
Germany	13.3	26.5	52.0	47.4
United Kingdom	5.0	11.2	4.0	16.0
Africa	0.6	1.3	0.2	0.1
Asia & Oceania	64.8	66.0	53.4	36.4
China	39.0	38.0	7.8	7.0
India	6.0	6.0	2.0	2.0
Indonesia	0.1	0.0	20.0	5.0
Japan	1.0	2.0	0.3	0.3
Korea, South	0.0	0.2	6.3	6.3
Thailand	8.9	7.0	10.2	10.2
World	1493.5	1405.6	403.7	414.2

Data: U.S. Energy Information Administration

policy support. Thus, it seems likely that, for the foreseeable future, the development of biofuels industries in other regions with advantageous growing conditions will also depend on implementation of supportive policies.

Similarly, the development of corn ethanol in the USA resulted from supportive policies, though the motivations were different (Box 8.3). The rapid phasing out in 2005 of a gasoline octane-booster called methyl *tert*-butyl ether (MTBE) for environmental reasons created a demand for a high octane additive that could be satisfied by ethanol. During that same period, corn prices were depressed to a level where crop subsidies were necessary to keep farmers profitable. In order to stimulate demand, and to address persistent concern about dependency on foreign petroleum, the US government instituted a subsidy for corn ethanol and implemented an annually expanding mandate for blending of ethanol into the gasoline supply.

In 2013, consumption of ethanol in the US may have begun to plateau because of a perceived “blend wall”. The blend wall refers to the fact that until 2011, the US Environmental Protection Agency (EPA) authorized the blending of ethanol in gasoline up to 10% of total volume to produce “E10” for most vehicles (US DOE 2013). In 2012, the US EPA raised the blending limit to 15% for cars manufactured after 2001. However, the belief that auto manufacturers would void warranties and resistance from large gasoline distribution franchises to allow station owners to sell E15 has caused delayed implementation of the new fuel blend. Adoption of flex-fuel vehicles in the US has been extremely slow. Although there are approximately 10 million flex-fuel vehicles in the USA (US EIA 2011), this only represents about 5% of the light-duty fleet, effectively limiting expansion of the ethanol fuel market. Similarly, there are few flex-fuel vehicles in other developed or developing countries other than Brazil; however there may be potential for additional ethanol consumption in previously untapped markets including some EU countries, and countries in Latin America, Asia and Africa. Some studies indicate that about 21 million hectares of sugarcane (less the current area of soy in Brazil) would be enough to implement 5% ethanol blending in the global gasoline demand in 2025 (Cerqueira Leite et al. 2009).

Box 8.3. Corn Ethanol in the USA

As noted in a previous account of the history of corn ethanol (Youngs 2012), from which modified excerpts are reproduced here for convenience, interest in biofuels began with mass production of personal automobiles. Henry Ford was a proponent of both ethanol and biodiesel but the low cost of petroleum derivatives allowed fossil fuels to dominate the transportation fuel market. When price volatility and embargoes in the 1970s created fuel shortages, the U.S. began subsidizing production of corn ethanol for blending with gasoline.

“The first push for corn ethanol was short-lived, fading quickly with falling oil prices during the economic boom of the 1980s and political changes in many oil producing countries. Interest rebounded in the 1990s – blending of ethanol had the added benefit of anti-knock properties and could replace tetraethyl lead as a combustion facilitator, reducing smog formation. The Clean Air Act Amendments of 1990 required reformulated gasoline to contain at least 2% oxygen by weight. The Winter Oxyfuel Program (1992) required 2.7% oxygen in cold months for cities with elevated carbon monoxide with ethanol as the common oxygenate. The Year-Round Reformulated Gasoline Program (1995) required 2% oxygen. MTBE (methyl-tert-butyl ether) and ethanol were the cheapest oxygenates and both were widely used. Ethanol was popular in the farming states of the Midwest, while MTBE was used elsewhere in the country. At its peak use, MTBE represented 87% of reformulated gasoline oxygenate. However, environmental impact studies in

