Policy Research Working Paper 5364

Biofuels

Markets, Targets and Impacts

Govinda R. Timilsina
Ashish Shrestha

The World Bank
Development Research Group
Environment and Energy Team
July 2010

Policy Research Working Paper 5364

Abstract

This paper reviews recent developments in biofuel markets and their economic, social and environmental impacts. Several countries have introduced mandates and targets for biofuel expansion. Production, international trade and investment have increased sharply in the past few years. However, several existing studies have blamed biofuels as one of the key factors behind the 2007–2008 global food crisis, although the magnitudes of impacts in these studies vary widely depending on the underlying assumptions and structure of the models. Existing studies also have huge disparities in the magnitude of long-term impacts of biofuels on food prices and supply; studies that model only the agricultural sector show higher impacts, whereas studies that model the entire economy show relatively lower impacts. In terms of climate change mitigation impacts, there exists a consensus that current biofuels lead to greenhouse gas mitigation only when greenhouse gas emissions related to land-use change are not counted. If conversion of carbon rich forest land to crop land is not avoided, the resulting greenhouse gas release would mean that biofuels would not reduce cumulative greenhouse gas emissions until several years had passed. Overall, results from most of the existing literature do not favor diversion of food for large-scale production of biofuels, although regulated production of biofuels in countries with surplus land and a strong biofuel industry are not ruled out. Developments in second generation biofuels offer some hope, yet they still compete with food supply through land use and are currently constrained by a number of technical and economic barriers.

This paper—a product of the Environment and Energy Team, Development Research Group—is part of a larger effort in the department to analyze economic, social and environmental impacts of biofuels. Policy Research Working Papers are also posted on the Web at http://econ.worldbank.org. The author may be contacted at gtimilsina@worldbank.org.

Produced by the Research Support Team

Biofuels: Markets, Targets and Impacts[§]

Govinda R. Timilsina[*] & Ashish Shrestha
Environment and Energy, Development Research Group
The World Bank, Washington DC

Key Words: Biofuels, Climate Change, Food Crisis

[§] We sincerely thank Miguel A. Carriquiry, Xiaodong Du and participants of the 5th Dubrovnik Conference on Sustainable Development of Energy Water and Environment Systems held in Dubrovnik, Croatia during September 29 to October 3 2009, for valuable comments. We acknowledge the Knowledge for Change Program (KCP) Trust Fund for the financial support.

[*] Corresponding author, e-mail: gtimilsina@worldbank.org. The views expressed in this paper are those of the author only, and do not necessarily represent the World Bank and its affiliated organizations.

1. **Introduction**

The oil crisis of the 1970s prompted interest in biofuels[1] as an alternative to fossil fuels for use in transportation in many countries. Brazil accelerated its national ethanol program (Proálcool) after oil prices peaked in 1979; the United States (US) launched a corn-based ethanol program at almost the same time but at a smaller scale than Brazil (Worldwatch, 2007). Other countries, such as China, Kenya and Zimbabwe, were also stirred into action by the oil crisis, but their attempts to promote biofuels did not succeed (Liu, 2005, Karekezi et al, 2004)[2]. Subsequent drops in oil prices removed much of the incentive and stalled the momentum to expand biofuels production in most countries, with the notable exception of Brazil. Issues related to energy supply security, oil price volatility and climate change mitigation caused a resurgence of interest in biofuels, with rapid expansion in output, mandates and targets to guarantee consumption, and investment in the development of advanced biofuel technologies. Declining production costs are making biofuels more competitive, especially when oil prices are high, but in almost all cases, they still require subsidies to compete with gasoline and diesel today.

Climate change consciousness has served as an important additional driver to the popularity of biofuels because it assists climate change mitigation efforts by displacing fossil fuel consumption. Given the enormous share of transportation in energy consumption, biofuels could contribute to the reduction of CO_2 emissions from the transport sector, but it could also lead to the conversion of forest lands and pastures to crop lands, thereby increasing CO_2 emissions from the agricultural sector. Whether or not biofuels cause net reduction of GHG emissions requires further investigation. Moreover, the increasing scale of biofuel production and the escalation of food prices in 2007 and 2008 created serious concerns regarding the possible role of biofuels in the 2007-2008 food crisis that resulted in riots in many parts of the world.

---

[1] Only liquid transport fuels are considered here, although there are other fuels derived from biomass.

[2] For example, efforts to cultivate oil plants in China to insure against disruptions in diesel fuel supply were abandoned after the drop in oil prices in the mid-1980s (Liu, 2005); the sugar cane based ethanol programs in Kenya and Zimbabwe began in early eighties but failed due to drought, poor infrastructure and inconsistent policies (Karekezi et al, 2004).

A number of existing studies (e.g., USAID; 2009; FAO, 2008a; BNDES and CGEE, 2008; OECD, 2008) have attempted to present an overall picture of the current status of biofuels. These studies, however, have focused on specific issues. For example, USAID (2009) focuses on the sustainability of biofuels in Asia, while FAO (2008a) concentrates on the relationship of biofuels with food prices. On the other hand, BNDES and CGEE (2008) discuss the Brazilian experience with ethanol in detail, and OECD (2008) assesses the impact of biofuel support policies. A succinct but broad assessment of biofuels is still lacking, particularly addressing some crucial issues, such as promises of biofuels, their economics, investment trends and potential economic, social and environmental impacts. This paper aims to fill this gap.

This paper is organized as follows. Section 2 discusses the status of biofuel technologies, followed by a look at production, consumption and trade patterns in recent years in Section 3. It then reviews biofuel policies and mandates around the world in Section 4. The cost of production and investment trend are presented in Section 5. Section 6 discusses impacts of biofuels on food prices followed by presentation of environmental impacts in Section 7 and land use impacts in Section 8. Finally we draw key conclusions in Section 9.

2. Technologies

Based on the feedstock used for production and the technologies used to convert that feedstock into fuel, biofuel technologies can be classified into two groups: first and second generation biofuels. Technologies that normally utilize the sugar or starch portion of plants (e.g., sugarcane, sugar beet cereals and cassava) as feedstock to produce ethanol and those utilizing oilseed crops (e.g., rape seed, sunflower, soybean and palm oil) to produce biodiesel are known as first generation biofuels (Rutz and Janssen, 2007; OECD-FAO, 2008). On the other hand, biofuels produced using technologies that convert lignocellulosic biomass (e.g., agricultural and forest residues) are called second generation biofuels, as are biofuels produced from advanced feedstock (e.g., jatropha and micro-algae) (Worldwatch, 2007). Whereas first generation biofuels have already been in commercial production for several years in many countries, second generation technologies have yet to begin commercial production, with some exceptions (e.g., Jatropha in India)[3]. While first generation biofuels directly compete with food supply, second generation can produce both food and fuel together unless non-food crops[4] are preferred. Because cellulosic biomass is the most abundant biological material on earth, the successful development of commercially viable second-generation biofuels could greatly enlarge the volume and variety of feedstocks (FAO, 2008a). However, although the cost of cellulosic feedstock is lower than that of first-generation feedstocks, cellulosic biomass is more difficult to break down than starch, sugar and oils, and the technology to convert it into liquid fuels is more expensive.

First generation ethanol is produced from sugars and starches. Simple sugars in a variety of sugar crops are extracted and then yeast-fermented, and the resulting wine distilled into ethanol. Starches require an additional step – first they are converted into simple sugars through an enzymatic process under high heat, which uses additional energy and increases the cost of production (BNDES and CGEE, 2008). Ethanol is typically blended with gasoline, and has a higher octane value than gasoline but produces about 70% less energy. Biodiesel is derived from lipids and is produced by mixing the oil with an alcohol like methanol or ethanol through the chemical process of transesterification. The biodiesel, or fatty-acid methyl ester (FAME), made from this process has 88 to 95% of the energy content of conventional diesel, but better lubricity and a higher cetane value, and so can deliver fuel economy close to that of conventional diesel. Jatropha, an oilseed bush that thrives on marginal and semi-arid land, has attracted much attention as a feedstock for large-scale biodiesel production in India (Sethi, 2003), where researchers project that up to 15 billion liters of biodiesel may be produced from the cultivation of jatropha on 11 million hectares of wasteland by 2012 (Mandal, 2005).

Second generation ethanol is produced through the conversion of lignocellulosic biomass. In contrast to the first generation ethanol, which is produced from the sugar or starch fraction of the plant (i.e., a small percentage of the total mass), lignocellulosic conversion processes would enable full use of the lignocellulosic material found in a range of biomass sources, such as waste

---

[3] Some of the literature refers to more advanced technologies, such as those producing biofuels from microalgae, as third generation biofuels (Christi, 2008). This study, however, treats these technologies as second generation biofuels.

[4] Non-food crops such as switchgrass, miscanthus, jatropha compete with food supply through land-use change.

seed husks and stalks (making use of plant residues not needed for food production) and fast-growing grasses and trees (Doornbosch and Steenblik, 2007). Lignocellulosic biomass is comprised of polysaccharides (cellulose and hemicellulose), which are converted into sugars through hydrolysis or chemical (or combined) processes; the sugars are then fermented into ethanol using existing fermentation technology[5]. While no commercial scale lignocellulosic ethanol plants are operational as of early 2008, around 15–20 companies, mostly in the US, are involved in pilot plant studies with different biotechnological and thermo-chemical biomass conversion routes (OECD, 2008).

The use of microalgae for biodiesel production appears to be a very promising future technology (Christi, 2008) since 80% or more of the dry weight of algae biomass, compared to 5% for some food crops, may be retrieved as oil for some species (Christi, 2007). They also create little pressure on arable land because they can be cultivated in a wide variety of conditions, even in salt water and water from polluted aquifers (GBEP, 2008).

3. Production, Consumption and Trade

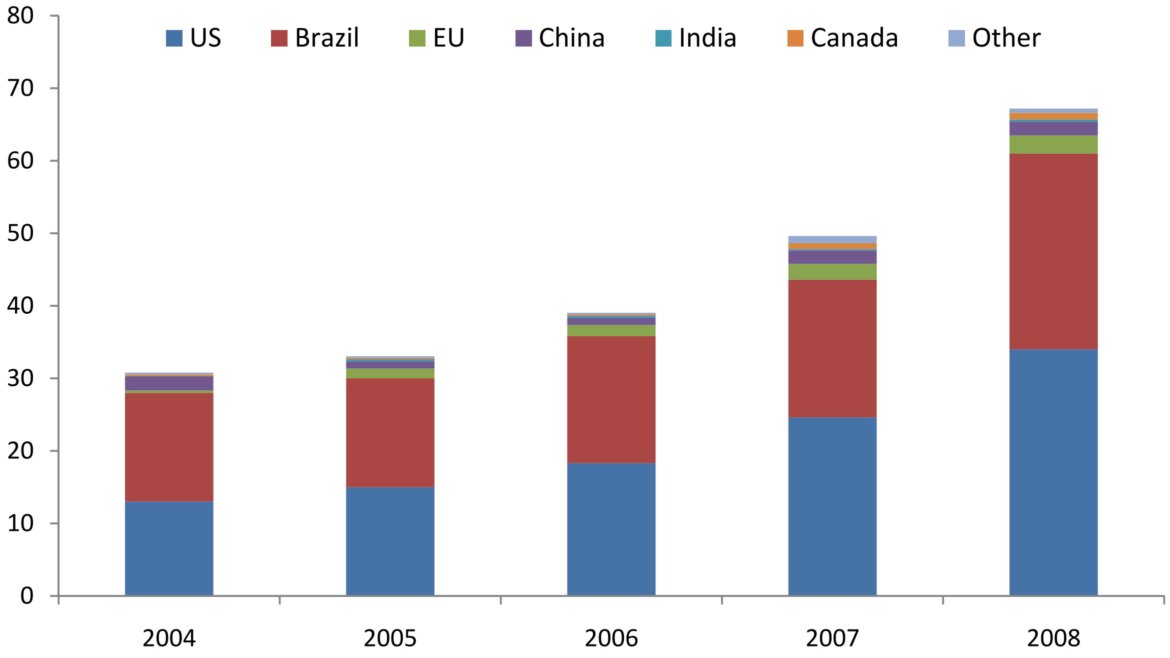
3.1 Production and Consumption

Global production of fuel ethanol grew from 30.8 billion liters in 2004 to over 67 billion liters in 2008 at an average annual growth rate of 22%. The two leading producers, the US and Brazil, accounted for more than 90% of the total in 2008 (see Figure 1).

---

[5] There exists another approach for converting lignocellulosic biomass into biofuels. This approach involves the gasification of the feedstock to produce synthetic gas or syngas (a mixture of mainly CO, H_2, CO_2 and water vapor, as well as some light hydrocarbons and other volatile and condensable compounds). This syngas is then converted to a variety of fuels, such as synthetic diesel, through Fischer-Tropsch synthesis, the same technology used in gas-to-liquids and coal-to-liquids plants (Worldwatch, 2007).

Figure 1: World Ethanol Production



Source: REN21 (2005; 2006; 2008; 2009), Renewable Fuels Association (2008)

Table 1 presents biofuels production by country for the 2004-2008 period. In 2006, the US surpassed Brazil, the longtime leader, to become the leading fuel ethanol producer in the world by producing over 18 billion liters (20% more than the previous year) (REN21, 2008). Aside from the US and Brazil, significant production increases are found in France, China and Canada in recent years. Australia, Germany, Spain Colombia, India, Jamaica, Malawi, Poland, South Africa, Sweden, Thailand, and Zambia also engage in the commercial production of ethanol.

