Fuel Versus Food

Ujjayant Chakravorty,[1,2] Marie-Hélène Hubert,[1,2] and Linda Nøstbakken[2]

[1]Department of Economics and [2]Department of Marketing, Business Economics, and Law, University of Alberta, Edmonton, Canada T6G 2R6; email: ujjayant@ualberta.ca, mhubert@ualberta.ca, linda.nostbakken@ualberta.ca

Annu. Rev. Resour. Econ. 2009. 1:645–63

First published online as a Review in Advance on July 9, 2009

The *Annual Review of Resource Economics* is online at resource.annualreviews.org

This article's doi: 10.1146/annurev.resource.050708.144200

1941-1340/09/1010-0645$20.00

Key Words

agricultural production, biofuel economics, climate policy, environmental regulation, land allocation

Abstract

Many countries have actively encouraged the production of biofuels as a low-carbon alternative to the use of fossil fuels in transportation. To what extent do these trends imply a reallocation of scarce land away from food to fuel production? This paper critically reviews the small but growing literature in this area. We find that an increase in biofuel production may have a significant effect on food prices and, in certain parts of the world, in speeding up deforestation through land conversion. However, more research needs to be done to examine the effect of newer generation biofuel technologies that are less land intensive as well as the effect of environmental regulation and trade policies on land-use patterns.

1. INTRODUCTION

In 2004, an estimated 14 million hectares (ha) worldwide were being used to produce biofuels and their by-products, representing approximately 1% of global cropland (IEA 2006). In recent years, many countries have adopted policies to encourage the supply of energy from land-based sources. Several factors are contributing to this trend, including the need for cleaner energy sources, a desire for less dependence on foreign countries for vital energy supplies, and the perceived benefits from boosting a domestic agriculture sector that has been dependent on subsidies for survival.

Bioethanol and biodiesel account for the majority of fuel from land. However, these liquid forms of bioenergy supply only a small share of the world energy market—approximately 1% of world renewable energy supply and 1.8% of the world's transportation fuels. Almost 90% of biofuels are ethanol, and the remaining 10% are biodiesel.[1] Rajagopal & Zilberman (2007) divided the land-based fuels into three main categories: U.S. ethanol from corn, Brazilian ethanol from sugarcane, and German biodiesel from rapeseed. In Brazil, ethanol provides approximately 22% of gasoline demand, whereas in the United States, this share is less than 3% (OECD 2008). The global biofuel market is dominated by two countries: Brazil and the United States, who together supply three-quarters of the commodity.

Land-based fuel production has received much policy attention in recent years. Nonetheless, its current share is relatively small in most countries, except for Brazil. However, in the future, government policies that encourage renewable energy sources may result in a larger share of transportation fuels coming from land that historically has been used for food production, forestry, and other critical uses. Probiofuel policies have led to a rapid increase in acreage under biofuels in the United States, the European Union, and developing countries such as China and India, albeit from a very small base. Policies that encourage land-based fuel production may lead to a reduction in acreage used for food production, with a corresponding reduction in food supply and increase in food prices. Furthermore, land that is not well suited for agriculture, but is currently used for forestry or grasslands, may be converted for fuel production. Large-scale land conversion may in turn lead to a leakage of sequestered carbon into the atmosphere, which could significantly reduce the potential environmental benefits from substitution of gasoline by biofuels.

On the demand side, 99% of energy services in the transportation sector are currently provided by petroleum. Consumption in this sector is expected to increase by approximately two-thirds by the year 2030 (IEA 2007, Rajagopal & Zilberman 2007). Several substitutes such as solar, wind, nuclear, and other renewables exist to replace polluting fossil fuels in the electricity sector. However, first-generation biofuels are the only viable substitutes currently available in transportation. Other substitutes, such as second-generation biofuels and fuel cells, hold considerable promise but are still at the research and development stage.[2]

[1]Typically, conventional or first-generation biofuels are classified into two broad categories: ethanol and biodiesel. Conventional ethanol in OECD countries is produced mainly from starchy crops such as corn, wheat, and barley, but it can also be made from potatoes and cassava, sugarcane, and sugar beet. In tropical countries like Brazil, ethanol is produced exclusively from sugarcane, whereas molasses is used in India. Biodiesel is produced from transestherfication of vegetable oils or animal fats. Biodiesel can also be produced from used vegetable oils (Rajagopal & Zilberman 2007).