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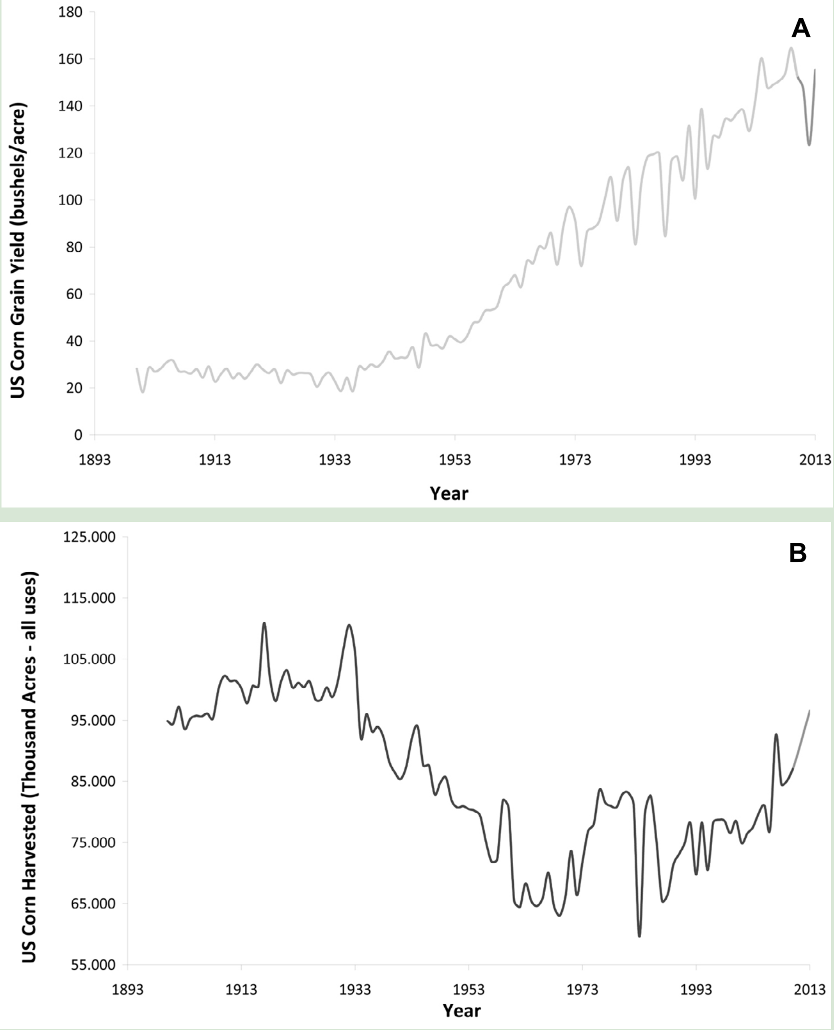
» the mid to late 1990s showed MTBE was not only toxic, it moved easily into water systems exacerbating contamination events (Squillace et al. 1997). California, the largest user of MTBE at the time, was the first state to ban the compound in 2003. With other states following suit. With ethanol as the only economically viable replacement, a new corn ethanol boom began. The Energy Policy Act of 2005 established the first renewable fuel standard, mandating volumetric requirements for biofuel use."

The use of corn ethanol in the U.S. has been a continuing source of controversy. On one hand, by increasing demand for corn, the industry has had a positive economic impact on rural farm communities, contributed to investments in yield improvements and reduced dependency on imported petroleum. On the other hand, critics note that intensive production of corn requires inputs of fertilizer and agrichemicals that cause pollution, soil loss and negative impacts on biodiversity. The animal products industry (i.e., meat, milk, eggs) experiences increased costs for feed grain, and many people question the morality of converting corn to fuel when there are hungry people. "Industry critics have alarmed the public by stating that as much as 40% of the corn acreage is used for ethanol, implying that farmers are shifting from food to fuel production (hence the "food versus fuel" debate). While it is true that a large acreage is being used for corn ethanol, the actual production of corn for food and feed (domestic and exported) has not been reduced. The U.S. produced 13.2 billion bushels of corn in 2009, a new record - up from 9.5 billion bushels in 2001 (Figure 8.2). Feed corn and residual use has fluctuated between 5 and 6 billion bushels per year from 1992 to 2009 and exports have remained steady at around 2 billion bushels per year (Figure 8.2). In 2009, 42.5% of corn was used for feed, 32.1% for ethanol, 15.7% for exports, 3.5% for high-fructose corn syrup, and 6.2% went to other uses (starch, sweeteners, cereal, beverage alcohol and seed) (NCGA 2011).

As a result of improved productivity and some redistribution of acreage out of subsidized set-aside land and soybeans, the U.S. expanded corn production to meet the ethanol blending market. The yield per acre has risen with a fairly constant trend, increasing 1.6 bushels per acre per year. Whereas an acre of U.S. farmland produced an average 138.2 bushels in 2001, the average yield was 152.8 bushels per acre in 2010. The number of corn acres also increased from roughly 75 million in 2001 (a low point in the trend) to 88 million acres in 2012 (a return to the acreage used for corn production in 1933) (USDA NASS, 2014). Total farmed acres in the U.S. have remained flat at around 240 million acres for the eight major crops (corn, sorghum, barley, oats, wheat, rice, cotton, and soy) (FAOSTAT 2009). »

Increased corn production was not without impacts. The ethanol boom of the mid-2000s coincided with rising oil prices, which negatively impacted all agricultural production, including corn, causing food prices to rise. Petroleum prices affect the cost of activities on the farm (planting, field maintenance, and harvesting) as well as fertilizer prices and, of course, transportation from farms to feedlots, food processors, and consumers. Conditions incited speculation in commodity markets including general agricultural markets and corn ethanol. The outcome was a substantial rise in food prices, which many blamed directly on the corn ethanol mandate. However, John Baffes and Tasso Haniotis at