Table 1: Biofuel Production, Top 15 Countries

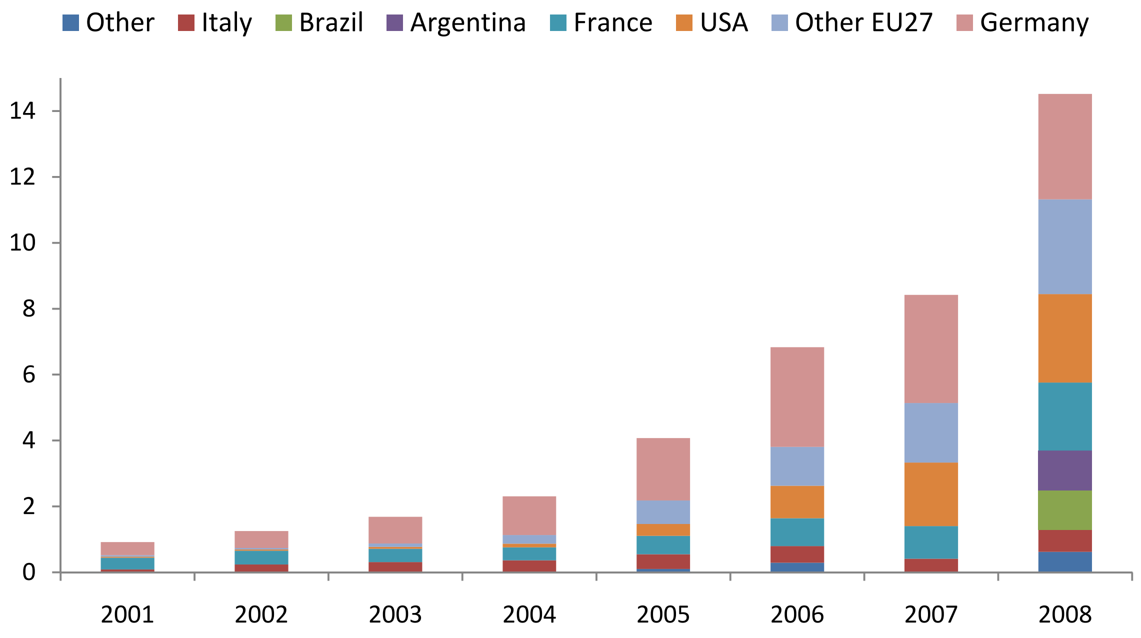
Country	Fuel Ethanol						Biodiesel					
	Major Feedstock	Production (Billion Liters)					Major Feedstock	Production (Billion Liters)				
		2004	2005	2006	2007	2008		2004	2005	2006	2007	2008
US	Corn	13	15	18.3	24.6	34	Soybean	0.11	0.36	0.99	1.93	2.69
Brazil	Sugar cane	15	15	17.5	19	27	Soybean			0.07		1.2
Germany	Wheat	0.02	0.2	0.5		0.5	Rapeseed	1.18	1.9	3.02	3.28	3.2
France	Sugar beet, wheat	0.1	0.15	0.25		1.2	Rapeseed	0.4	0.56	0.84	0.99	2.06
China	Corn, sugar cane	2	1	1	1.8	1.9	Soybean, rapeseed			0.07		0.1
Argentina	Sugar cane	--	--	--	0.02	--	Soybean					1.2
Italy	Cereals	--	--	0.13		0.13	Oil seeds	0.36	0.45	0.51	0.41	0.68
Spain	Barley, Wheat	0.2	0.3	0.4		0.4	Oil seeds	0.01	0.08	0.11	0.19	0.24
India	Sugar cane, wheat	--	0.3	0.3	0.2	0.3	Soybean, rapeseed			0.03		0.02
Canada	Wheat	0.2	0.2	0.2	0.8	0.9	Oil seeds		0.1	0.05		0.1
Poland	Rye	--	0.05	0.12		0.12	Rapeseed		0.11	0.13	0.09	0.31
Czech Republic	Sugar beet	--	0.15	0.02		--	Rapeseed	0.07	0.15	0.12	0.07	0.12
Colombia	Sugar cane	--	0.2	0.2	0.3	0.3	Soybean	--	--	--	--	--
Sweden	Wheat	--	0.2	0.14		0.14	Rapeseed	0.002	0.001	0.01	0.07	0.11
Malaysia	--	--	--	--		--	Oil palm			0.14		
UK	--	--	--	--		--	Rapeseed	0.01	0.06	0.22	0.17	0.22
Denmark	Wheat	--	0.1	--		--	Oil seeds	0.08	0.08	0.09	0.1	0.15
Austria	Wheat	--	0.1	--		--	Oil seeds	0.06	0.1	0.14	0.3	0.24
Slovakia	Corn	--	0.1	--		--	Oil seeds	0.02	0.09	0.09	0.05	0.17
Thailand	Sugar cane, cassava	0.2	--	--	0.3	0.3	Oil Palm					0.40
Australia	Sugar cane	0.07	--	--	0.1	--	--	--	--	--	--	--
EU	Various	--	--	--	2.16	--	--	--	--	--	--	--
World Total		31	33	39	49.6	67		2.3	4.1	6.9	8.4	14.7

Note: Ethanol figures do not include ETBE, a mixture of ethanol and isobutylene (petrochemical) used in low-concentration gasoline blends up to about 8-10% in fuels in parts of Europe, particularly France and Spain.

Source: REN21 (2005, 2006, 2008, 2009); Renewable Fuels Association (2008); EBB (2009); EIA (2009)

Although total production of biodiesel around the world remains small in comparison to ethanol, its growth is higher than that of ethanol, at an average annual growth rate of 50% between 2004 and 2008. This growth from 2.3 billion liters in 2004 to 14.7 billion liters in 2008 is illustrated in Figure 2. Germany, France and Italy are the biggest producers in the EU, but the US passed France to become the second biggest producer of biodiesel after Germany in 2007 (OECD, 2008).

Figure 2: World Biodiesel Production



Source: EBB (2009); EIA (2009); REN21 (2009)
Note: Data for Argentina and Brazil unavailable for 2007.

Worldwide biodiesel production grew by 43% between 2005 and 2007 despite slow growth within the EU, the traditional center of biodiesel production (OECD, 2008). This growth in other countries, especially the US, led to a decline in the EU's share of global biodiesel production, which had been more than 90% until 2004 to less than 60% in 2007 (F.O. Licht, 2008; EBB, 2008). In recent years, some countries outside Europe and the US have begun to produce biodiesel. For example, Brazil opened its first biodiesel plant, which uses a mixture of vegetable oil and sewage as feedstock, in March 2005 (OECD-FAO, 2008). Indonesia and Malaysia have recently begun producing biodiesel for the European market, and Argentina started biodiesel production in 2007 (OECD, 2008).

Despite this tremendous growth in biofuel production, the share of biofuels in total transport fuel demand was above 2% in 2004 in just three countries – Brazil, Cuba and Sweden (IEA, 2006a), and global output accounted for approximately 1% of total road transport fuel consumption in 2005 (Doornbosch and Steenblik, 2007). In 2007, ethanol production still only amounted to about 4% of the global gasoline consumption of 1,300 billion liters (REN21, 2008).

3.2 Trade

Global trade in biofuels relative to production remains modest; only about one-tenth of total biofuel production by volume is traded internationally (Kojima et al., 2007). Global trade in fuel ethanol is estimated at about 3 billion liters per year in 2006 and 2007, compared to less than one billion liters in 2000 (F.O.Licht, 2007). Even as US ethanol production increased by 20 percent in 2006, with dozens of new production plants becoming operational, blending mandates led to ethanol imports increasing six times to about 2.3 billion liters (REN21, 2008). The US, the world's largest ethanol importer, received more than half of its ethanol imports from Brazil, the world's leading exporter, at 3.5 billion liters annually.[6] Brazil was responsible for about half of the ethanol exports to the EU, the second largest importer of ethanol in 2006. China, the second largest exporter of ethanol at 1 billion liters annually, exports mainly to Japan, South Korea and other Asian countries (OECD, 2008).

About 12%, or 1.3 billion liters, of total biodiesel production in 2007 was internationally traded. The EU, at more than 1.1 billion liters per year, is by far the largest importer, while Indonesia and Malaysia are the main exporters, combining to export about 800 million liters (Kojima et al., 2007). While the US also appears to be a major biodiesel trader, this was in fact due to the importing of biodiesel to be blended with small quantities of conventional diesel for export to Europe in order to take advantage of a tax credit (EIA, 2009). The loophole has since been closed.

---

[6] Exact ethanol trade statistics are difficult to gather since fuel and non-fuel ethanol typically share the same tariff and are reported together (OECD, 2008). The share of non-fuel ethanol in the international trade in ethanol is estimated to have dropped from 75% at the turn of the century to around 50 to 60% in recent years. Ethanol trade statistics here refer to the total of fuel and non-fuel ethanol.

Since some major players, namely the US and the EU, have targeted biofuel production for domestic consumption, not many countries beside Brazil have the ability to be large exporters of ethanol or other biofuels. South and Central America, and Africa to a lesser extent, possess the greatest differential between technical production potential for biofuels and expected domestic transport energy demand, and so countries in these regions have the most potential to export to North America, Europe and Asia (Doornbosch and Steenblik, 2007). Yet trade opportunities are further restricted by the high tariffs many countries, such as India, have established to protect their agriculture and biofuel industries. While import tariffs are relatively low in OECD countries, high subsidies serve as a barrier to lower-cost foreign exporters and protect domestic producers. In other cases, trade in biofuels is limited by regulatory measures, such as the EU's sustainability criteria for palm oil imports from Malaysia and Indonesia, and Thailand's ban on palm oil imports (USAID, 2009).

Global trade in biofuels is expected to increase due to comparative advantage of some countries to others to produce biofuels, such as favorable climate, lower labor costs and the greater availability of land. Girard and Fallot (2006) show that tropical countries have two to three times higher productivity when water scarcity is not a factor. Johnston and Holloway (2007) find that Malaysia and Indonesia are the two countries with the highest absolute biodiesel production potential in the world (other developing countries, i.e., Argentina, Brazil and the Philippines, also feature in the top ten) and also the lowest average production costs per liter. Moreover, many countries may not be able to meet their biofuel targets and mandates with domestic production alone (Doornbosch and Steenblik, 2007).

4. Biofuel Policies and Mandates

Biofuel programs have proliferated around the world in recent years, whether motivated by a desire to bolster agricultural industries or achieve energy security or reduce GHG emissions or improve urban air quality. Table 2 lists biofuels blending mandates and timetables for their implementation (where available) around the world.

The growth of ethanol output in the US, derived mainly from corn (maize), has been driven by fiscal incentives (e.g., tax, subsidies) and regulatory instruments (e.g., biofuel blending mandates) (Timilsina and Dulal, 2008). The Energy Policy Act of 2005 established a Renewable Fuel Standard (RFS) program, which increases the biofuel mandate to 36 billion gallons by 2022 from 9 billion gallons in 2008 (EIA, 2009). The Farm Bill of 2008 introduced a tax credit of \$1.01 per gallon for cellulosic ethanol starting from 2009 (US DOE, 2008). The pre-existing tax credit for biodiesel of \$1.00 was also extended (to the end of 2009).

In Brazil, the government mandates 20-25% ethanol blends in all regular gasoline sales and the use of ethanol in government vehicles. It also promotes the sale of flexible-fuel vehicles, which represent 85% of all auto sales in Brazil (REN21, 2008). While ethanol production in Brazil was supported through price guarantees and subsidies, as well as public loans and state-guaranteed private bank loans, during the industry’s development, it no longer receives any direct government subsidies (Worldwatch, 2007). However, it is still supported through policies such as the ban on diesel-powered personal vehicles and one of the highest import tariffs on gasoline in the world.

The EU Biofuels Directive of 2003 targets a 5.75% share of biofuels in transport energy by 2010, and 10% by 2020, prompting rapid growth in the production of biofuels (USAID, 2009). Despite its higher production costs, biodiesel is sold for \$0.18 to \$0.24 less per liter than conventional diesel in Germany due to the \$0.59 tax exemption it enjoys there (Hogan, 2005).

Table 2: Biofuels Targets and Blending Mandates

Country	Biofuel Targets	Blending Mandates
Australia	350 million liters of biofuels by 2010	E2 in New South Wales, increasing to E10 by 2011; E5 in Queensland by 2010
Argentina		E5 and B5 by 2010
Bolivia		B2.5 by 2007 and B20 by 2015
Brazil		E22 to E25 existing (slight variation over time); B3 by 2008 and B5 by 2013
Canada		E5 by 2010 and B2 by 2012; E7.5 in Saskatchewan and Manitoba; E5 by 2007 in Ontario
Chile		E5 and B5 by 2008 (voluntary)
China	12 million metric tons of biodiesel by the year 2020	E10 in 9 provinces
Colombia		E10 and B10 existing
Dominican Republic		E15 and B2 by 2015
Germany	5.75% share of biofuels in transport by 2010; 10% by 2020	E5.25 and B5.25 in 2009; E6.25 and B6.25 from 2010 through 2014
India		E5 by 2008 and E20 by 2018; E10 in 13 states/territories*
Italy	5.75% share of biofuels in transport by 2010; 10% by 2020	E1 and B1
Jamaica		E10 by 2009
Japan	20% of total oil demand met with biofuels by 2030; 500 million liters by 2010	
Korea		B3 by 2012
Malaysia		B5 by 2008
New Zealand	3.4 % total biofuels by 2012	
Paraguay		B1 by 2007, B3 by 2008, and B5 by 2009; E18 or higher (existing)
Peru		B2 in 2009; B5 by 2011; E7.8 by 2010
Philippines		B1 and E5 by 2008; B2 and E10 by 2011
South Africa		E8-E10 and B2-B5 (proposed)
Thailand	3 percent biodiesel share by 2011; 8.5 million liters of biodiesel production by 2012	E10 by 2007 and B10 by 2012
United Kingdom		E2.5/B2.5 by 2008; E5/B5 by 2010
United States	130 billion liters/year of biofuels nationally by 2022; 3.4 billion liters/year by 2017 Pennsylvania	E10 in Iowa, Hawaii, Missouri, and Montana; E20 in Minnesota; B5 in New Mexico; E2 and B2 in Louisiana and Washington State;
Uruguay		E5 by 2014; B2 from 2008-2011 and B5 by 2012

Source: REN21 (2009); USAID (2009); BNDES and CGEE (2008); Worldwatch (2007). Note:* Poor sugar cane yields in 2003 to 2004 forced India to import ethanol to meet state blending targets. It has postponed broader targets until adequate domestic supplies become available.