[2]The biofuel sources discussed above such as land-based corn and sugarcane are typically referred to as first-generation biofuels. A second generation of biofuels is derived from agricultural or forest by-products and residues such as straw, woodchips, and grasses. Only the cellulosic parts of the plant are used. Second-generation biodiesel can be produced from biomass by gasification or Fischer-Tropsch synthesis (OECD 2008). Other substitutes such as methanol, hydrogen, and synthetic diesel are produced via gasification from lignocellulosic biomass (Hamelinck & Faaij 2006).

With the agricultural sector also becoming a provider of clean energy, land availability and food needs can limit the growth in plant-based fuels production. World food requirements are likely to maintain a significant level of growth in the coming decades (FAO 2007). A change in dietary habits toward meat and dairy products is also expected to accompany the rise in per capita income and food consumption in developing countries (Cranfield et al. 1998, Delgado et al. 1999). This shift in food consumption preferences increases the demand for land because meat and dairy are intensive users of agricultural land. In addition, there is relatively little unused, arable land left available for a major expansion of current agricultural production (Wiebe 2003, FAO 2007). However, the use of second-generation biofuels produced from crop residues and high-yielding herbaceous energy crops are being explored as possible options that can mitigate the competition for land between food and energy production. Herbaceous crops are plants with soft rather than woody tissues. This energy source includes corn cover and wood chips, which are classified as crop residues, as well as high-yielding energy crops such as miscanthus and switchgrass. Although the total production costs of second-generation biofuels exceed that of first-generation biofuels (IEA 2009), they have the advantage of being less land intensive and being able to grow on lands of lower qualities (Khanna 2008).

This article provides a review of some of the major issues and economic trade-offs between fuel production for transportation and the production of food from land. The remainder of the paper is organized as follows: In Section 2, we discuss the main economic models that have been developed and used to study biofuel production and its economic and policy implications. Section 3 discusses the allocation of land between food and fuel. The economics of biofuels are presented in Section 4. In Section 5, we provide a brief overview of government policies toward biofuel production, including trade and agricultural policies, and discuss their potential impacts on biofuel and food production. We then discuss some of the environmental impacts of biofuel production in Section 6. Section 7 concludes the paper.

2. ECONOMIC MODELS OF BIOFUELS

Several models have been developed to study the interaction between biofuels and food. The production of biofuels and the development of the biofuel industry are highly dependent on land availability and food demand as well as on the price of conventional transportation fuels, mainly petroleum. Accordingly, the models that have been developed to study fuel versus food can generally be divided into two main categories, based on whether they describe only the agricultural sector or both the agricultural and transportation sectors. Below, we give a brief overview of some of these modeling efforts focusing particular attention on the underlying structure of the models.

2.1. Models of the Agricultural Sector

The main modeling efforts at the global level focusing only on the agricultural sector are led by the Food and Agricultural Policy Research Institute (FAPRI 2007) and the International Food Policy Research Institute (IFPRI) (Msangi et al. 2007). Both studies develop

They require much less land relative to first-generation biofuels. Third-generation biofuels may be produced from algae and biotech feedstocks. When developed, second- and third-generation biofuels are expected to be less land intensive.

partial equilibrium models to explore the potential impact of biofuels production on food prices, agricultural production, food security, and international trade in the medium term (until 2016 or 2020). In these models all prices are endogenous, but the scarcity of land resources is not considered explicitly and petroleum prices are taken as given. The impact of the development of biofuels is explored by introducing an exogenous demand for transportation. The models are used to project demand and supply for agricultural products, as well as to predict trade patterns between different regions of the world.

Three scenarios are defined and studied by the IFPRI model. A first scenario focuses on the recent boom in biofuels production, but it leaves out second-generation biofuels. The second scenario introduces second-generation biofuels, and the third adds improvements in crop productivity. The results are compared with a benchmark model without biofuels production. An increase in food prices in this model also affects caloric availability and child nutrition in poor-income economies. The FAPRI (2007) model considers only one scenario and aims at analyzing the expected impact of biofuels production on agricultural markets until the year 2016.