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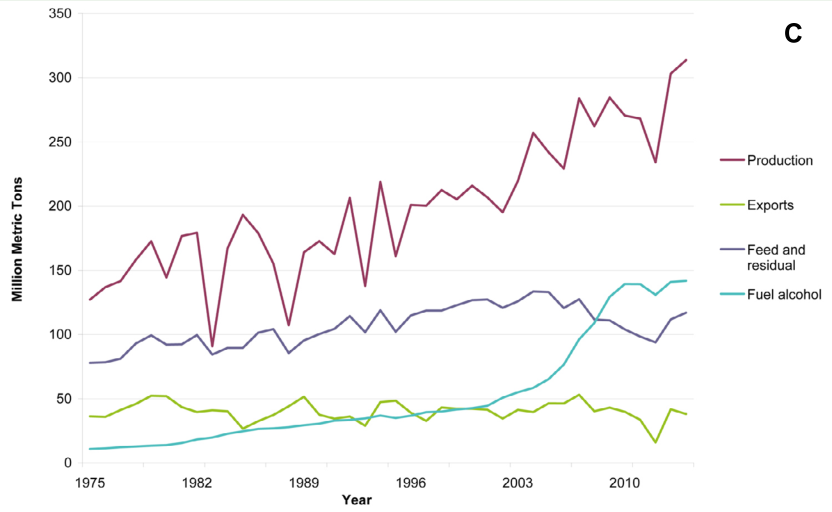

Figure 8.2. Corn grain yield (A), harvested corn acres (B) and uses (C). USDA National Agricultural Service 2014.

The World Bank Development Prospect Group stated "*We conclude that a stronger link between energy and non-energy commodity prices is likely to have been the dominant influence on developments in commodity, and especially food, markets… We also conclude that the effect of biofuels on food prices has not been as large as originally thought, but that the use of commodities by investment funds may have been partly responsible for the 2007/08 spike*" (Baffes and Haniotis, 2010). While the actual contribution of corn ethanol versus oil prices and market speculation are difficult to sort out, the clear potential for a negative impact of food-based biofuels was sobering."

Demand for ethanol is also limited by the fact that the diesel and jet fleets, which comprise about 60% of the European market and about 30% of the US market, cannot directly utilize ethanol. The demand for bio-based, low-carbon diesel and jet fuel to satisfy mandates has led to the use of various sources of lipids to produce fatty acid esters (i.e., biodiesel) or hydrogenated alkanes (renewable or green diesel). Because the technology for conversion of fats and oils to biodiesel is very simple (Chapter 12, this volume), it is possible to produce biodiesel at any scale down to single users or small cooperatives (Pienaar and Brent 2012; Skarlis et al. 2012). The use of waste cooking oils for biodiesel is an environmentally attractive option, although it is limited in scale.

Lifecycle analyses of biodiesel from palm or soy indicate a GHG reduction of about 70% (Nogueira, 2011) (see also Chapter 17, this volume). The net energy return is about 3.5 GJ output per GJ of energy input, which is substantially better than the 1.2

GJ per GJ estimated for corn ethanol but much worse than the roughly 6 or 9 GJ per GJ for lignocellulosic or sugarcane ethanol, respectively. While, biodiesel from oil seeds is also potentially suitable for local production in developing economies, we believe it is unlikely to expand and may present a less than ideal use of land compared with other options on an industrial scale in developed economies. For example, in Brazil, soy yields about 700 liters per hectare of oil and in Europe, rapeseed yields about 1100 liters per hectare.

By contrast, oil production from palm is highly productive, yielding about 4700 liters per hectare. Because its geographical range is limited, it may be that palm biodiesel will expand significantly in those regions, such as in degraded cropland or pasture, where it can be established without major GHG deficits or ecosystem destruction. For example, according to studies by EMBRAPA, there are about 30 million hectares suitable for planting oil palm in Brazil (4% of national area) (Yui and Yeh 2013). In this zoning, the eco-physiological requirements of the palm and environmental constraints were taken into account, including soil, climate, and topography, and areas protected by legal or other regulatory restrictions were excluded. Palm plantations also produce as much as ten metric tons per hectare per year of palm fronds that may be useful for conversion to lignocellulosic fuels and may further improve the lifecycle impacts. The challenge associated with expanded use of palm will be in identifying land that can support the growth of palm but which does not lead to the loss of native ecosystems or the release of large amounts of carbon during land conversion (see Chapters 9 and 17, this volume, for discussions on land use and land use change emissions).