China has set a biofuel production target of 12 million tons[7] for the year 2020, and it is projected that, depending on the types of feedstock, 5–10% of the total cultivated land in China would be needed to meet that target (Yang et al., 2009). Thailand has established an ethanol program with a target of replacing all conventional gasoline with E10 gasohol (gasoline containing 10% by volume of ethanol) by 2012 (Amatayakul and Berndes, 2007). Other Asian countries such as India, Indonesia, Malaysia, the Philippines, Vietnam and Japan have all introduced blending targets, fiscal incentives, import tariffs or some combination thereof to promote biofuels, some of destined to be exported to Europe to meet the EU's ambitious targets (USAID, 2009).

5. Cost and Investment

5.1. Biofuel Production Cost

Aside from sugar cane based ethanol in Brazil, biofuels are not presently competitive without substantial government support if oil prices are below US$70 per barrel (Doornbosch and Steenblik, 2007). As more than half of the production costs of biofuels are dependent on the price of the feedstock, reductions in cost are closely tied to the prices of feedstock commodities.

Cost of ethanol: According to the IEA (2006a), the costs of ethanol production in new plants in Brazil are the lowest in the world at $0.20 per liter ($0.30 per liter of gasoline equivalent). This subsequently declined even further to $0.18 per liter (Worldwatch, 2007). As compared to the cost of sugarcane based ethanol in Brazil, ethanol from grains costs 50% more in the US and a 100% more in the EU. Transportation, and blending and distribution costs can add some $0.20 per liter to the retail price. Meanwhile, production costs for ethanol (previously from wheat, but from sweet sorghum and cassava going forward) in China are between $0.28 and $0.46 per liter, depending on the price of the feedstock, and sugar-based ethanol production costs in India are around $0.44 per liter (Worldwatch, 2007). The IEA (2006a) foresees a reduction of one-third in the cost of ethanol by 2030 due to technological improvements and lower costs of feedstock. However, the increasing demand for ethanol due to mandates and targets, the impacts of the fuel vs. food debate on its supply, and recent trends of feedstock prices implies that the cost of

---

[7] All mentions of tons refer to metric tons.

ethanol may not drop down. Moreover, unless the price of oil is high, production of ethanol may not be competitive without substantial level of subsidies.

The cost of cellulosic ethanol, which is still in demonstration stage, is high, typically about typically about $1.00 per liter on a gasoline-equivalent basis. Given the speed of technological developments in an emerging field and uncertainty over the long-run costs of feedstock, projections of the future costs of lignocellulosic ethanol differ substantially, but the IEA (2006b) notes that the costs are anticipated to drop to $0.50 per liter in the long term. Significant technological progress will be necessary to make this happen: achievement of better ethanol concentrations before the distillation, lower costs for enhanced enzymes (resulting from biotechnological research) and improved separation techniques. There are some indications that this may be feasible. For example, Brazil’s leading manufacturer of sugar and biofuel equipment, Dedini SA, announced in May 2007 that it had devised a means to produce cellulosic ethanol from bagasse on an industrial scale at below $0.41 per liter on a gasoline equivalent basis (Doornbosch and Steenblik, 2007). Another path to competitive lignocellulosic ethanol may be come from the generation of valuable co-products in biorefinery, which could cut the costs of feedstock. Hamelinck et al. (2006) estimate production costs of ethanol from the hydrolysis of cellulosic biomass to be $0.63 per liter in the following 5-8 years, $0.37 per liter in 8-12 years, and $0.25 per liter in 13-20 years.[8]

Cost of biodiesel: Generally, production of biodiesel from palm oil costs around $0.70 per liter, whereas biodiesel produced from rapeseed oil may cost up to $1.00 per liter, with soybean diesel in between (IEA, 2006a). The cost of biodiesel production in China, mainly from used cooking oil, ranges from $0.21 to $0.42 (Worldwatch, 2007). The IEA (2006a) anticipates a decline in biodiesel production costs of more than 30% in the US and EU between 2005 and 2030 along with a decline of feedstock costs. However, the prices of biodiesel feedstocks have been moving in the other direction since the IEA’s estimates were produced.

Substantial research is also being dedicated to lowering the costs of producing diesel from biomass using the Fischer-Tropsch process, most of which concentrate on the use of heat or

---

[8] Production costs per liter of ethanol, not per liter of gasoline equivalent.

chemicals, rather than microbes, to break down the biomass. Although the Fischer-Tropsch process permits higher yields per hectare than current biodiesel production, production cost for large-scale plants are estimated to be about $0.90 per liter of diesel equivalent in the near term and expected to fall to $0.70-0.80 in the medium term (IEA, 2006b). While micro-algae is projected as a future source for biodiesel, production cost is still extremely high, in the range of US$2 to US$22 per liter (Pate and Hightower, 2008). Making algae a viable commercial option will require further improvements in genetic and metabolic engineering to produce higher yielding and hardier strains. Although economies of scale in production could lower the cost, it is challenging to increase the yield to a level that ensures micro-algae based biodiesel is competitive with other biodiesel technologies. Nevertheless, the feasibility of biodiesel production from micro-algae can be expedited if large-scale production facilities can be integrated with other processes, such as wastewater treatment and utilization of carbon dioxide from power plants (USAID, 2009).

5.2. Investments in Capacity

An estimated $15-16 billion was invested in biofuels refineries worldwide in 2008 (REN21, 2009). An emerging significant component of venture capital investment went to cellulosic ethanol, estimated at more than $350 million in 2008 (REN21, 2009). Biofuels production plants under construction and announced construction through 2008 were valued in excess of $2.5 billion in the United States, $3 billion in Brazil, and $1.5 billion in France (REN21, 2008). In the case of traditional or first generation ethanol, North America and Brazil exhibit rapid expansion in capacity. In the US, construction of 12 new ethanol plants was completed in 2004, raising the total to more than 80. Construction was begun on an additional 16 in the same year, representing production capacity of 2.6 billion liters per year and an estimated $1 billion of investment (REN21, 2005). At the end of 2005, 95 operation ethanol plants were in existence in the US with a capacity of 16.4 billion liters per year, and construction of 35 new plants ($2.5 billion of investment) and expansion of 9 existing ones, i.e., additional capacity of 8 billion liters per year, were underway in 2006 (REN21, 2006). Most of these are dry mills that produce ethanol as the primary output as opposed to wet mills, which are designed to manufacture products like maize oil, syrup and animal feed along with ethanol (IEA, 2006a). The ethanol industry association in the US estimates construction costs in 2005 as follows: $0.40 per liter for a new dry mill plant, and $0.27 per liter for expansion of an existing plant (Urbanchuk, 2006).

Canada has six new ethanol plants with capacity of 0.7 billion liters/year were under construction, while in Brazil, 80 new sugar mills/distilleries were licensed in 2005 to augment the 300 already in operation, as part of a national plan to raise sugarcane production by 40 percent by 2009 (REN21, 2006). Most of the refineries in Brazil are in the centre and south of the country, where sugar yields are highest, and about 250 separate producers, mostly grouped into two associations comprising 70% of the market (IEA, 2006a). The average capacity of ethanol plants in the US is three times greater than the average capacity of those in Brazil; the largest corn dry-milling plant in the US produces 416 million liters per year whereas the largest plant in Brazil produces 328 million liters per year by crushing sugar cane (Worldwatch, 2007). While there may be a number of reasons for the difference in capacities, chief among them is the fact that harvested corn can be stored for an extended period of time, unlike sugar cane, which needs to be processed soon after harvest so that the sugar will not deteriorate. Elsewhere, China reversed its decision to invest in facilities to produce more ethanol from grain on account of its food policies in 2006, and has instead targeted cassava and sweet potatoes as feedstocks for future increases in ethanol production (Trostle, 2008). South Africa, which exports ethanol to the EU, is building a pilot 500-kilolitre per year ethanol plant (IEA, 2006a).

Like the fuel ethanol industry, the biodiesel industry also grew rapidly (more than three fold in the EU between 2004 and 2006), adding four billion liters/year and an estimated $1.2 billion of investment, to bring operating capacity to over 6 billion liters per year. Biodiesel Production, a part of the German group Sauter, invested 50 million euros in 2004 to establish a biodiesel production plant with a capacity of 250,000 tons in Cartegena, Spain, while Ibserol, a subsidiary of the German food group Nutas, invested 25 million euros in a biodiesel facility (100 ton capacity) that was to begin production in Portugal in 2005 (REN21, 2005). Biodiesel production capacity is also rising swiftly in the United States. The 44 new plants under construction in 2005 were expected to double the existing capacity of 1.3 billion liters of the 53 operating plants (REN21, 2006). Brazil is using soybean oil as a feedstock to expand production of biodiesel in the Center West to replace petrol-diesel traditionally trucked in from the coast, and Argentina is expanding biodiesel production from soybean oil for the export market, while Canada is using rapeseed oil to increase biodiesel production in the Prairie Provinces (Trostle, 2008).

In Asia, Malaysia aims to capture 10% of the global biodiesel market by 2010 (REN21, 2008). However, of the 92 licenses were approved for biodiesel facilities in 2006 and 2007, only 14 facilities were built, of which eight are now operating, producing at less than 10 percent of total capacity due to the high cost of palm oil (GSI, 2008). Similarly, Indonesia planned to expand palm oil plantations by 1.5 million hectares by 2008 for a total of 7 million hectares under palm cultivation. Existing biodiesel facilities and those under construction in China will deliver 3% of China's expected diesel consumption by 2010, i.e., annual capacity of about 2 million tons (Worldwatch, 2007). However, RaboBank has warned of a surplus capacity of 1 million MT in Asia by 2010 (USAID, 2009).

Investments in jatropha plantations are surging in Africa, India, Indonesia and China (Keeney and Nanninga, 2008). India's stated target of 20 percent biofuel by 2011 will demand 13 million hectares of jatropha plantations, and BP is funding a $9.4 million project there to investigate its potential. Indonesia plans to plant 1.5 million hectares of jatropha by 2010, while the Chinese forestry administration, in March 2007, announced its intention to develop 13 million hectares of trees with high oil content, including jatropha.

Research and development (R&D) investments on advanced biofuel technologies are also substantial in several countries. The US Department of Energy (DOE) is investing more than $400 million to lower the cost of second generation biofuels though a directed research program, and has also approved 6 projects for up to $385 million in funding as part of the demonstration program (Ahring, 2007). While no commercial scale lignocellulosic ethanol plants are operational as of early 2008, around 15–20 companies, mostly in the US, are involved in pilot plant studies with different biotechnological and thermo-chemical biomass conversion routes (OECD, 2008). With the efforts of the industry and strong support from the DOE, the first commercial lignocellulosic plant, may be operational in the US in 2012.

In Europe, a company funded by DaimlerChrysler, Volkswagen and Royal Dutch Shell has been operating a demonstration plant for the production of biodiesel from wood wastes via the gasification/Fischer-Tropsch pathway in Freiberg since 2003. The technology is being developed to reach the pre-commercial stage in the next three years, with a capacity of 13,000 tons of biomass-to-liquid per year, and eventually for a commercial facility capable of delivering 200,000 tons per year (Rudloff, 2005). Other gasification/Fischer-Tropsch schemes are also being tested in Europe, and biodiesel from this technology is expected to reach markets in the next decade (Seyfried, 2005). The RFA (2008) concludes that commercial scale plants are unlikely in the EU before 2018.

6. Impacts of Biofuels on Food Prices

Expenditures on food amount to a large part of the budget of the poorest households, and so rising food prices threaten them with food insecurity, which is the lack of secure access to enough safe and nutritious for normal growth and development and for an active, healthy life (FAO, 2008a). The FAO (2008b) estimates that there were already 923 million undernourished people worldwide, and rapid growth in biofuel production, which is a significant source of demand for some agricultural commodities, such as sugar, maize, cassava, oilseeds and palm oil, has the potential to affect food security at both the national and household levels mainly through its impact on food prices.