Other models of the agricultural sector incorporate endogenous demand for land. Schneider & McCarl (2003) extended the FASOM (Forest and Agricultural Sector Optimization Model) of Adams et al. (1996), which is a partial equilibrium model of the U.S. agriculture and forest sectors, in order to examine the potential role of biofuels production within a portfolio of land-based carbon mitigation strategies. This is an optimization model, where the objective is to maximize the economic surplus net of the costs of inputs under land-allocation constraints. To account for imperfect substitutability between alternative uses of land, available land is divided into different land types, and the model tracks land competition among food, feed, energy, and forest uses. It allows for land allocation among several crops, pastures, and forestry.

Other spatial models have been developed at the global level. IIASA (International Institute for Applied Systems Analysis), in a joint effort with FAO (2009), has developed a model of the global food system where production, consumption, and world food trade dynamics are projected for the near future. Because land quality differs dramatically across geographical areas, they are divided into different agroecological zones. One of the key features of this model is that it takes into account the spatial climate change impacts on agricultural yields. Scenarios have been defined to quantify the impacts of first- and second-generation biofuels on agriculture, the world food system, and land use. The study analyzes a scenario in which biofuel targets are implemented in current OECD countries as well as in some major developing countries.

Other studies have dealt with the impact of biofuel policies in the public economics tradition. One strand of this literature develops partial equilibrium trade models to analyze the interaction between biofuel policies such as tax credits or mandates and agricultural policies such as deficiency payments or farm subsidies (Hochman et al. 2008, de Gorter & Just 2009a). Another literature focuses on the welfare effects of tax credits and mandates in the United States (de Gorter & Just 2009b).

2.2. Models of Agriculture and Transportation

We divide our presentation of models of agriculture and transportation into two parts on the basis of whether the models are partial or general equilibrium. Most of the models presented below are set up within a general equilibrium framework.

2.2.1. Partial equilibrium models. The nature of land-based fuel production implies that biofuels compete with food production for scarce land resources. Hence, the opportunity cost of land must be taken into account when considering the production costs of biofuels. This is done by Chakravorty et al. (2008), who developed a stylized model within a Ricardian-Hotelling framework. In this dynamic framework, land allocation decisions are based on the rent maximization principle. The model focuses on the supply of biofuels in the context of scarce energy resources in which available land is allocated between the food and energy industries. The demand for clean energy is modeled by introducing an exogenous cap on the carbon stock in the atmosphere. Biofuel serves as a perfect substitute for petroleum and is considered carbon neutral.

Whereas the previous model is set in a resource economics tradition, another set of models evaluates the welfare and greenhouse gas effects of biofuels policies. These studies focus on U.S. biofuels policies. Elobeid & Tokgoz (2008) developed a partial equilibrium model of the world ethanol market to study the impact of U.S. trade barriers on the U.S. ethanol market. This model distinguishes among six regions: the United States, Brazil, the European Union 15, China, Japan, and the rest of the world. The model is used to analyze the implications of a U.S. tariff on ethanol imports as well as a tax credit on U.S. and Brazilian ethanol. Ando et al. (2009) explored the welfare and greenhouse gas effects of the U.S. Renewable Fuel Standard (RFS) in the presence of biofuels subsidies. Their study is based on the assumption of a closed economy with homogenous consumers that benefit from vehicle miles traveled. Vehicle miles are produced by blending gasoline and biofuels, but consumers suffer from disutility caused by congestion and greenhouse gas emissions. Finally, Lasco & Khanna (2009) extended the previous framework to that of an open economy (the United States versus Brazil).

2.2.2. General equilibrium models. The GTAP (Global Trade Analysis Project) model (Hertel 1997) has been altered to take into account land scarcity and has been combined with the GTAP-E model (Burniaux & Truong 2002), which is a model of the energy sector (Banse et al. 2008; Hertel et al. 2009a, 2009b). This model takes into account the heterogeneity of land across geographical areas by dividing the global land area into different agroecological zones (Lee et al. 2005). Each zone is defined according to the length of the growing season, and they are in turn subdivided into three climatic zones (tropical, temperate, and boreal). Land-use changes within each zone are determined by changes in relative rents, and the magnitude of these changes is driven by a constant elasticity of transformation. In the model, first-generation biofuels are used in conventional vehicles that are compatible with blends up to 10% bioethanol, and flexi-fuel vehicles are typically designed for blends of 85% ethanol. To treat biofuels and petroleum as complementary inputs, the altered GTAP model incorporates a constant elasticity of substitution production function for the transportation sector (McDougall & Golub 2008). The model allows for substitution between petroleum products and three types of biofuels: ethanol, biodiesel produced from oil, and biodiesel from vegetable oil. To take into account the fact that bioethanol can be produced from different feedstocks, ethanol production is modeled using a constant elasticity of substitution production function. The value of the elasticity of substitution between different fossil fuels and biofuels reflects existing technological barriers. Second-generation biofuels and other technologies currently at the research and development stage are not considered in this model.