Based on measurements of the productivity of C4 perennial grasses, such as switchgrass, Miscanthus and Arundo (Chapter 10, this volume), a recent study by the European Environment Agency (EEA 2013) concluded that it would be possible to produce much larger amounts of lignocellulosic biomass on the land used for soy or rapeseed production than the total seed yield of those crops. In 2008, total plant lipid production worldwide would have been equivalent to only about 36 billion gallons (136 billion liters) of biodiesel, about 20% of global diesel consumption. As commercial development of lignocellulosic fuels matures, we envision that biodiesel production from oilseeds may be displaced by perennial grass species because the total yield of fuel per unit of land could be more than four-fold greater. However, it should be noted that oil production from soybean is a byproduct of protein (soymeal) production, thus the demand for soy and the associated availability of its oil and derived fuel co-products are largely driven by the demand for animal feed at present.

8.3 Low-Carbon Heat and Power

Besides liquid biofuels, modern bioenergy includes also bioelectricity, which is increasingly competitive in some places around the world and has high relevance for mitigating GHG emissions. With GHG reductions of 55 to 98% for most systems (Chapter 17, this volume), the EU has included biomass power alongside other renewables in all of its “20-20-20” carbon mitigation scenarios (Tasios 2013). Globally, biomass power capacity is currently about 60 GW (IRENA 2012) and is projected to grow to 270 GW by 2050 (BNEF 2011).

Using efficient steam power systems, generally in cogeneration schemes, wood represents an important share of total primary energy supply in some industrialized countries (e.g. Finland (28%), Latvia (28%), Sweden (27%), Denmark (19%)) (AEBIOM 2013). In 2010, wood accounted for 44% of electricity from biomass (IRENA 2012). Waste biomass accounts for nearly one-third of biomass electricity capacity. Energy recovery from wastewater and municipal organic waste have increased with changes to policy regarding water quality and landfill in the US and EU (Chapter 12, this volume). The use of agricultural residues and energy grasses for heat and power is also growing. Sugarcane bagasse is largely used for power generation in countries such as Brazil, Guatemala and Mauritius, where electricity sold to the grid represents a significant income in sugar mills, with good potential for expansion (Chapter 14, this volume). The introduction of advanced thermal cycles can increase the current efficiency and almost double the amount of electricity produced (IEA 2007).

Public acceptance of biomass power is mixed. In many respects biomass power is seen to compete directly with other renewables; however, biomass can also provide a flexible option for balancing supply and demand for intermittent renewables such as wind and solar. Biomass can function as a source of constant or baseload power or, when converted to biogas or syngas, it can operate in fast-ramping turbines to accommodate demand peaks, effectively substituting for natural gas. Finally, as highlighted by the IPCC, combining biomass electricity with carbon capture and storage (CCS), although logistically and economically challenging, is one of the few options for carbon negative energy production with substantial climate stabilization potential (IPCC 2014).

8.4 The Unrealized Potential of Biogas

In many regions of the world biogas may be the best option for producing energy from biomass. Biogas is a methane-rich gas produced by the degradation of organic materials by microorganisms (Chapter 12, this volume). Biogas can be produced from carbonaceous feedstocks via anaerobic digestion by methanogenic bacteria primarily, or, less commonly, by catalytic gasification (also called “bio-synthetic natural gas,” or bioSNG, to distinguish it from synthetic natural gas produced by the gasification of coal). The former is well suited to high-moisture feedstocks such as waste streams or green harvest, while the latter is more effective for feedstocks with low moisture contents (below about 15% by mass).

Biogas is well suited for both developed and developing economies because the capital investment is small, the facilities can be from single-family units to industrial scale and the technology is mature. The two main sources for biogas production are organic wastes, such as manure or landfill organics, and harvested biomass, such as dried or ensiled grasses. In Asia, where biogas facilities are abundant, the feedstock is usually based on waste. By contrast, in 2012, Germany had more land area devoted to dedicated energy crops for biogas, primarily corn silage and grasses, digested with or without manure, than for production or biodiesel or ethanol (IEA Bioenergy 2013) (Chapter 14, this volume).

Biogas, which is generally about half methane and half carbon dioxide, with small contributions from other gases such as H_2S and NH_3, can be used in a number of ways. Post-digestion treatment depends upon the selected end use. With minimal post-treatment, namely some drying and desulphurization, biogas can be combusted to provide local heat or, with more extensive desulphurization, heat and power for use on-site. Alternatively, biogas can be used in fuel cells or can be upgraded to methane, which can be compressed for used in modified vehicles. Worldwide, there were about 17 million natural gas vehicles that could use upgraded biogas, including 1.7 million in Brazil, 1.5 million each in India and China, and 2.2 million in Argentina.