Some studies criticize biofuels as one of the factors responsible for the 2008 food crisis[9]. These studies concur that the diversion of the US corn crop to biofuels is the strongest demand-induced force on food prices, given that the US accounts for about one-third of global maize production and two-thirds of global exports (Mitchell, 2008)[10]. An estimated 93 million tons of wheat and coarse grains, more than half of the growth in wheat and coarse grain use during the period, were

---

[9] Other factors include strong income growth and subsequent demand for meat products and feed grains for meat production in emerging economies, such as China and India (Schnepf, 2008); adverse weather conditions, such as the severe drought in Australia (FAO, 2008a); the devaluation of the US dollar, growth in foreign exchange holdings by major food-importing countries, and protective policies adopted by some exporting and importing countries to suppress domestic food price inflation (Trostle, 2008); lower level of global stocks of grains and oilseeds (Zilberman et al. 2008) and increased oil prices (Schmidhuber, 2006).

[10] The expansion of maize area in the US by 23% in 2007 entailed the contraction of soybean area by 16%, leading to lower soybean output and playing a part in the 75% rise in soybean prices from April 2007 to April 2008.

used for ethanol production in 2007, double the level of 2005 (OECD–FAO, 2008). Most of this growth comes from the United States of America alone, where the use of maize for ethanol grew to 81 million tons in 2007 and is expected to rise by another 30 percent in 2008 (FAO, 2008b). Moreover, Collins (2008) attributed 52% of the increase in soybean oil use between 2005/06 and 2007/08 to biodiesel production. Table 3 summarizes the recent literature on the impacts of increased biofuel production on food prices.

Baier et al. (2009) estimate that the increase in worldwide biofuels production over the two years ending June 2008 accounted for almost 17 percent of the rise in corn prices and 14 percent of the rise in soybean prices. More specifically, they attribute nearly 14 percent of the rise in corn prices and nearly 10 percent of the rise in soybean prices to the increase in US biofuels production, whereas EU biofuels production growth accounted for roughly 2 percent of the increase in the price of these crops. In addition, the increase in EU biofuel production was responsible for around 3 percent of the increase in the price of barley. In the case of sugar, they find that the growth of sugar-based ethanol production in Brazil accounted for the entire escalation of the price of sugar over the same timeframe.

Although individual crop prices appear to be affected by biofuels, the impact of biofuels on global or aggregated food prices are rather small. Worldwide biofuels production growth over the two years ending June 2008 is estimated to account for a little over 12 percent of the rise in the IMF’s food price index, of which, roughly 60%, 14% and 15% can be attributed to increased biofuels production in the US, Brazil and the EU respectively (Baier et al., 2009). This means that that about 88% of the rise in global food prices is caused by factors other than biofuels.

Table 3: Impacts of Increased Biofuel Production on Food Prices

Study	Coverage & Key Assumptions	Key Impacts of Biofuels on Food Prices
Banse et al. (2008)	2001-2010; Reference scenario without mandatory biofuel blending , 5.75% mandatory blending scenario (in EU member states), 11.5% mandatory blending scenario (in EU member states),	Price change under reference scenario , 5.75% blending, and 11.5% blending, respectively: Cereals: -4.5%, -1.75%,+2.5% Oilseeds: -1.5%, +2%, +8.5% Sugar: -4%, -1.5%, +5.75%
Baier et al. (2009)	24 months ending June 2008; historical crop price elasticities from academic literature; bivariate regression estimates of indirect effects	Global biofuel production growth responsible for 17%, 14% and 100% of the rises in corn, soybean and sugar prices, respectively, and 12 % of the rise in the IMF's food price index.
Lazear (2008)	12 months ending March 2008	US ethanol production increase accounted for 20% of the rise in corn prices.
IMF (2008)	Estimated range covers the plausible values for the price elasticity of demand	Range of 25-45% for the share of the rise in corn prices attributable to ethanol production increase in the US
Collins (2008)	2006/07-2008/09; Two scenarios considered: (1) normal and (2) restricted, with price inelastic market demand and supply	Under the normal scenario, the increase in ethanol production accounted for 30% of the rise in corn price; Under the restricted scenario, ethanol could account for 60% of the expected increase in corn prices.
Glauber (2008)	12 months ending April 2008	Increase in US biofuels accounted for about 25 percent of the rise in corn prices; US biofuels production accounts for about 10 percent of the rise in global food prices IMF global food commodity price index.
Lipsky (2008) and Johnson (2008)	2005-2007	Increased demand for world biofuels accounts for 70 percent of the increase in corn prices.
Mitchell (2008)	2002-mid-2008; ad hoc methodology: impact of movement in dollar and energy prices on food prices estimated, residual allocated to the effect of biofuels.	70-75 percent of the increase in food commodities prices was due to world biofuels and the related consequences of low grain stocks, large land use shifts, speculative activity and export bans
Abbott et al. (2008)	Rise in corn price from about $2 to $6 per bushel accompanying the rise in oil price from $40 in 2004 to $120 in 2008	$1 of the $4 increase in corn price (25%) due to the fixed subsidy of 51-cents per gallon of ethanol

Table 3 (Cont'd): Impacts of Increased Biofuel Production on Food Prices

Study	Coverage & Key Assumptions	Key Impacts of Biofuels on Food Prices
Rosegrant et al. (2008)	2000-2007; Scenario with actual increased biofuel demand compared to baseline scenario where biofuel demand grows according to historical rate from 1990-2000	Increased biofuel demand is found to have accounted for 30 percent of the increase in weighted average grain prices, 39 percent of the increase in real maize prices, 21 percent of the increase in rice prices and 22 percent of the rise in wheat prices.
Fischer et al. (2009)	(1) Scenario based on the IEA's WEO 2008 projections; (2) variation of WEO 2008 scenario with delayed 2nd gen biofuel deployment; (3) aggressive biofuel production target scenario; (4) and variation of target scenario with accelerated 2nd gen deployment	Increase in prices of wheat, rice, coarse grains, protein feed, other food, and non-food, respectively, compared to reference scenario: (1) +11%, +4%, +11%, -19%, +11%, +2% (2) +13%, +5%, +18%, -21%, +12%, +2% (3) +33%, +14%, +51%, -38%, +32%, +6% (4) +17%, +8%, +18%, -29%, +22%, +4%

Banse et al. (2008) show that if the mandatory 5.75% biofuel blending in EU member states is implemented, it would cause real prices of cereals, oilseeds and sugar in 2010 to be 2.75%, 3.5% and 2.5% higher than that in the reference scenario. In the case of the implementation of mandatory 11.5% biofuel blending, the corresponding price changes would be 7%, 10% and 9.75% (see Table 3). Rosegrant et al. (2008) show that increased biofuel demand accounted for 30 percent of the increase in weighted average grain prices in 2000-2007 compared to the historical baseline. More specifically, increased biofuel demand is estimated to account for 39 percent of the increase in real maize prices, whereas it is estimated to account for 21 percent of the increase in rice prices and 22 percent of the rise in wheat prices.

Some of the rises in food commodity prices are not caused by market forces, such as the price of gasoline, pertaining to biofuels, but rather by policy induced demand growth. McPhail et al. (2008) argue that the elimination of federal tax credits and tariffs, and to a far lesser extent, mandates, in the US would reduce ethanol production by 18.6 percent, resulting in the decline of the price of corn by 14.5 percent. However, if gas prices are high enough, i.e., $3 per gallon or higher, biofuel production may be profitable without support policies; ethanol production can be expected to rise from the current levels of 6.5 billion gallons to 14 billion gallons, and corn price would remain at about $4 a bushel.

The existing literature not only assesses the impacts of biofuels on the 2007-2008 food crisis but also projects the impacts on food prices in the future. The International Food Policy Research Institute (IFPRI) finds price increases for maize of 23% to 72%, wheat of 8% to 30%, oilseeds of 18% to 76%, and sugar of 11.5% to 66%, in response to countries implementing the plans they have announced for biofuels by 2020 (ODI, 2008). Trostle (2008) projects price rises of 65%, 64%, 33% and 19%, for maize, sorghum, wheat and soy oil, respectively, due to the expansion of biofuels, rising energy costs and demand from emerging economies. Moreover, should biofuel production be frozen at 2007 levels for all countries and for all crops used as feedstock, maize prices can be expected to decline by 6 percent by 2010 and 14 percent by 2015, along with lesser price reductions for oil crops, cassava, wheat, and sugar (Rosegrant et al., 2008). If a global moratorium on crop-based biofuel production is imposed from 2007 onwards, by 2010, prices of key food crops would drop even further: by 20 percent for maize, 14 percent for cassava, 11 percent for sugar, and 8 percent for wheat.

Taheripour et al. (2010) emphasize the importance of including by-products when modeling the impact on non-energy commodity prices of expanded biofuel production in response to US and EU biofuel mandates. They show that the price of coarse grains increases sharply in the US, EU, and Brazil by 22.7%, 23.0%, and 11.9%, respectively, over the period 2006-2015; once by-products are incorporated into the model, the price of coarse grains exhibits significantly lower growth rates of 14%, 15.9%, and 9.6%, respectively. The inclusion of by-products reduces the price rise of oilseeds in the EU from 62.5% to 56.4% in the same period. The prices of most other agricultural commodities grow at a slightly lower rate when by-products are accounted for.

Fischer et al. (2009) model the prices of food staples in 2020 and 2030 under several different scenarios for biofuel production. Under a scenario based on the International Energy Agency's World Energy Outlook 2008 projections, price increases for both cereals and other crops in 2020 are about 10 percent higher compared to a reference scenario where biofuel development after 2008 is kept constant at the 2008 level. Since the contribution of second-generation biofuels is still small in 2020, a variation of this scenario, featuring delayed introduction of second-generation technologies, only results in moderate further crop price increases. In the more aggressive target scenario, based on the mandates and targets announced by several developed and developing countries, the impact of increased biofuel production on crop prices is much more significant: prices rises of about 30 percent. When the target scenario is modified to incorporate the accelerated introduction of cellulosic ethanol, the price impact on cereals is cut in half to about 15 percent. Because of the high targets in developing countries, which feature a higher share of biodiesel and somewhat slower deployment of second-generation technologies, the price impact on non-cereal crops (especially vegetable oils) is greater than that on cereals.

In addition to the impacts on food price, Fischer et al. (2009) also examine the impact of expanded biofuel production on food supply. Although higher agricultural prices lead to increased cereal production, at range from around 100 million tons to 330 million tons under various scenarios, the increased cereal production is diverted to biofuel production and demand for food and feed would decrease. However the percentage reduction in food demand is found to be small; even in the worst case, the reduction in global cereal food consumption is about 29 million tons, which constitutes about a 1% of the global cereal consumption of 2,775 million tons in the reference case where biofuel production is frozen at 2008 levels.

One interesting observation from the existing literature is that the magnitude of the impacts of biofuels on food prices is very much sensitive to the models used to assess those impacts. Partial equilibrium models (e.g. Rosegrant et al., 2008; Trostle, 2008; ODI, 2008), which model the food and agricultural sector in isolation, ignoring this sector’s interaction with other sectors of the economy, find higher impacts on food prices. On the other hand, general equilibrium models, which account for interactions of various sectors and agents (e.g., Banse et al., 2008; Fischer et al., 2009) find the impacts to be relatively small.

7. Environmental Impacts of Biofuels

7.1. Impacts on Climate Change Mitigation

Biofuels replace fossil fuels, thereby avoiding associated GHG emissions. However, a large-scale expansion of biofuels could cause the release of GHG emissions to the atmosphere through land-use change as farmers might clear existing forests to meet increased crop demand to supply food and feedstock for biofuels. The climate change mitigation potential through fossil fuel replacement varies across types of feedstock, depending on feedstock production process/technology (e.g., usage of nitrogen fertilizer) and fossil fuel consumption in both production of feedstocks and subsequent conversion to biofuels. For example, useful heat and electricity may be cogenerated along with liquid fuel in some biofuel production systems, and plants differ in their use of fossil inputs or residual plant materials like straw for process energy (Fischer et al. 2009). Even for a particular feedstock, standard life-cycle analyses (LCA) of biofuels in the literature exhibit a wide range in terms of the overall reduction in GHG emissions due to varying underlying assumptions on system boundaries, co-product allocation, and energy sources used in the production of agricultural inputs and feedstock conversion to biofuels. Nevertheless, most studies show that biofuels do yield some emission reductions relative to their fossil fuel counterparts when emissions from the direct or indirect land use changes brought about by biofuel feedstock production are excluded.

Based on life-cycle assessments, ethanol from sugarcane in Brazil is found to deliver the greatest reductions in GHG emissions. This is due to high yields and the use of sugarcane waste (i.e., bagasse) for process energy as well as for the cogeneration of electricity (Macedo et al., 2008). The 25% ethanol blending mandate (E25) was calculated to reduce 1.87 ton of CO_2eq for each cubic meter ethanol used in 2005/2006 in Brazil. OECD (2008) estimates that sugar cane ethanol reduces GHG emissions by 90% as compared to an equivalent amount of gasoline. The next best are second-generation biofuels from cellulosic feedstocks, which have yet to become widespread commercially, with typical life-cycle GHG reductions in the range of 70 to 90% relative to gasoline or diesel (IEA, 2006a). Numerous studies anticipate that advanced biofuels could dramatically reduce life-cycle GHG emissions compared to first generation biofuels because of higher energy yields per hectare and energy for processing available from the left-over parts of the plants (mainly lignin), similar to the use of bagasse in ethanol production in Brazil today (FAO, 2008a). Some studies indicate that the savings could approach and even exceed 100% in cases, such as where the cogeneration of electricity displaces coal-fired electricity from the grid (Doornbosch and Steenblik, 2007). Similarly, syndiesel production via gasification with Fischer-Tropsch processing can supply GHG savings of close to 100% or even higher than regular diesel when including credits from the surplus renewable electricity that is produced (RFA, 2008).