General equilibrium models have been used to explore the impact of different mandatory blending policies on world agricultural production. Whereas some models focus on the impacts of the European directive on the world agricultural markets (Banse et al. 2008), others explore the consequences of the implementation of both E.U. and U.S. biofuels policies (Birur et al. 2008, Hertel et al. 2009b).

Reilly & Paltsev (2009) developed a model of transportation and agriculture based on the Massachusetts Institute of Technology Emissions Predictions and Policy Analysis model, which is a recursive-dynamic multiregional equilibrium model of the world economy (Paltsev et al. 2005). This is a bottom-up model built on the GTAP data set, and it gives a detailed representation of energy markets while accounting for regional production, consumption, and bilateral trade flows. The model estimates the emissions of greenhouse gases, including CO_2, as well as other air pollutants. Production and consumption sectors are modeled with constant substitution elasticities. Two biomass technologies are considered: the production of electricity and a liquid fuel from biomass. The demand for land is incorporated in the model, but even though the model is set up at the world level, land is treated as a homogeneous input. The model considers different energy sectors, such as heat, electricity, and transportation and accounts for the price-induced substitution of energy between polluting fossil fuels and clean bioenergy.

In the studies presented above, growth in agricultural yields is treated as exogenous. Keeney & Hertel (2008) have adopted the GTAP model with endogenous yield growth. For example, the recent increase in food prices is likely to induce technological progress in the agricultural sector. Induced innovation studies, such as Hayami & Ruttan (1971), have estimated long-run supply responses of agricultural yields to food prices. Keeney & Hertel (2008) incorporated such supply response functions into the GTAP model to consider the effect of technological progress.

The results from the above studies are discussed in the rest of the paper. In **Table 1**, we summarize the different approaches taken by the above models. Most of them focus on the economics of biofuels supply and in particular address the issue of government policy and how that can affect biofuels production. A smaller sample of the models explicitly considers environmental impacts from biofuels production. A fewer number explicitly consider the role of fossil fuel scarcity and the effect rising prices of energy may have on the supply of biofuels.

Next, we consider some of the main factors that are behind the increased demand for biofuels and discuss current trends in land allocation between food and biofuels.

3. THE ALLOCATION OF LAND BETWEEN FOOD AND FUEL: CURRENT TRENDS

Between 2004 and 2007, when both ethanol and biodiesel production grew rapidly in the United States and other countries, there was a dramatic increase in food prices for several commodities such as corn, wheat, and vegetable oils. This is in sharp contrast to the long-run decline in world food prices of almost 75% over the period 1974–2005 (*The Economist* 2007). Short-run increases in food prices were generally caused by supply shortages arising from poor harvests. In a recent study, Martin (2008) suggested that approximately one-quarter to one-third of the price increase in recent years can be explained by the increased production of energy from land. Other factors explaining the recent rise in

Table 1 Modeling structure employed by different studies

Sector	Reference	Land use and land-use changes	Economics of biofuels	Government policy toward biofuels	Environmental impacts of biofuels
Agricultural	FAPRI (2007)	No[a]	Yes[b]	Yes	No
	IFPRI (2007)	No	Yes	No	No
	Schneider & McCarl (2003)	Yes	Yes	Yes	Yes
	IIASA(2009)	Yes	Yes	Yes	Yes
	Hochman et al. (2008)	No	Yes	Yes	No
	de Gorter & Just (2009a)	No	Yes	Yes	No
	de Gorter & Just (2009b)	No	Yes	Yes	No
Agricultural and transportation	Chakravorty et al. (2008)	Yes	No	Yes	Yes
	Elobeid & Tokgoz (2008)	No	Yes	Yes	No
	GTAP models[c]	Yes	Yes	Yes	No
	Reilly & Paltsev (2009)	Yes	Yes	Yes	Yes
	Ando et al. (2009)	No	Yes	Yes	Yes
	Lasco & Khanna (2009)	No	Yes	Yes	Yes

[a]Indicates that the model does not account for the given factor.
[b]Indicates that the model includes the given factor.
[c]Sources: Birur et al. (2008), Hertel et al. (2009b).

world food prices are droughts and increased demand for agricultural products from highly populated developing countries.