The IEA's scenarios prior to 2012 did not assign any market share to natural gas vehicles, suggesting that they thought it unlikely for such vehicles to make a significant contribution in the future. However, the low price of newly available fossil natural gas has prompted an expansion of natural gas-powered heavy-duty vehicles and the associated fuelling infrastructure in some regions, which could ultimately create the conditions for utilization of biogas in transportation. In 2012, the IEA projected a possible six-fold increase in use of natural gas in transportation by 2035 (IEA 2012a).

8.5 Cellulosic Biofuels Have Arrived

Science and technology play a crucial role in developing sustainable biofuels. In the Brazilian experience, several obstacles successively emerged against ethanol market development and were overcome essentially by aggregating knowledge and innovation. Thus, questions regarding the feasibility of using high ethanol blends or pure ethanol in engines (drivability, cold starting, compatibility of metallic and polymeric engine materials with the oxygenated fuel, etc.), the conformity to the environmental legislation and the ample debate on sustainability (energy balance, water use, soil conservation, biodiversity, economic and social impact, etc.) were tackled and solved with the relevant contribution of scientific and academic communities, allowing a remarkable improvement in the whole production process of ethanol. In recent decades, Brazilian ethanol productivity has grown at a rate of 4% per hectare per year (Goldemberg and Guardabassi 2010). As a direct consequence of this continuous upgrading, in 2010, the conventional ethanol from sugarcane was designated by the Environmental Protection Agency as an "advanced biofuel", meeting a minimum lifecycle greenhouse gas reduction of 50% over fossil fuel. This advancement is permanent and new frontiers for biofuels production are under exploration.

In 2013, the first biorefineries capable of converting lignocellulose to liquid fuels began commercial production. Mossi & Ghisolfi Group opened the word's first commercial lignocellulosic ethanol plant in Crescentino, Italy. The Beta Renewables subsidiary will produce 13 million gallons (50 million liters) of lignocellulosic ethanol annually from agricultural residues and the grass *Arundo donax*. A second facility based on the same design began operation in 2014 in Northeastern Brazil, with others planned for the US, Colombia, and China. Additionally, the startup company, KiOR, and the chemical company Ineos began commercial production of cellulosic fuels in the US. Ineos is using a combined thermal gasification and biological fermentation to produce ethanol from wood and municipal wastes in Florida. The KiOR plant has the capacity to produce 50 million liters per year of hydrocarbon fuel by thermal decomposition of pine at a facility in the southern US. The “bio-oil” produced by KiOR needs upgrading in a petroleum refinery before use. Thus, unlike ethanol, which essentially bypasses the need for petroleum refineries, KiOR’s technology substantiates the large existing refinery complex and can lead to production of diesel and jet fuels.

And so, the long-awaited jump from pilot-scale experiments to small-scale commercial production has been taken. Several additional commercial-scale facilities have recently started-up in the USA (Chapter 12, this volume). It is noteworthy that several conversion technologies reached the market in the same time frame. Presumably, the first generation of commercial facilities will provide significant opportunities to learn how to improve biomass conversion processes, reducing risk to subsequent capital investments.

8.6 Diesel and Jet-fuel from Sugars

Worldwide, advanced biofuel capacity increased by 30% in 2012 with over 100 plants and 4.5 billion liters in capacity (IEA 2012c). Parallel with the development of lignocellulosic fuels, a number of companies have demonstration units producing “drop in” fuels of various types. For example, Gevo and Butamax are attempting to produce isobutanol, Amyris is working on isoprenoid based fuels, and Renewable Energy Group Inc is producing alkanes and long chain alcohols, all by fermentation. The conceptual attraction of drop-in fuels is that they can be blended into gasoline in higher quantities than ethanol or can be blended into diesel or jet fuel. However, all of the companies that use fermentation routes appear to have experienced technical difficulties in producing commercial quantities of fuels at acceptable costs. Thus, it is unclear which, if any, drop-in fuels will reach commercial success. Similarly, diesel and jet fuels produced from algae can be considered a special case of drop-in fuels if the algae are grown on sugars, as is done by Solazyme. Several detailed techno-economic analyses have concluded that production of algal fuels under photosynthetic conditions is unlikely to reach economic feasibility for the foreseeable future (Davis et al. 2012).

The dark horse of biofuels is the possibility of converting ethanol to gasoline, diesel and jet fuel through catalytic conversions. Various types of dehydration and condensation reactions, such as the Guerbet reaction, are known to operate at high efficiencies. The reason that such conversions are not currently done industrially may be due to the fact that there is currently no premium for the energy content of a liquid fuel. In the US, for example, consumers pay as much for ethanol as gasoline on a volumetric basis, even though ethanol has lower energy content. Thus, there is no financial incentive to convert ethanol to gasoline and the price differentials for diesel and jet fuel are not currently high enough to cover the cost of conversion. However, if a carbon tax or mandate were to increase the value of low-carbon hydrocarbon fuels and if fuels were priced on energy content, the landscape in biofuels might be expected to shift decisively toward ethanol as a synthon and increased demand would follow.