Ethanol from sugar beets offers life cycle GHG reductions of roughly 40% to 60% (IEA, 2006a), putting it in the middle of the pack amongst biofuels, while ethanol produced from wheat generates slightly lower GHG reductions of 30% to 55 % (Fischer et al., 2009), although there is considerably more variation in the values for wheat in the literature, from as low as 18% to as high as 90%. Ethanol from maize generates the smallest reductions of GHG, and its performance is most variable, with results ranging from zero savings (even negative in some cases) up to more than 50 % savings compared to using fossil gasoline. Farrell et al. (2006) report that corn based ethanol, in the US, could reduce only 13% GHG emissions because the production process is so energy intensive[11]. EBAMM (2005) finds that corn-based ethanol delivers net emission savings of only 130 kg CO_2eq/m^3 of ethanol, almost 15 times less than that delivered by sugarcane ethanol. Despite this poor GHG balance, corn based ethanol occupies the largest share of the global biofuels market (as of 2007) due to vast US production (OECD, 2008). However, more recent studies (e.g., Liska et al., 2009) shows that the reduction potential could be significantly improved to 48% to 59% through enhanced yields and crop management, biorefinery operation, and co-product utilization[12].

Of biodiesel from first generation feedstocks, biodiesel from palm oil is generally considered to yield the most substantial GHG savings, typically in the range of 50–80 percent (FAO, 2008a). However, estimates of GHG savings from biodiesel from palm oil are especially prone to understating the full GHG impacts since palm plantations in South East Asia often replace

---

[11] The energy inputs comprise almost 80% of the energy output.

[12] It could be increased to 67% in the case of an advanced closed-loop biorefinery with anaerobic digestion.

tropical forest or peat land, resulting in the release of tremendous amounts of CO_2 from those natural reservoirs. Biodiesel derived from sunflower and from soybean both deliver significant GHG savings, but a wide range of values is found in the literature, depending on the different assumptions used in each study, particularly in the case of soybean biodiesel. Whereas emission savings from biodiesel based on sunflower appear to converge around 60 to 80%, the emission savings from soybean biodiesel tend to be around 50 to 70%. The wide variation in values is explained by the disparity in agricultural yield across regions, the assumptions made regarding the allocation of glycerin (an important co-product from the manufacture of soybean biodiesel), as well as the type of chemicals and process energy utilized (Menichetti and Otto, 2009). Another important feedstock for biodiesel is rapeseed, and a large number of studies have analyzed the GHG impacts of biodiesel from rapeseed. GHG savings from rapeseed based biodiesel typically range 40 to 60 percent (IEA, 2006a).

The rosy picture of the GHG savings potential of biofuels disappears once the release of carbon stored in forests or grasslands during land conversion to crop production is taken into account[13]. Several studies find that if emissions related to land-use change caused by biofuel expansion are included, the emissions would be so high that it would take tens to hundreds of years to offset those emissions through the replacement of fossil fuels. The number of years required to offset GHG released from land conversion by the emission reduction through the replacement of fossil fuels with biofuels is also known as the ‘carbon payback period’ (see e.g., Fargione et al. 2008; Danielsen et al. 2009; Searchinger et al. 2008). Fargione et al. (2008) estimate that it would take 48 years to repay if Conservation Reserve Program land is converted to corn ethanol production in the US; over 300 years to repay if Amazonian rainforest is converted for soybean biodiesel production; and over 400 years to repay if tropical peatland rainforest is converted for palm-oil biodiesel production in Indonesia or Malaysia. Similarly, Danielsen et al. (2009) estimate that 75 to 93 years of biofuel use would be necessary for the carbon savings to make up for the carbon lost via forest conversion, varying upon how the forest is cleared. They also estimate that the conversion of peatland would require more than 600 years to yield GHG savings, whereas cultivation of oil palm on degraded grassland could produce GHG savings within 10 years.

---

[13] Note however that converting degraded savannas for sugar cane production, or jatropha cultivation, may increase below-ground carbon stocks (Fischer et al., 2009).

Searchinger et al. (2008) argue that a decline in US corn exports due to the diversion of corn to increase ethanol output by 56 billion liters above projected levels in 2016 will encourage other countries to increase corn production. If the new production occurs on land that was previously forest or grassland, 167 years of use of ethanol from maize in the US will be necessary to offset the emissions from this indirect land-use change. Even second generation biofuels are not attractive from this perspective. For example, if switchgrass is grown for biofuels on U.S. corn lands, the ensuing indirect land-use change would have a carbon payback period of 52 years and would increase emissions over 30 years by 50%. Hertel et al. (2010a), in a general equilibrium study, find the indirect land use change caused by the escalation of US maize ethanol production to satisfy the 2015 mandated level of 56.7 billion liters to be two-fifths of that estimated by Searchinger et al. (2008). Their estimate of the emissions resulting from this indirect land-use change amounts to one-fourth of that calculated by Searchinger et al. (2008)[14]. When combined with the direct emissions from US maize ethanol production, this corresponds to a carbon payback period of 28 years.

Using an engineering technique, Fritsche & Wiegmann (2008) compare GHG balances for biofuels that include the effect of direct as well as well as indirect land use change on emissions (see Table 4). All the biofuels considered generate GHG savings when the effects of land use change are excluded, but these savings are diminished considerably when grassland is converted to the cultivation of feedstock rather than using existing cropland. Indirect land use change resulting from biofuel production is found to have an even greater impact on GHG emissions from biofuels, showing biofuels to increase GHG emissions relative to their fossil fuel counterparts in most of the cases.

---

[14] Hertel et al. (2010) estimate the associated CO_2 emissions at 800 grams of CO_2 per MJ, or 27 grams per MJ per year over 30 years of ethanol production, while Searchinger et al. (2008) estimate about 3000 grams of CO_2 per MJ, or around 100 g per MJ if allocated over 30 years.

Table 4: Greenhouse Gas Balances of Biofuels in 2005

			GHG Emissions (% change)		
	Feedstock	Previous Land Use	No LUC	With Direct LUC	With Indirect LUC
Biodiesel	Waste Oil	n.a.	-90	n.a.	n.a.
	Rapeseed	Cropland	-58	-58	+5 to +69
	Rapeseed	Pasture	-58	-25	+39 to +102
Ethanol	Sugar cane (Brazil)	Cropland	-71	-71	-35 to +1
	Maize	Cropland	-55	-55	-22 to +11
	Maize	Pasture	-55	-37	-5 to +28
	Wheat	Cropland	-49	-49	+6 to +63
	Wheat	Pasture	-49	-20	+36 to +92

Source: Fritsche & Wiegmann (2008) in Fischer et al. (2009)

Note: Waste oil includes waste vegetable and animal oils. LUC stands for land use change. Direct LUC refers to emissions including those arising from the land conversion to cultivate the biofuel, whereas indirect LUC refers to emissions including those arising from the conversion of land elsewhere to replace production displaced by biofuel cultivation.

Using a general equilibrium approach to capture emissions from land use change, Fischer et al. (2009) estimate net GHG savings under various scenarios for the deployment of biofuels (see Table 5). Since the carbon losses from land use change are incurred at the time of land conversion, while greenhouse gas savings from the substitution of biofuels for fossil fuels accrue gradually over time, the net GHG savings resulting from the first-generation biofuels would not be positive in the first 20 years in any of the scenarios, and only in some scenarios in the first 30 years. It would take 50 years to achieve a sizable savings of GHG emissions, even in the aggressive biofuel deployment scenario that includes second generation biofuel (scenario TAR-V1).

Table 5: Net Cumulative Greenhouse Gas Savings (Gt CO_2e)

Biofuel	Scenario	2000-2020	2000-2030	2000-2050
First generation	WEO-V1	-2.4 to -1.6	-0.8 to 0.7	2.8 to 6.2
	WEO-V2	-2.6 to -1.8	-1.3 to -0.3	1.4 to 5.3
	TAR-V1	-5.3 to -4.1	-3.5 to -0.6	5.3 to 12.4
	TAR-V3	-3.6 to -2.5	-0.8 to 1.6	5.7 to 10.8
Second generation	WEO-V1	< 0.05	0.1 to 0.4	1.8 to 3.3
	WEO-V2	0	0	0.4 to 0.8
	TAR-V1	< 0.05	0.2 to 0.8	3.4 to 6.2
	TAR-V3	-0.2 to 0.6	1.4 to 3.5	9.4 to 16.2
Total	WEO-V1	-2.4 to -1.6	-0.7 to 1.1	4.5 to 9.4
	WEO-V2	-2.6 to -1.8	-1.3 to 0.3	1.8 to 6.1
	TAR-V1	-5.3 to -4.0	-3.2 to 0.2	8.7 to 18.6
	TAR-V3	-3.8 to -1.8	0.7 to 5	15.1 to 27

Source: Fischer et al. (2009)

Note: Biofuel deployment projected by the IEA as the reference scenario in the World Energy Outlook 2008 is reflected in the WEO scenarios, while more aggressive biofuel penetration reflecting the successful implementation of announced biofuels targets around the world is encapsulated in the TAR scenarios. The scenarios are further differentiated by variants representing the schedule of second generation biofuel deployment, featuring either expected deployment (V1), delayed deployment (V2) or accelerated deployment (V3). The range of estimates signifies optimistic and pessimistic assumptions regarding the possible GHG savings from biofuels and the carbon impacts of land use change.

Some studies evaluate the attractiveness of biofuels as a GHG mitigation option. A rough, indicative calculation by the OECD projects that lowering GHG through policy support to biofuels in the US, Canada, and Europe in 2013-2017 would cost taxpayers and consumers on average between USD 960 and 1,700 per ton of CO_2-equivalent avoided (OECD, 2008). Righelato and Spracklen (2007) find that emission reductions through biofuels would be less attractive economically as compared to afforestation in pasture land. Similarly, Danielsen et al. (2009) suggest that reducing deforestation may be a more effective climate change mitigation strategy than the use of biofuels. Tax credits for ethanol production tend to encourage an overall increase in vehicle miles traveled and a delay in the adoption of more fuel-efficient cars, which can lead to greater GHG emissions, while binding mandates, by pushing fuel prices up, may produce some GHG reductions from reduced vehicle miles traveled and increases in fuel economy (Bento, 2009). Tollefson (2008) asserts that an improvement of one mile per gallon in average US vehicle fuel efficiency may decrease GHG emissions the same as all current United States ethanol production from maize. Doornbosch and Steenblik (2007) estimate that GHG mitigation costs of US ethanol based on corn and EU ethanol based on sugar beet and corn would be as high as US$500/tCO2 and US$4,520/tCO2 respectively. Similarly, Enkvist et al. (2007) finds that energy efficiency improvement in heating and air-conditioning systems would be cheaper by €40 than biofuels. Amatayakul and Berndes (2007) estimate the annual average cost of the substitution of gasoline with ethanol in Thailand to be 25-195 US$/t$CO_2$eq which is much higher than the price of project-based certified emission reductions traded during 2006; this would be, however cheaper than the cost of substitution of fossil fuels with biofuels in Europe.

7.2. Biofuels and Local Air Quality

In most urban areas, road transport is the primary source of particulate matter (PM_{10}) and emissions from fuel combustion, which poses an important public health concern (Krzyzanowski et al., 2005). The replacement of fossil fuels with biofuels for transportation has the potential to reduce local air pollution in several ways. First, apart from rapeseed-based biodiesel, biofuels generally cause less primary PM_{10} and volatile organic chemicals (VOCs) than fossil fuels[15] . Many studies can be found in the scientific literature on exhaust emissions of biodiesel or biodiesel blends. Second, compared to their fossil fuel counterparts, biodiesel does not produce sulfur emissions, while ethanol substantially lowers sulfur emissions, and both emit far less carbon monoxide (CO), which are two major threats to local air quality (USAID, 2008; EPA, 2002).

However, biofuels, particularly biodiesel, generate up to 70% higher NOx emissions (and could also raise concentrations of NO_2-based secondary PM_{10}), depending on feedstock, which enables ozone formation in conjunction with VOCs and other pollutants (NARSTO, 2000). Most studies show a slight increase in NOx and a reduction of PM when diesel is replaced with biodiesel (Cardone et al., 2003; Kalligeros et al., 2003; McCormick and Aleman, 2005). However, if the objective is the improvement of local air quality, the performance of biodiesel should also be compared to fuels other than fossil diesel that are currently available. Table 6 compares the average tailpipe NO_x, PM and VOC emissions of a medium-sized passenger car running on

---

[15] A recent study in Thailand, however, found that biofuel in motorcycles could produce slightly higher VOC emissions than gasoline (PCD, 2008).

different biodiesel blends with premium unleaded petrol, liquefied petroleum gas (LPG) and compressed natural gas (CNG). It can be seen that far greater reductions in NO_x and PM can be achieved by shifting from diesel to these other readily available fossil fuels than by switching to biodiesel blends (Russi, 2008). Even though biodiesel can deliver better performance in terms of VOC than LPG, a 20% blend is necessary to surpass the performance of premium unleaded petrol and pure biodiesel is required to exceed the performance of CNG. These levels of blending are unlikely to be viable on a large scale.

Table 6: Average Tailpipe Pollutant Emissions Compared to Low Sulfur Diesel

	NO_x	PM	VOC
	(%)	(%)	(%)
Biodiesel (100%)	+10	-37	-76
Biodiesel (20% blend)	+3	-10	-24
Biodiesel (5.75% blend)	+1	-2	-4
Petrol (premium unleaded)	-88	-95	-9
LPG	-96	-95	36
CNG	-89	-94	-73

Note: Emissions based on medium-sized passenger car.
Source: Beer et al. (2004) and Morris et al. (2003) in Russi (2008).