An increase in corn prices—a commodity that can be used to generate energy—also leads to an increase in the price of meat and dairy products because corn accounts for more than half the cost of animal feed in countries such as the United States (Yacobucci & Schnepf 2007). Thus, large-scale conversion of corn to ethanol will affect the supply of corn in the world market. The United States exports two-thirds of the world's corn, and developing countries with large populations such as China and Mexico are large importers. In 2004, 11% of the corn harvested by U.S. farmers was used for ethanol production. As a result, a shift toward biofuels in the United States will inevitably result in higher prices of corn in these countries. In fact, the spike in the price of tortillas in Mexico during January 2007 was widely attributed to this phenomenon.

Approximately 1% of total world cropland was used to produce biofuels and their by-products in 2004 (IEA 2006). Brazil has the highest share of acreage devoted to biofuels production; sugarcane is currently produced on 5.6 million ha in Brazil, which accounts for approximately 10% of the country's cropland. Elsewhere, even though the acreage used for land-based energy production is quite small, not much new land is available for energy production. Future growth in biofuels supply will thus have to come from new technologies or from substitution of current acreage away from food to fuel production.

Of the total land available in the world (approximately 13.5 billion ha) forests cover 4.2 billion ha while agriculture (croplands and pastures) accounts for 5 billion ha, of which 1.6 billion ha are cropland. The remaining land is mainly urban and ill-suited for agriculture. The Food and Agriculture Organization (FAO 2008) considers an additional 2 billion ha as potentially suitable for agriculture. This estimate should, however, be treated with caution. First, according to Wiebe (2003), these 2 billion ha exhibit low crop yields and are highly vulnerable to land degradation, which undermines their long-term production capacity. Nonetheless, some biofuel crops, such as cassava, castor, and sweet sorghum, can be grown under unfavorable environmental conditions, but the energy efficiency of these crops is low. Second, the world's forests and wetlands supply valuable environmental services such as biodiversity conservation, carbon sequestration, and water filtration. As a result, some of these areas are or will likely be zoned for protection and hence unavailable for agricultural production. As surplus land availability is limited, an increased focus on biofuels will undoubtedly come at the expense of land under food production.

This increasing focus on biofuels and its attendant demand for crops may be offset in part by taking advantage of the potential for increased yields that lies in currently available technologies. Even if crop yields grow at a lower rate than in the past, actual yields are still far below their potential in most regions (FAO 2008). For instance, in Malaysia and Indonesia, which are the world's largest producers of biodiesel after the European Union, current palm oil yields amount to 4 tons per hectare, but they could potentially be increased to 6 tons per hectare with available know-how. In China, the average sugarcane yield is only 60 tons per hectare and has the potential to rise to approximately 85 tons per hectare.

4. THE ECONOMICS OF BIOFUELS

There are two important dimensions that need to be taken into account when considering the economics of biofuels: energy yields and production costs. Both are highly dependent on the feedstock used, and local conditions determine which feedstock can be used in which region of the world. For instance, in the United States, ethanol is produced from corn, which is a far more demanding plant in terms of land quality than sugarcane, which is used in Brazil. There are also large differences in the availability and in the quality of land between different regions (Wiebe 2003). For instance, surplus land available in the United States and in European countries is small compared to countries like Brazil and Indonesia. Thus, to determine where the production of biofuels will occur, it is crucial to consider not only the amount of land available but also its quality.

The economic potential for biofuels can be better understood by comparing the costs and yields of the major producers: Brazil and the United States. Brazilian ethanol is based on sugarcane and is by far the most efficient, with average yields of 1665 gallons per

hectare. In the United States, ethanol from corn yields approximately 800 gallons per hectare (Seauner 2008). The sugar in sugarcane can be converted directly into ethanol, but in corn-based ethanol production, the carbohydrate must first be converted into sugar. Moreover, the cane stalks from sugarcane harvesting (bagasse) are burned to fuel the plant, which further reduces the cost of production. The higher efficiency of the transformation process leads to cheaper ethanol from sugarcane relative to corn. Producing one gallon of ethanol in Brazil costs approximately $0.83, whereas the corresponding amount for U.S. corn-based ethanol is $1.09 (all amounts noted are in U.S. dollars) (Lasco & Khanna 2009). Although ethanol can also be produced from other crops such as cereals and beets, the cost of these crops is even higher (Ryan et al. 2006). In comparison, biodiesel production in Germany is more expensive with average costs that are approximately twice those of U.S. ethanol. With crude oil prices of $35 per barrel or more, Brazilian ethanol is already economically competitive (FAO 2008).