8.7 Biofuels Done Right

One of the challenges associated with the public discourse on biofuels is that there are many different ways of producing a liquid fuel from biomass (Chapter 12, this volume). Some pathways, such as producing palm-based biodiesel by converting tropical peat land to plantations, appear to result in more carbon emissions than would result from burning fossil fuels. Others, such as sustainable mechanical production of ethanol from sugarcane without burning, can lead to large reductions in carbon emissions compared to the use of fossil fuels. Thus, a central task of the academic community involved in biofuels research, including the contributors to this volume, is to provide understanding to allow good decision-making.

The most important tool for deciding among various routes to biofuels is life cycle analysis (LCA) discussed in Chapter 17, this volume. The underlying concept is that by careful accounting of the energy inputs and outputs and the associated environmental impacts such as greenhouse gas (GHG) emissions, it is possible to determine whether a biofuel is preferable to a fossil fuel. Although we endorse the LCA concept, the actual use can be fraught with issues because: 1) there are no generally accepted criteria to establish the time frame in which effects on emissions from land conversion are estimated. Selection of different time frames can change the sign of an LCA; 2) the inclusion of hypothetical indirect effects such as indirect land use change (Chapter 17, this volume), predicted by untestable and highly aggregated economic models, is problematic because such concepts do not allow validation of results and cannot attribute predicted effects to specific actors; 3) many of the processes being modeled do not exist at industrial scale (e.g. lignocellulosic conversions) and are prone to the effects of convenient assumptions; 4) there is disagreement on how different types of water use should be accounted for (Chapter 18, this volume); and 5) the ability to adequately peer review results is compromised by the non-transparency and interdisciplinary nature of the modeling and data sources. Because the very clear and quantitative measure of performance provided by LCA can be hugely affected by assumptions and implementation in all these areas, it is possible to use LCA to advance ideological positions. There are ISO standards for LCA and some curated life-cycle inventory databases exist; however, there are many studies published that do not adhere to these standards.

Since the SCOPE report in 2009 (SCOPE 2009), there has been significant progress in the use of LCA in government biofuel policies. The use of LCA in policy and the continued evolution of standardized models used by government agencies are important steps toward ensuring rational use of natural resources and actual progress toward reduction of carbon emissions associated with transportation fuels. It is to be hoped that the roughly 50 countries that currently have biofuels mandates will incorporate similar legislation (Figure 8.3). It should be noted that Brazil, which has the largest mandate for the use of biofuels, does not require an LCA analysis because of widespread acceptance of the fact that sugarcane ethanol has a very low GHG footprint compared to fossil fuels. In view of the CCST study (Long et al. 2011; Youngs and Somerville, 2013), which found that it would be necessary to replace all transportation fuels with biofuels in order to achieve substantial GHG reductions, the current blending mandates and targets seem very modest.

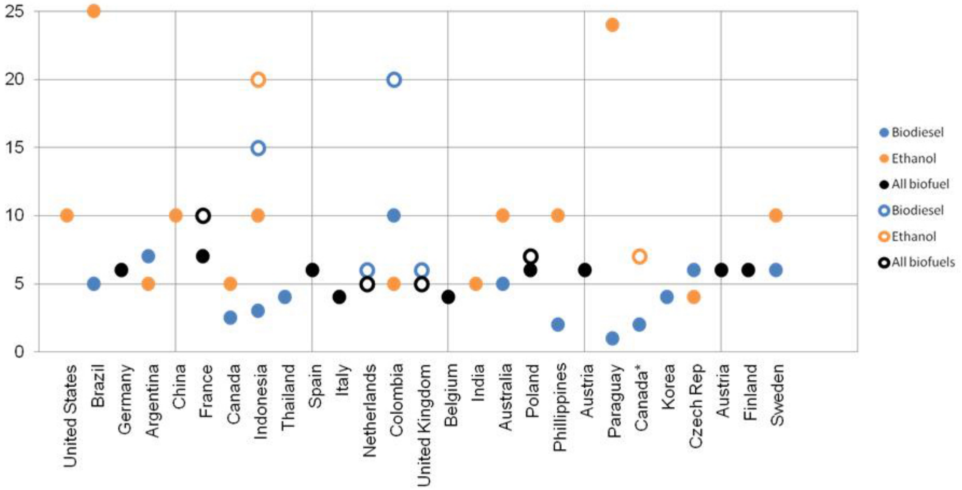

Figure 8.3. Blending mandates and targets in key countries. From (IEA 2012c).