Jacobson (2007) shows that a broad displacement of gasoline with high ethanol blends in the US would lead to greater emission of local air pollutants and negative health impacts from deteriorating air quality. Moreover, the cultivation of biofuel feedstocks can also affect local air quality through fugitive emissions of air pollutants. The frequent burning of cleared vegetation for biofuel production, as practiced in Brazil, Indonesia and Malaysia for example, causes severe smog and has adverse effects on human morbidity and mortality (Schwela et al., 2006). In addition, palm oil production may result in the fugitive emission of methane from water surfaces and liquid processing wastes (Yapp et al., 2008).

7.3. Impacts on Biodiversity and Ecosystems

The effect of biofuel production on biodiversity depends on the type of land utilized. If degraded lands are restored for biofuel feedstock production, the impact could be positive. On the other hand, if peat lands are drained or natural landscapes are converted to biofuel plantations, the effect is generally negative. Since many current biofuel crops are especially suited for cultivation in tropical areas, biofuel expansion could convert natural ecosystems in tropical countries that are biodiversity hotspots into feedstock plantations (CBD, 2008). Ogg (2008) points out that European biofuel subsidies are major drivers of rainforest loss in Indonesia, the source of the lowest cost vegetable oil (palm) in the world (FAPRI, 2008). The expansion of oil palm plantations, for example, which do not require much fertilizer or pesticide, can trigger the loss of rainforests and the biodiversity in them. Koh and Wilcove (2008) estimate that half of oil palm plantations expanded in Malaysia and Indonesia replaced natural forests. Similarly, more than 60% of Brazil's sugarcane cultivation is done in the Mata Atlantica region, one of the foremost biodiversity hotspots in the world, and sugarcane and soybean production are contributing to the clearing of the Cerrado, the world's most biodiverse savannah (USAID, 2009). Nelson and Robertson (2008) find that areas rich in bird species diversity could be at risk from the expansion of agricultural lands in Brazil. Large scale expansion of biofuels could result in loss of agro-biodiversity due to the intensification of agriculture through mono-cropping since most biofuel feedstock plantations rely on a single species (FAO, 2008a). The Royal Society (2008) highlights the vulnerability of grasses used as biofuel feedstocks, such as sugar cane, to new pests and diseases. These pests and diseases have the potential to destroy the crop and spread into natural habitats (Kartha, 2008).

Second-generation biofuels present another set of problems: some of the promising feedstocks are classified as invasive species, which will require proper management in order to avoid unintended consequences (FAO, 2008a). In addition, many of the enzymes necessary to process the feedstock would also have to be carefully contained in industrial production processes as they have been genetically modified to improve their efficiency (CFC, 2007). However, there is also some evidence to suggest that biodiversity can be enhanced and ecosystem functioning restored by biofuel feedstock cultivation when it consists of the introduction of new perennial mixed species to degraded or marginal areas (CBD, 2008). Tilman et al. (2006) use experimental data from test plots on degraded and abandoned soils to demonstrate that, compared to maize-ethanol or soybean-biodiesel, low-input high diversity mixtures of native grassland perennials yield higher net energy gains, greater GHG emission reductions and less agrichemical pollution, and that this performance is positively correlated to the number of species.

The potential impact of biofuels on water supply is another serious concern. Approximately 70% of the freshwater around the world is already dedicated to agriculture (Comprehensive Assessment of Water Management in Agriculture, 2007). The main biofuel feedstocks, in particular, sugarcane, oil palm and maize, require relatively plentiful water at commercial yield levels. This implies increased demand for irrigation and strain water supply. For example, despite the fact that 76% of the sugarcane produced in Brazil is under rainfed conditions, some irrigated sugar-producing regions in northeastern Brazil are already approaching the hydrological limits of their river basins, e.g., the São Francisco river basin (FAO, 2008a). De Fraiture et al. (2008) find that the strain on water resources would be so significant that large biofuel programs based on traditional feedstocks would be challenging in India and China.

Increased water pollution due to biofuels is also a concern in some countries. Moreira (2006) points out that water pollution due to increased use of fertilizers and agrochemicals, sugarcane washing and other stages in the ethanol production process remain major concerns in Brazil. Higher crop prices tend to encourage farmers to intensify fertilizer application on existing cropland in order to enhance yields during years with good weather conditions and take advantage of higher crop prices (Abler and Shortle, 1992; Herten et al., 1990). Simpson et al. (2008) note that expanded or intensified corn acreage for ethanol, even when accounting for fertilizer and land conservation measures, will result in a significant loss of nitrogen and phosphorous to water. Runge and Senauer (2007) warn that the displacement of maize-soybean rotations with continuous maize cultivation for ethanol production in the United States will have negative consequences: the ensuing runoff from additional nitrogen fertilizer application will compound problems, such as eutrophication in the “dead zone” in the Gulf of Mexico.

Biofuels also affect soils both positively and negatively. Conversion of forest to plantations may lead to the loss of soil carbon (Guo and Gifford 2002 and Murty et al. 2002), but growing perennials, such as oil palm, sugarcane, switch grass, instead of annuals crops could increase soil cover and organic carbon levels. The impacts differ with crop type, soil type, nutrient demand and land preparation necessary. Sugarcane generally has less of an impact on soils than rapeseed, maize and other cereals because soil fertility is maintained in sugarcane cultivation by recycling nutrients from sugar-mill and distillery wastes (IEA, 2006a). However, the diversion of agricultural residues, such as bagasse, as an energy input to biofuel production reduces the amount of crop residues available for recycling, which could degrade soil quality, and soil organic matter in particular (Fresco et al., 2007). Hill et al. (2006) explain that soybean production for biodiesel in the US requires far less fertilizer and pesticide per unit of energy produced than maize production for ethanol, and that both feedstocks fare poorly in comparison to second generation feedstocks such as switchgrass, woody plants or diverse mixtures of prairie grasses and forbs. Finally, the IEA (2006a) finds that perennial lignocellulosic crops such as eucalyptus, poplar, willow or grasses can be grown on poor-quality land, increasing soil carbon and quality, with less-intensive management and fewer fossil-energy inputs.

8. Impacts of Biofuels on Land Use

The demand for land to produce biofuels augments the traditional demands of agriculture and forestry. Moreover, global population growth as well as rising per capita consumption of developing countries can be expected to increase demand for land for food supply in the future. While some of this demand may be met with improved crop yields per unit area, which has been increasing at about 1.5% in recent decades for staple crops, this would only increase production by 40% by 2030, requiring a conservatively estimated 500 Mha more land to be brought into cultivation in order to meet the additional demand for food alone (Bustamante et al, 2009). There exist a large number of studies estimating land requirement to meet specified biofuel targets (see Gurgel et al., 2007; FAPRI, 2008; Nowicki et al., 2007; European Commission, 2006; OECD, 2006; FAO, 2008c; Ravindranath et al., 2009; Ozdemir et al, 2009; Russi, 2008). However, the results vary considerably due difference in methodological approach, different assumptions about crops used and conversion efficiencies from biomass to fuel.

Where will the land for additional biofuel production come from? Gurgel et al. (2007) find that the expansion of biofuel cultivation will occur largely at the expense of natural forest and pasture land (especially when no land supply response is assumed), whereas cropland, managed forest, and natural grassland show little net change. Much of this land dedicated to biofuel feedstock cultivation is found in Africa and Central and South America, and also, to a lesser extent, in the

US, Mexico and Australia and New Zealand, reflecting the existence of vast natural forests and pastures in those areas and the superior biomass productivity of tropical regions, whereas China and India, due to their immense food demand and relatively lower biomass land productivity, are not found to be regions supporting significant expansion of land for biofuel feedstocks. Hertel et al. (2010b) also show that largest net reductions in land cover tend to be in pasture land, although large percentage decreases in forest land are found in Brazil and the EU. Another important factor is that when biofuel producing countries convert cropland to biofuel production, the reduced food exports and higher commodity prices induce land to be cleared for crops in tropical countries such as Brazil, Argentina and Indonesia to satisfy the unmet food demand (Ogg, 2009).

Aside from land conversion for biofuel feedstock cultivation, Hertel et al. (2010b) use the Global Trade Analysis Project (GTAP) model show that the harvested area for various crops can also be expected to change as a result of expanded biofuel production from 2006 to 2015 to satisfy US and EU biofuel mandates. They find substantial increases in harvested area for oilseeds in the EU, Canada and Oceania (47.8%, 19.4% and 19.3%, respectively) and for sugarcane in Brazil (22.9%). Coarse grain acreage is seen to rise by 6.2% in the US but only increases moderately in most other regions (except for significant declines in Brazil and the EU). Oilseed acreage, however, exhibits significant gains in all regions, implying that the EU biofuels mandate will have immense repercussions on the global oilseeds market. Hertel et al. (2010a) incorporate market-mediated responses and by-product use into their analysis of the land requirements of increased maize ethanol production in the US to meet the mandated volume in 2015. They show that these factors reduce the gross feedstock land requirement of 15.2 Mha so that only 0.28 ha of land conversion occurs for every hectare of maize cultivation diverted to ethanol production, resulting in the global conversion of 3.8 Mha of forest and pasture land to cropland due to the US mandate.

One approach to counteracting the growing scarcity of arable land would be to bring abandoned agricultural land back into production. Field et al. (2008) estimate that significant amounts of abandoned agricultural land – between 475 and 580 Mha – could be allocated to biofuel production. Although abandoned cropland, pasture land, forests, or other natural areas could all be suitable for biofuel cultivation, De Vries et al. (2007) suggest that mainly grassland will be targeted for conversion. This refers to abandoned land and permanent pastures, which have certain advantages in that there are no bans on their conversion, whereas some countries, for example, India and China, have legal bans on the conversion of forest land for crop cultivation. Moreover, permanent pastures cover an area of 3,378 Mha worldwide, and although some proportion of that will be unsuitable for cropping, it dwarfs the current arable area of 1,411 Mha (FAO, 2009).

It is often said that biofuel production should focus on degraded or marginal lands, yet degraded lands are ill suited for agriculture by definition, typically lacking water and nutrients. Some crops, such as jatropha, are promoted as feedstocks that can withstand droughts, but yields are low in areas of low rainfall, and each potential feedstock presents known constraints in soils, water supply, and temperature (Bustamante et al., 2009). Since diversion of water for irrigation has its own impacts on biodiversity and fishery resources, lands with sufficient water supply but that are not in high demand may be the best candidates for conversion to biofuel production (De Fraiture et al., 2009). Some marginal lands just lack chemical inputs, and are thus good targets for enhanced food production, while some have physically degraded soils of little value for food production or forest but could be candidates for perennial grasses and trees, which build soil carbon in areas that meet temperature requirements, and may serve as second generation biofuel feedstock.

More importantly, when and if the production of cellulosic ethanol becomes commercially viable, crop and forestry residues that are not currently part of the energy supply chain will be able to contribute to biofuel production, relieving some of the pressure on land. For example, Graham et al. (2007) note that 100 Mt of corn residues could be salvaged for biofuel production from land planted to corn in the USA alone. It is important to note that agricultural and forestry wastes represent the only sources of biofuel feedstock that do not necessitate land use change beyond what occurs for food production and existing forestry activities.

9. Conclusions and Further Remarks

The world has witnessed rapid growth in the production and consumption of biofuels over the past several years. Production of fuel ethanol and biodiesel grew by 26% and 172%, respectively, between 2004 and 2006. While high oil prices might have favored this growth, it was mainly driven by policies such as mandates, targets and subsidies catering to energy security and climate change considerations. However, apprehension due to the global food crisis in 2007-2008 and ambiguity regarding the environmental footprint of biofuels led many industrialized as well as developing countries to reconsider their earlier optimism regarding biofuels and adopt a more cautious approach. They announced that their biofuels program would be redesigned in order to avoid a fuel vs. food conflict. This also led to a shift in focus from first generation biofuels to second generation or advanced biofuels technologies. In addition, the current financial crisis and the drop in oil prices from prior peaks is expected to further retard the growth of biofuels in the near future.

The contribution of biofuels to the escalation of food prices in 2008 and the ensuing food crisis is a point of some contention. Most studies agree that expanded biofuel production, by raising demand for feedstock commodities, does put upward pressure on food prices, but there is considerable variation in estimates of the magnitude of this effect. This estimation is complicated by the presence of several other important drivers of food price, such as oil price, climate variability and currency fluctuation. For the most part, general equilibrium studies tend to find a lower impact on food price from biofuel production since they include the effect of price responses. Second generation biofuels may enable us to cease diverting agricultural commodities fit for human consumption to fuel production and may even enable us to utilize the waste material from agricultural production, but they may still compete for land with food crops.

Despite differences in results and uncertainties of calculations, the literature indicates that greenhouse gas balances are not favorable for all biofuel feedstocks, particularly when cultivation of feedstock causes the conversion of native ecosystems to crop lands directly or indirectly. However, the cultivation of perennial biofuel feedstocks on reclaimed marginal or degraded land may yield GHG savings. Assessments of the impact of biofuels on urban air quality are mixed; they may improve local air quality in terms of some pollutants but exacerbate the situation in terms of other pollutants. In any case, other fuels such as LPG and CNG can deliver greater improvements in air quality.