In their study of the conversion of marginal lands into agricultural land, Banse et al. (2008) showed that increasing food prices are less important compared with studies where the endogenous demand for land is explicitly incorporated into the model. Banse et al. (2008) reported that most food prices follow a decreasing trend. The exception is oilseed, which shows a small price increase of 1% in their model. In contrast, the IFPRI model (Msangi et al. 2007) predicts a significant increase in oilseed and sugar prices.

Several studies evaluate the possible implications of the E.U. biofuels targets. Banse et al. (2008) found that to reach these targets European imports from land-abundant countries such as South America will have to increase. This will increase the share of all energy crops that the European Union imports from 42% to 53%. We return to this issue below when we look at the implications of government policies toward biofuels production.

Second-generation biofuels feedstocks, such as switchgrass and miscanthus, can be grown on marginal lands that are not productive in traditional agricultural uses (Hochman et al. 2008). In temperate areas such as Illinois, the energy yield of miscanthus can reach 1400 gallons per hectare compared to only 800 gallons per hectare produced from corn (Khanna 2008). However, their production costs are still high compared with the costs of producing first-generation biofuels (Rajagopal & Zilberman 2007). It costs $2.74 per gallon to produce ethanol from miscanthus, but only $2.12 for ethanol produced from corn (Khanna 2008). Other substitutes, such as methanol, hydrogen and synthetic diesel, may be produced via gasification from lignocellulosic biomass (Hamelinck & Faaij 2006). To date, few economic studies have examined the role of second-generation biofuels in the future energy mix. A study by IIASA (2009) reveals that production of lignocellulosic plants on approximately 125 million ha, an area representing less than 10% of current world croplands, would be sufficient to achieve a biofuels target share of 10% in world transport fuels in 2030. Under this scenario, mandatory or voluntary blending targets are implemented in major OECD countries including the United States, the European Union, and developing countries such as China and India.

Many studies analyze the relationship between biofuels and food prices. The competition for limited land resources between fuel and food results in important consequences, such as malnutrition and food shortages, especially in poorer regions. Analysis using the IFPRI model shows that biofuel production has a substantial impact on world food prices. The largest increase in prices is observed for oil seeds and sugarcane. When only first-generation biofuels are modeled, corn and oil seeds prices rise by 76% and 66%,

respectively. However, when second-generation biofuels and productivity improvements are taken into account, these numbers fall to 45% and 49%, respectively, and accounting for crop productivity improvements renders the price effect even smaller, although still significant.

The IFPRI model also looks at the effects on calorie availability and child nutrition in poor-income economies, particularly focusing on Sub-Saharan Africa. The results of the first-generation biofuels scenario when compared with the no-biofuels case show an 11% reduction in daily calorie availability (275 calories) and a significant increase in the number of children suffering from malnutrition. The effects are obviously smaller when technological progress is considered, in the form of second-generation biofuels and improvements in crop productivity.

There is a close link between the profitability of biofuels and the prices of food and oil. Low food prices mean a lower opportunity cost of land, an input in the production of first-generation biofuels. In contrast, a high oil price is equivalent to a high output price for biofuels. From 2004 to 2007, low food prices combined with high oil prices considerably improved the profitability of biofuels, which resulted in high levels of investment in the biofuels industry. As a result, the United States currently has approximately 134 ethanol plants, compared with 63 plants in 2003. High food prices since 2008 have reduced investment in the biofuels industry. Hochman et al. (2008) employed a partial equilibrium trade framework to examine this stylized fact. Specifically, their model looks at the impacts of biofuels production on food prices within a dynamic system that takes into account inventory considerations. That is, food inventories will deplete relatively fast to meet biofuels demands, which in turn will change expectations and contribute to rising food prices. On the one hand, higher demand for biofuels can increase income of crop producers. Therefore, it undermines the needs for policy intervention—price supports, output restrictions, or deficiency payments—in the agricultural sector. On the other hand, low food prices can improve the competitiveness of biofuels compared with petroleum. It fuels investment in the bioenergy industry—building of new plants and research and development in second-generation biofuels. However, high food prices may depress biofuels competitiveness and slow down investments. This can cause bankruptcies at the firm level, as were observed in the U.S. farm sector in 2008.