8.8 Abundant Idle Land for Bioenergy Production

Perhaps the most controversial aspect of biofuels concerns the issue of land use (Chapter 9, this volume). The first question, in this respect, is whether there is any idle land. Several authors have investigated this question by using historical records and global satellite imaging to estimate the amount of land that has been farmed in the past but is not currently farmed (Cai et al. 2010; Campbell et al. 2008). These analyses concluded that approximately 1.5 billion acres of such land is available worldwide. This land can be considered to have lost most of its ecosystem services when it was originally converted to agriculture. The conversion from a natural ecosystem to agriculture would also have released GHGs. Thus, allocating this land to production of biofuels should not interfere with food production and the environmental costs were paid previously. Although it seems certain that this land is of poor quality (i.e., "marginal land"), there is a lot of it. In some cases the idle land appears to be too dry for conventional crop production. However, we speculate that it may be suitable for production of water-efficient species such as Agaves that can have up to ten times the water use efficiency of C3 species such as wheat or rice and are very drought tolerant (Somerville et al. 2010). Some Agaves have high sugar content and low lignin and should be well suited for production of first or second generation biofuels (Chapter 10, this volume).

Brazil appears to have large amounts of land that could be converted to sugarcane production with little or no impact on food production or ecosystem services. There are approximately 200 million hectares of cattle in Brazil, most of which are raised at very low stocking density in the Cerrado region (Chapter 9, this volume). Native Cerrado soils and rainfall support relatively low productivity ecosystems. However, liming and fertilizer treatment can result in conversion of Cerrado pastures into highly productive sugarcane production. Thus, a key to long-term expansion of Brazilian sugarcane production is to understand how to intensify cattle production. The Brazilian government has passed Agroecological zoning legislation (Chapter 19, this volume) that will allow expansion of sugarcane from approximately 9 million hectares in 2012 to more than 64 million hectares (EMBRAPA 2009). By some estimates, this could produce enough ethanol to supply approximately 10% of global transportation fuels while still maintaining current sugar production trends, if the bagasse is also used to make lignocellulosic ethanol (Cerqueira et al. 2009; Somerville et al. 2010). The factors limiting this expansion seem to be access to capital, depressed ethanol prices in Brazil due to gasoline price controls, infrastructure limitations, and trade barriers or tariffs. A commitment by one or more of the major economies to an increased ethanol blending mandate (Figure 8.3) could create the conditions for rapid expansion of sugarcane ethanol production in Brazil.

Another large amount of underutilized land can be found in Africa. The World Bank has estimated that as much as 600 million hectares of land suitable for agriculture is available in the Guinea savannah region of Africa (Morris et al. 2009). In this case there would be some impacts on ecosystem services that would need to be evaluated but the GHG impacts may be relatively small if sugarcane or perennial grasses could be grown for biofuels on some of the land. As noted in the World Bank report (Morris et al. 2009) there are many logistical and societal issues standing in the way of the eventual use of this land in addition to concerns about ecosystem conversion. It is to be hoped that the leadership shown by Brazil in the development and implementation of the Forest Code laws may provide useful guidance about how some of this land can be brought into use. (See also Chapters 6, 15, 16, 19, and 21, this volume for discussions on certification, biodiversity, social considerations and sustainable development).

Estimates of biomass availability for production of lignocellulosic biofuels in the USA have indicated that more than one billion tons of biomass could be available annually (Perlack et al. 2005). That amount of biomass could provide for production of liquid fuels that would substitute on an energy basis for approximately half of US liquid fuel consumption of about 200 billion gallons (760 billion liters). Additionally, the USA has about 750 million acres (303 million hectares) of woodland and forest, much of which is privately held, that was not included in the capacity survey. The declining use of wood for paper may allow the use of some wood for biofuel production in the USA and elsewhere. One factor limiting the use of this billion-plus tons of biomass supply is the commercialization of an efficient lignocellulose to fuel conversion technology (Chapter 12, this volume). It seems likely that this limitation will be removed during the next decade as the first commercial lignocellulosic fuel plants implement process improvements. Public acceptance of some biomass feedstocks may also limit some opportunities. Improved understanding of socio-economic and environmental impacts will heavily influence the development of some resources.

Thus, without attempting a comprehensive survey of how much biomass could be available worldwide it is apparent that there is significant potential to expand biofuel production several-fold over current levels of about 100 billion liters. The exact amount that might eventually be produced will depend on evolution of the conversion technology, local sensibilities, national policies regarding carbon emissions and a wide variety of other factors. The key conclusion for the purposes of this study is that significant expansion of biofuel production is possible but will require appropriate financial incentives (Chapter 20, this volume), innovation and some tradeoffs.