Expanded biofuel production, particularly at the scale necessary to meet US and EU biofuel mandates, will have significant impacts on land use around the world. It comes as no surprise that cropped area for biofuel feedstock commodities such as maize, sugarcane and oilseeds are anticipated to grow, sometimes at the expense of other agricultural products. However, additional land will also need to be brought into cultivation to satisfy the demand for feed and fuel. Most of this additional land is expected to come from existing pasture land, given that pasture is plentiful in comparison to other types of land and its conversion generally generates fewer undesirable consequences in terms of GHG emissions and other environmental factors. The use of marginal land for biofuel feedstock cultivation would be ideal, but making such land productive enough (whether via the selection of suitable crops, or the supply of requisite inputs, etc.) to be a serious option is an ongoing challenge, albeit one that the realization of second generation technologies may make feasible.

While biofuels are an important renewable energy resource that can substitute for fossil fuels, particularly in the transport sector, the prospects for their success are still uncertain. Unlike renewable energy such as solar and wind, where energy carriers are free of costs, biofuels' energy carrier, feedstock, accounts for the highest share of total production costs. Whether or not biofuels play a significant role in the future energy supply mix depends on the development of biofuel production that avoids or lowers food vs. fuel competition while also contributing to environmental goals. Dramatic improvements in global agricultural productivity through wider adoption of best agricultural practices in developing countries could help to some extent. Second generation biofuels have the potential to overcome many of the limitations of first generation biofuels. However, since even first generation biofuels are not economically viable in the absence of fiscal incentives or high oil prices (with a few exceptional cases), commercial scaling up of second generation biofuels seems unlikely in the near future.

References

Abbott, Philip C., Christopher Hurt and Wallace E. Tyner. 2008. What's Driving Food Prices? Issue Report. Farm Foundation. July 2008.

Abler DG, Shortle JS (1992). Environmental and farm commodity policy linkages in the US and the EC. Euro. Rev. of Agric. Econ. 19 (2): 197-217.

Ahring, B. 2007. Sustainable Biofuels for the Transport Sector. Discussion Paper 2007-4. OECD-ITF Joint Transport Research Centre.

Amatayakul, W., and Berndes, G. 2007. Fuel ethanol program in Thailand: energy, agricultural, and environmental trade-offs and prospects for CO2 abatement. Energy for Sustainable Development, Volume 11, Issue 3, September 2007, Pages 51-66.

Baier, Scott, Mark Clements, Charles Griffiths, and Jane Ihrig. 2009. Biofuels Impact on Crop and Food Prices: Using an Interactive Spreadsheet. International Finance Discussion Papers: Number 967, March 2009. Board of Governors of the Federal Reserve System.

Banse, M., Hans van Meijl, A. Tabeau, and G. Woltjer. 2008. Impact of EU Biofuel Policies on World Agricultural and Food Markets. Paper prepared for presentation at the 107th EAAE Seminar "Modelling of Agricultural and Rural Development Policies". Sevilla, Spain, January 29th -February 1st, 2008

Banse, M., H. van Meijl, A. Tabeau, and G. Woltjer. 2008. "Will EU Biofuel Policies Affect Global Agricultural Markets" European Review of Agricultural economics. 35(2):117-141.

Bento, Antonio M. 2009. Biofuels: Economic and public policy considerations. Pages 195-203 in R.W. Howarth and S. Bringezu (eds.).

BNDES and CGEE. 2008. Sugarcane-based bioethanol: energy for sustainable development. Rio de Janeiro: BNDES.

Bustamante, M.M.C., J. Melillo, D.J. Connor, Y. Hardy, E. Lambin, H. Lotze-Campen, N.H. Ravindranath, T. Searchinger, J. Tschirley, H. Watson. 2009. What are the final land limits?. Pages 271-291 in R.W. Howarth and S. Bringezu (eds). 2009. Biofuels: Environmental Consequences and Interactions with Changing Land Use. Proceedings of the Scientific Committee on Problems of the Environment (SCOPE) International Biofuels Project Rapid Assessment, 22-25 September 2008, Gummersbach Germany. Cornell University, Ithaca NY, USA.

Cardone, M., Mazzoncini, M., Menini, S., Rocco, V., Senatore, A., Seggiani, M., Vitolo, S., 2003. Brassica carinata as an alternative oil crop for the production of biodiesel in Italy: agronomic evaluation, fuel production by transesterification and characterization. Biomass and Bioenergy 25 (6), 623–636.

CBD. 2008. The potential impact of biofuels on biodiversity. Note by the Executive Secretary for the Conference of the Parties to the Convention on Biological Diversity (CBD), 19–30 May 2008, Bonn, Germany (draft, 7 February 2008).

CFC. 2007. Biofuels: strategic choices for commodity dependent countries. Commodities Issues Series. Common Fund for Commodities (CFC). Amsterdam.

Collins, K. 2008. The Role of Biofuels and Other Factors in Increasing Farm and Food Prices: A Review of Recent Development with a Focus on Feed Grain Markets and Market Prospects. Report commissioned by Kraft Food Global, June 19, 2008. Available at: http://www.foodbeforefuel.org/files/Role%20of%20Biofuels%206-19-08.pdf.

Comprehensive Assessment of Water Management in Agriculture. 2007. Water for food, water for life: a comprehensive assessment of water management in agriculture. London, Earthscan and Colombo, International Water Management Institute.

Danielsen, F., Beukema, H., Burgess, N.D., Parish, F., Bruhl, C.A., Donald, P.F., Murdiyarso, D., Phelan, B., Reijnders, L., Struebig, M., Fitzherbert, E.B. 2009. Biofuel Plantations on Forested Lands: Double Jeopardy for Biodiversity and Climate. Conservation Biology, April 2009. Vol.23, Iss.2; p.348-358.

De Fraiture, C; Giordano, M; Liao, Y. 2008. Biofuels and implications for agricultural water use: blue impacts of green energy. Water Policy 2008. Vol.10; p.67-81.

De Fraiture, C. And G. Berndes. 2009. Biofuels and water. Pages 139-153 in R.W. Howarth and S. Bringezu (eds.). 2009. Biofuels: Environmental Consequences and Interactions with Changing Land Use. Proceedings of the Scientific Committee on Problems of the Environment (SCOPE) International Biofuels Project Rapid Assessment, 22-25 September 2008, Gummersbach Germany. Cornell University, Ithaca NY, USA.

De Vries B., D. van Vuuren, M. Hoogwijk. 2007. Renewable energy resources: their global potential for the first half of the 21st century at a global level – an integrated approach. Energy Policy 35(4): 2590-2610.

Doornbosch, R. and Steenblik, R. 2007. Biofuels: Is the Cure Worse Than the Disease? OECD Round Table on Sustainable Development. Paris, 11-12 September 2007.

EBAMM, 2005. ERG Biofuels Analysis Meta-Model. Release 1.0, Energy and Resources Group, University of California, Berkeley.

EBB. 2008. Statistics – The EU Biodiesel Industry. European Biodiesel Board, accessed from http://www.ebb-eu.org/stats.php in February 2009.

EIA. 2008. International Energy Outlook. DOE/EIA-0484 US Department of Energy/EIA, Energy Information Administration (EIA). Washington. D.C.

EIA. 2009. Short-Term Energy Outlook Supplement: Biodiesel Supply and Consumption in the Short-Term Energy Outlook. Energy Information Administration (EIA). US Department of Energy. April 2009.

Enkvist, P.-A., Naucler, T. & Rosander, J. 2007. A cost curve for greenhouse gas reductions. The McKinsey Quarterly, February.

EPA, 2002. Clean Alternative Fuels: Ethanol. United States Environmental Protection Agency (EPA). Fact Sheet EPA420-F-00-035.

European Commission. 2006. Communication from the Commission to the Council and the European Parliament. Renewable Energy Road Map. Renewable energies in the 21st century: building a more sustainable future. COM (2006) 848 final. Brussels.

FAPRI. 2008. US and world agricultural outlook. FAPRI Staff Report 08-FSR 1 ISSN 1534-4533. Food and Agricultural Policy Research Institute (FAPRI). Iowa State University and University of Missouri-Columbia, Ames, IO.

FAO. 2006. Global land use change matrix, Forest Resource Assessment WP 134, Food and Agriculture Organization of the United Nations (FAO). Rome.

FAO. 2008a. The State of Food and Agriculture. Biofuels: Prospects, Risks, and Opportunities. Food and Agriculture Organization of the United Nations (FAO). Rome.

FAO. 2008b. Soaring food prices: facts, perspectives, impacts and actions required. Document HLC/08/INF/1 prepared for the High-Level Conference on World Food Security: The Challenges of Climate Change and Bioenergy, 3–5 June 2008, Rome.

FAO. 2008c. Climate Change, Biofuels and Land. Infosheet for the High-level Conference on World Food Security: the Challenges of Climate Change and Bioenergy. Rome, 3-5 June 2008.

FAO. 2009. Land Use Database. FAOSTAT: http://faostat.fao.org/site/377/default.aspx#ancor

FAPRI. 2008. US and world agricultural outlook. FAPRI Staff Report 08-FSR 1 ISSN 1534-4533. Food and Agricultural Policy Research Institute (FAPRI). Iowa State University and University of Missouri-Columbia, Ames, IO.

Fargione, F.; Hill, J.; Tilman, D.; Polasky, S. and Hawthorne, P. 2008, Land clearing and the biofuel carbon debt. Science 319: 1235 – 1238.

Field, C., J.E. Campbell, D.B. Lobell. 2008. Biomass energy, the scale of the potential resources. Trends in Ecol. & Evol. 23: 65-72.

Fischer, Günther, Eva Hizsnyik, Sylvia Prieler, Mahendra Shah and Harrij van Velthuizen. 2009. Biofuels and Food Security. Prepared by the International Institute for Applied Systems Analysis (IIASA) for OPEC Fund for International Development (OFID). May 2009.

F.O.Licht. 2007. World Ethanol & Biofuels Report.

F.O.Licht. 2008. World Ethanol & Biofuels Report, Vol. 6 No. 10 (January 29, 2008).

Fresco, L.O., Dijk, D., and de Ridder, W. 2007. Biomass, food & sustainability: is there a dilemma? Utrecht, Netherlands, Rabobank.

GBEP. 2008. A Review of the Current State of Bioenergy Development in G8 +5 Countries. Global Bioenergy Partnership (GBEP)

Gibbs, H. K., M. Johnston, et al. 2008. Carbon payback times for crop-based biofuel expansion in the tropics: the effects of changing yield and technology. Environmental Research Letters 3(3).

Girard, Philippe and Abigail Fallot. 2006, Review of Existing and Emerging Technologies for the Production of Biofuels in Developing Countries, Energy for Sustainable Development, Volume X No.2 (June), pp 92-108

Glauber, J. 2008. Statement to the US Senate Committee on Energy and Natural Resources. Full Committee Hearing to Receive Testimony on the Relationship Between US Renewable Fuels Policy and Food Prices. SD-366. Washington DC: Hearing.

Goldemberg, J., et al., 2008. The Sustainability of Ethanol Production from Sugarcane. Energy Policy 36(4).

GSI. 2008. Biofuels, at what cost? Government Support for biodiesel in Malaysia. Global Subsidies Initiative (GSI): Geneva.

Graham, R. L., R. Nelson, J. Sheehan, R. D. Perlack and L. L. Wright. 2007. Current and Potential US Corn Stover Supplies. Agronomy Journal 99:1-11

Guo, L. B. and R. M. Gifford. 2002. Soil carbon stocks and land use change: a meta analysis. Global Change Biol 8 (4): 345-360.

Gurgel, Angelo; Reilly, John M.; and Paltsev, Sergey. 2007. "Potential Land Use Implications of a Global Biofuels Industry," Journal of Agricultural & Food Industrial Organization: Vol. 5 : Iss. 2, Article 9.

Hamelinck, Carlo N., André P.C. Faaij (2006), Outlook for Advanced Biofuels, Energy Policy 34, pp.3268-3283

Hertel, Thomas W., Alla A. Golub, Andrew D. Jones, Michael O'Hare, Richard J. Plevin, and Daniel M. Kammen. 2010a. Effects of US Maize Ethanol on Global Land Use and Greenhouse Gas Emissions: Estimating Market-mediated Responses. *BioScience* 60(3): 223–231.

Hertel, Thomas W., Wallace E. Tyner and Dileep K. Birur. 2010b. The Global Impacts of Biofuel Mandates. The Energy Journal, Vol. 31, No. 1.

Hill, J., Erik Nelson, David Tilman, Stephen Polasky and Douglas Tifany. 2006. "Environmental, Economic, and Energetic Costs and Benefits of Biodiesel and Ethanol Biofuels." Proceedings of the National Academy of Science, Vol 103, No. 30, pp. 11206-11210.

Hogan, M. 2005. 'German Biodiesel sales strong as oil prices rise', Reuters, 19 August

IEA. 2006a. World Energy Outlook 2006, Chapter 14, The Outlook for Biofuels. International Energy Agency (IEA). OECD Publications, Paris.

IEA. 2006b. Energy Technologies Perspectives, Chapter 5, Road Transport Technologies and Fuels. International Energy Agency (IEA). OECD Publications, Paris.

IMF. 2008. Is Inflation Back? Commodity Prices and Inflation. In World Economic Outlook October 2008 (pp. 83-128). Washington DC: International Monetary Fund (IMF).

IPCC. 2007. Mitigation of Climate Change, Contribution of Working Group III to the Fourth Assessment Report, Draft. Intergovernmental Panel on Climate Change (IPCC). http://www.mnp.nl/ipcc/pages_media/AR4-chapters.html

Jacobson, M.Z. 2007. Effects of ethanol (E85) versus gasoline vehicles on cancer and mortality in the United States. Environmental Science & Technology 41(11), pp. 4150-4157.