8.9 Bioenergy Risks and Tradeoffs

The attractive thing about petroleum is that once a field is located and mapped, it is usually a reliable source of inexpensive hydrocarbons for a long time. By contrast, biofuels are messy. Rainfall can be unpredictable, pests and pathogens are relentless, large amounts of labor are required, policy supports are unreliable and the technology requires continuous attention. Even worse, the situation is changing in troubling ways. The world population is predicted to increase by another two or three billion people in the next forty years and they will need food and fiber, among other things (UN 2013). Thus, competition for arable land will intensify. Logically, the use of land for food will trump the use for production of fuel, reduction of carbon emissions, and presumably preservation of ecosystems. Some thoughtful people think these facts imply that the use of biofuels necessitates a choice between feeding and clothing the poor and supporting the energy-intensive lifestyles of the developed world. Some contend that switching to lignocellulosic fuels could remove the direct conversion of food to fuel but others think this tradeoff could be illusory because some of the land used to produce biomass might support food production (see Chapters 3, 4, 9, 10, 13, and 21, this volume for discussions on land availability, alternative feedstocks for marginal land, integrated land use, energy access and food security).

Some critics of biofuels assert that, through the simplistic law of supply and demand, if we stop production of biofuels, the price of grain and other foods will decline and the poor will be more readily able to obtain affordable food. Indeed, before the advent of corn ethanol, grain was sold below the cost of production because governments subsidized production to ensure a stable supply. However, those subsidies for grain producers also suppressed food production in many regions of the world because it was less expensive to import subsidized or free grain than to produce it locally. Also, if demand for grain is reduced, farmers will once again reduce acreage to match the demand by those who can afford to pay. Thus, it is not clear that reducing demand for biofuels will make food more affordable in the long run. One solution to this important issue is not to depend upon subsidy-based agriculture but to subsidize the poor to purchase food at the prevailing price. Such a policy would encourage local production and would ensure food availability for the poor while also facilitating rational choices about the value of land and the commodities and services that can be obtained therefrom. Obviously, incentivizing food production through pricing in areas of the world with high agricultural potential while ensuring food security for areas of low agricultural potential is complicated by many factors (Herrmann 2009). It is worth noting that the use of food commodities for biofuel production can *increase* food security if thoughtfully managed. The basic idea is that, during a crop-failure-induced food shortage, food that was grown for biofuel production can be redirected towards food uses. Indeed, the biofuel mandates in the USA have a provision that relaxes the mandate under situations of “severe harm”, which can include food or feed shortages (US Congress 2007). (See Chapters 3, 4, 20, and 21, this volume for discussions on economics, policy, poverty reduction, energy access and food security issues).

The other big risk to expanded production of biofuels is climate change – the motivation for making biofuels in the first place. Changes in rainfall patterns and other effects of climate change may alter the productivity of lands used for food or biofuel production. Thus, understanding the effects of climate change should be an important theme in agricultural research, as noted in a recent report to the US President (PCAST 2012). Additionally, the positive effects of biofuel-mediated reduction of carbon emissions on global ecosystems need to be estimated so that we can have an understanding of tradeoffs with potential negative effects associated with land use change, water use, or other factors. In other words, the important question is whether or not it makes sense to convert some low diversity land to biofuel production if it helps save high diversity ecosystems such as barrier reefs from climate change-induced disruption. (See Chapters 5, 9, 10, 16, and 18, this volume, for discussions on land availability, feedstocks, climate and environmental security and impacts on water, soil and biodiversity).

The energy company BP predicts that biofuel use will expand to approximately 5% of world transport fuels by 2030 (BP 2013). The US Energy Information Administration estimates biofuels at only 2.2% of world consumption of liquid fuels by 2030 (US EIA 2013). The interesting discrepancy in predictions illustrates the large degree of uncertainty about future trends in energy production and consumption. The future of biofuels is particularly cloudy because of the importance of government policy in sustaining demand. Unpredictable types of events that could enhance demand for biofuels include the implementation of carbon taxes or expanded mandates. The dire predictions of the IPCC suggest that we may expect slow progress toward lower carbon fuels but the rate of change cannot be known in advance. The development of cost-effective drop-in fuels produced from lignocellulose, starch, or sugar would probably also expand demand by allowing expanded use in diesel and aviation fleets, and in overcoming limitations associated with the "blend wall" in the USA or the shortage of flex-fuel vehicles in most regions. However, because of the relatively long time required to build biorefining capacity it seems unlikely that drop-in fuels will be a significant component of the biofuel mix before 2020 or beyond. In the long run, the development of new biofuel feedstocks that are suited to the very large amount of arid land of low conservation value might also expand production of biofuels to regions outside the USA and Brazil while also reducing land costs and concerns about negative environmental or social effects of some types of biofuels. Presumably, the productive use of such lands might generate policy support from local governments because of regional economic benefits. Conversely, demand could be reduced by policy concerns arising from food shortages which may be anticipated because of the intersections of climate-change induced crop failures, expanding population, and prosperity-induced increases in meat consumption.

Although the future of biofuels is unknowable, it is clear that the inherent opportunity will not be realized unless the scientific community continues a broad-based investigation of both technical innovations and the social, economic and environmental consequences of possible future scenarios. Hopefully this study will help define some of the goals for sustainable development.

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