Johnson, S. 2008, April 25. Commodity Prices: Outlook & Risks. Washington DC: International Monetary Fund.

Johnston, M. and Holloway, T., 2007. A Global Comparison of National Biodiesel Production Potentials. Environmental Science & Technology, 41 (23), 7967-7973.

Kalligeros, S., Zannikos, F., Stournas, S., Lois, E., Anastopoulos, G., Teas, Ch., Sakellaropoulos, F., 2003. An investigation of using biodiesel/marine diesel blends on the performance of a stationary diesel engine. Biomass and Bioenergy 24 (2), 141–149.

Karekezi, S. et al., 2004. Traditional Biomass Energy: Improving its Use and Moving to Modern Energy Use, Thematic background paper, Bonn, Renewables 2004, January

Kartha, Sivan. 2006. Bioenergy and Agriculture: Promise and Challenges Environmental Effects of Bioenergy :2020. Vision for Food, Agriculture, and the Environment, Focus 14, brief 4 of 12.

Keeney, Dennis and Claudia Nanninga. 2008. Biofuel and Global Biodiversity. Institute for Agriculture and Trade Policy. Minneapolis, Minnesota.

Kojima, Masami, Donald Mitchell, and William Ward. 2007. Considering Trade Policies for Liquid Biofuels, The International Bank for Reconstruction and Development/The World Bank, Washington, D.C.

Koh, Lian Pin, and David S. Wilcove. 2008. Is oil palm agriculture really destroying tropical biodiversity? Conservation Letters 1, pp. 60–64.

Krzyzanowski et al. 2005. Health effects of transport-related air pollution. World Health Organization – Europe. Geneva: WHO, pp. 190

Lazear, E. P. 2008. Statement to the US Senate Committee on Foreign Relations. Responding to the Global Food Crisis. Washington DC: Hearing.

Lipsky, J. 2008. Commodity Prices and Global Inflation. New York: Council on Foreign Relations.

Liska, Adam J.; Yang, Haishun S.; Bremer, Virgil R.; Klopfenstein, Terry J.; Walters, Daniel T.; Erickson, Galen E.; Cassman, Kenneth G. 2009. Improvements in Life Cycle Energy Efficiency and Greenhouse Gas Emissions of Corn-Ethanol. Journal of Industrial Ecology, February 2009. Vol.13, Iss.1; p.58-74

Liu, D, 2005. Chinese development status of bioethanol and biodiesel. Presentation to Biofuels: An Energy Solution, 2005 World Biofuels Symposium, Tsinghua University, Beijing, 13-15 November.

Mandal, R. 2005. The Indian Biofuels Programme – national mission on bio-diesel. Presentation to the International Conference and Expo, Biofuels 2012: Vision to Reality, New Delhi, 17-18 October.

Macedo, I.C., J.E.A. Seabra and J.E.A.R. Silva. 2008. Green house gases emissions in the production and use of ethanol from sugarcane in Brazil: The 2005/2006 averages and a prediction for 2020. Biomass and Bioenergy 32(7): 582-595.

McCormick, R.L., Aleman, T.L., 2005. Effect of biodiesel fuel on pollutant emissions from diesel engines. In: Knothe, G., Van Gerpen, J., Krahl, J. (Eds.), Biodiesel Handbook. AOC.

McPhail, Lihong Lu and Bruce A. Babcock (2008) "Short-Run Price and Welfare Impacts of Federal Ethanol Policies." Working Paper 08-WP 468, Center for Agricultural and Rural Development, Iowa State University.

Menichetti E., and M. Otto. 2009. Energy balance and greenhouse gas emissions of biofuels from a life-cycle perspective. Pages 81-109 in R.W. Howarth and S. Bringezu (eds). 2009. Biofuels: Environmental Consequences and Interactions with Changing Land Use. Proceedings of the Scientific Committee on Problems of the Environment (SCOPE) International Biofuels Project Rapid Assessment, 22-25 September 2008, Gummersbach Germany. Cornell University, Ithaca NY, USA.

Mitchell, D., 2008. A Note on Rising Food Prices. Policy Research Working Paper No. 4682. The World Bank, Washington DC.

Moreira, J.R. 2006. Bioenergy and agriculture, promises and challenges: Brazil's experience with bioenergy. Vision 2020, Focus 14, Brief 8 of 12. Washington, DC, International Food Policy Research Institute.

Murty, D., M.U.F. Kirschbaum, R.E. McMurtrie, H. McGilvray. 2002. Does conversion of forest to agricultural land change soil carbon and nitrogen? A review of the literature. Global Chang Biol 8(2): 105-123.
NARSTO, 2000. An Assessment of Tropospheric Ozone Pollution: A North American Perspective. North American Research Strategy for Tropospheric Ozone (NARSTO).

Nelson GC, and Robertson RD. 2008. Green gold or green wash: Environmental consequences of biofuels in the developing world. Rev. of Agric. Econ. 30(3): 517-529.

Nowicki, P., H. van Meijl, A. Knierim, M. Banse, J. Helming, O. Margraf, B. Matzdorf. R. Mnatsakanian, M. Reutter, I. Terluin, K. Overmars, D. Verhoog, C. Weeger, H. Westhoek (2007). Scenar 2020 - Scenario study on agriculture and the rural world. Contract No. 30 - CE - 0040087/00-08. European Commission, Directorate-General Agriculture and Rural Development, Brussels.

ODI. 2008. Review of the indirect effects of biofuels, economic effects and food insecurity, – A Report to the Renewable Fuels Agency, published on the RFA website at www.renewablefuelsagency.org. Overseas Development Institute (ODI).

OECD. 2006. Agricultural Market Impact of Future Growth in the Production of Biofuels. Organisation for Economic Cooperation and Development (OECD), Paris, France.

OECD, 2008. Biofuels Support Policies: An Economic Assessment. Organisation for Economic Cooperation and Development (OECD). Paris.

OECD–FAO. 2008. Agricultural Outlook 2008–2017. Organisation for Economic Cooperation and Development–Food and Agriculture Organization of the United Nations (OECD-FAO). Paris.

Ogg CW. 2008. Environmental challenges associated with corn ethanol production. Geopolitics of Energy 30(1):13-18.

Ogg, Clayton W. 2009. Avoiding more biofuel surprises: The fuel, food and forest trade-offs. Journal of Development and Agricultural Economics Vol. 1(1), pp. 012-017, April, 2009

Ozdemir, Enver D., Marlies Hardtlein, Ludger Eltrop. 2009. Land substitution effects of biofuel side products and implications on the land area requirement for EU 2020 biofuel targets. Energy Policy 37: 2986–2996

Pate, Ron and Mike Hightower. 2008. Overview of Biofuels from the Energy-Water Nexus Perspective and the Promise and Challenge of Algae as Biofuel Feedstock. Sandia National Laboratories. Presentation. Spring.

PCD. 2008. Biofuel Policy and Air Quality in Thailand. Presentation given at the Better Air Quality Workshop 12-14 November, 2008, Bangkok, Thailand.

Ravindranath, N.H., R. Manuvie, J. Fargione, J.G. Canadell, G. Berndes, J. Woods, H. Watson, J. Sathaye. 2009. Greenhouse gas implications of land use and land conversion to biofuel crops. Pages 111-125 in R.W. Howarth and S. Bringezu (eds.). 2009. Biofuels: Environmental Consequences and Interactions with Changing Land Use. Proceedings of the Scientific Committee on Problems of the Environment (SCOPE) International Biofuels Project Rapid Assessment, 22-25 September 2008, Gummersbach Germany. Cornell University, Ithaca NY, USA.

RFA, 2008. The Gallagher Review of the Indirect Effects of Biofuels Production. Renewable Fuels Agency (RFA). East Sussex, UK.

Renewable Fuels Association. 2008. Changing the Climate: Ethanol Industry Outlook 2008. Washington, DC.

REN21. 2005. Renewables 2007 Global Status Report (Paris: REN21 Secretariat and Washington, DC:Worldwatch Institute).

REN21. 2006. Renewables Global Status Report 2006 Update (Paris: REN21 Secretariat and Washington, DC:Worldwatch Institute).

REN21. 2008. Renewables 2007 Global Status Report (Paris: REN21 Secretariat and Washington, DC:Worldwatch Institute).

REN21. 2009. Renewables Global Status Report: 2009 Update (Paris: REN21 Secretariat).

Righelato, R. and D.V. Spracklen. 2007. Carbon mitigation by biofuels or by saving and restoring forests? Science 317, pp.902.

Rosegrant, Mark W. 2008. Biofuels and Grain Prices: Impacts and Policy Responses. Testimony for the U.S. Senate Committee on Homeland Security and Governmental Affairs. May 7, 2008.

The Royal Society. 2008. Sustainable biofuels:prospects and challenges. Policy document 01/08, January 2008. London.

Rudloff, M., 2005. Biomass-to-liquid Fuels (BTL) – made by Choren. Process, environmental impact and latest developments. Presentation to the Automobile and Environment Belgrade EAEC Congress, May.

Runge, C.F. & Senauer, B. 2007. How biofuels could starve the poor. Foreign Affairs, 86(3): 41–53.

Russi, Daniela. 2008. An integrated assessment of a large-scale biodiesel production in Italy: Killing several birds with one stone? Energy Policy 36: 1169–1180.

Rutz, D. & Janssen, R. 2007. Biofuel technology handbook. Munich, Germany, WIP Renewable Energies.

Schmidhuber, J. 2006. Impact of an increased biomass use on agricultural markets, prices and food security: A longer-term perspective. International symposium of Notre Europe, Paris, 2006.

Schneph, Randy. 2008. Higher Agricultural Commodity Prices: What are the Issues? CRS Report for Congress, No. RL34474. Washington: Congressional Research Service, May 29, updated.

Schwela, D.,et al. 2006. Urban Air Pollution in Asian Cities: Status, Challenges and Management: London, UK: Earthscan Publications, pp.276

Searchinger, R. Heimlich, R.A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, T. Yu. 2008. Use of US Croplands for Biofuels Increases Greenhouse Gases Through Land-use change. Science Express (Feb. 7, 2008).

Sethi, K.S.. 2005. Biofuels 2012: Vision to Reality. Planning Commission. The Energy and Resources Institute (TERI). New Delhi, India.

Seyfried, F. 2005. RENEW – Renewable Fuels for Advanced Powertrains. First Year Report for EU Sixth Framework Integrated Project. www.renew-fuel.com.

Simpson, T.W., A.N. Sharpley, R.W. Howarth, H.W. Pearl, and K.R. Mankin. 2008. The New Gold Rush: Fueling Ethanol Production while Protecting Water Quality. Journal of Environmental Quality 37:318-324.

Taheripour, Farzad, Thomas W. Hertel, Wallace E. Tyner, Jayson F. Beckman, Dileep K. Birur. 2010. Biofuels and their by-products: Global economic and environmental implications. *Biomass and Bioenergy, Volume 34, Issue 3, March 2010, Pages 278-289.*

Tilche, Andrea, and Michele Galatola. “The potential of bio-methane as bio-fuel/bio-energy for reducing greenhouse gas emissions: a qualitative assessment for Europe in a life cycle perspective.” Water Science and Technology 57. 11 (2008): 1683-1692.

Tilman, D., Hill, J. & Lehman, C. 2006. Carbon negative biofuels from low-input high-diversity grassland biomass. Science, 314(5805): 1598–1600.

Timilsina, G.R., and H.B. Dulal. 2008. Fiscal Policy Instruments for Reducing Congestion and Atmospheric Emissions in the Transport Sector: A Review, World Bank Policy Research Working Paper, 4652, The World Bank, Washington, DC.

Tollefson, J. 2008. Not your father’s biofuels. Nature, 451(21): 880–883.

Trostle, R., 2008. Global Agricultural Supply and Demand: Factors Contributing to the Recent Increase in Food Commodity Prices. ERS Report WRS-0801. Economic Research Service, US Department of Agriculture (USDA), Washington, D.C. http://www.ers.usda.gov/publications/wrs0801/.

Urbanchuk, John M. 2006. Contribution of the Ethanol Industry to the Economy of the United States. LECG LLC for the Renewable Fuels Association. February 21, 2006.

USAID. 2009. Biofuels in Asia: An Analysis of Sustainability Options. United States Agency for International Development (USAID).

US DOE. 2008. World Biofuels Production: Understanding the Challenges to Meeting the US Renewable Fuel Standard. United States Department of Energy (US DOE), USA.

Worldwatch Institute, 2007. Biofuels for Transportation: Global Potential and Implications for Sustainable Agriculture and Energy in the 21st Century. Washington, DC.

Yang, H., Zhou, Y., Liu, J. 2009. Land and water requirements of biofuel and implications for food supply and the environment in China. Energy Policy, Volume 37, Issue 5, May 2009, Pages 1876-1885

Yapp, Jason,et al. 2008. Market Based Solution to Greening the Palm Oil Industry - Clean Development Mechanism (CDM). International Palm Oil Sustainability Conference, Kota Kinabalu, Sabah, Malaysia, 13-15 April 2008. Available at: http://www.mpoc.org.my/download/papers/envo/IPOSC%202008/Market%20Based%20Solution%20to%20Greening%20the%20PO%20Industry.pdf

Zilberman, D., Sproul, T., Rajagopal, D., Sexton, S., and Hellegers, P., 2008. Rising energy prices and the economics of water in agriculture. Water Policy 10 Supplement 1 (2008) 11–21.