Chakravorty et al. (2008) showed that, as the exhaustible resource (petroleum) becomes scarcer, its price increases, thereby making land-based fuel production (biofuels) competitive. As a consequence, land shifts out from food production to energy production, which leads to an increase in the price of food. Ultimately, the scarce petroleum resource is exhausted and all energy is supplied by land. The question of whether petroleum or biofuels should be used has also been analyzed in the modified GTAP model. This model accounts for the price increase in crude oil relative to the increase in agricultural prices. Results indicate that the demand for energy resources—petroleum versus biofuels—depends critically on the relative price of fossil fuel and land-based energy.

5. GOVERNMENT POLICY TOWARD BIOFUELS PRODUCTION

A range of different regulatory policies have been proposed and implemented. These include mandatory blending, i.e., regulations requiring that a certain amount of ethanol be blended with gasoline in transportation fuels, subsidies to biofuel producers, as well as trade barriers aimed at biofuels imports. Other highly relevant policies for

the development of biofuels include carbon taxes or quotas. Although such regulations are not necessarily specific for biofuels, they still affect energy choice and hence the supply of biofuels indirectly. Next, we discuss some of these policies and examine their implications.

5.1. Mandatory Blending

Governments such as those of the European Union and the United States have established biofuel mandates to be achieved by target dates. For instance, the European Union expects its member states to ensure that biofuels and other renewables provide at least 5.75% of transportation fuels by the year 2010 and 10% by 2020 (Bureau et al. 2009). With an average share of renewables in the EU25 countries of only 2% in 2007 (OECD 2008), these goals may seem unrealistic. In the United States, the first RFS was instituted by the Energy Policy Act in 2005 (FAO 2008). It required modest levels of renewables to be blended into U.S. motor fuel: 4 billion gallons in 2006, increasing to 7.5 billion gallons in 2012. By comparison, the current level of biofuel use in the United States is close to 9 billion gallons (FAO 2008). Former President George W. Bush declared that the biofuels production target should be 35 billion gallons in 2017. The Energy Information and Security Act passed in 2007 expanded the RFS program by requiring the use of 36 billion gallons of ethanol per year by 2022, of which 21 billion gallons must be produced from second-generation feedstocks (Yacobucci & Schnepf 2007). Countries such as China, Japan, and Australia also have in place policies encouraging the production of biofuels (Rajagopal & Zilberman 2007). However, the Chinese government recently decided to slow down its ethanol plant expansion program because of worries that the rapid expansion could threaten the country's food security (Kojima et al. 2007).

The implementation of a mandate leads to a switch toward biofuels and away from gasoline in the country introducing the mandate (Ando et al. 2009). The impact of the policy on the world biofuels market depends on the market power of the country introducing the policy. If the country has market power, the additional demand of ethanol may lead to a rise in ethanol prices, which induces a substitution toward petroleum and away from ethanol in other countries (Lasco & Khanna 2009).

In terms of actual impacts of mandatory blending, the FAPRI model shows that ethanol production in the United States will expand much more rapidly than mandated by the Energy Policy Act of 2005, surpassing 7.5 billion gallons by 2008 and 12 billion gallons by 2010. However, in the absence of any incentives, the European Union is not expected to achieve the goal of a 5.75% share of renewable fuels by 2010. Biodiesel production in the European Union is expected to grow more slowly because of the increasing price of vegetable oil in the model and the assumption of stagnant future crude oil prices. If oil prices do not rise, then biofuel producers do not have an adequate incentive to supply the energy market.

Several other studies explore the impact of mandatory blending on the world agricultural sector. Some of them are focused on the European directive (Banse et al. 2008), while others consider the implementation of both E.U. and U.S. policies (Birur et al. 2008, Hertel et al. 2009b). All of them predict a positive impact on food prices as a result of mandatory blending. The implementation of mandatory blending in the European Union is projected to slow down the decline in the price of certain feedstocks such as cereals and

sugar (Banse et al. 2008). The effect on world prices is more significant when policies are implemented in both the European Union and the United States. Because not much surplus land is available in Europe, it is expected that half the crops used in biofuels production must be imported to meet the target (Banse et al. 2008). In contrast, in the United States, the additional ethanol needed to meet these mandated targets will, to a large degree, be produced domestically. These studies also show that the impact of mandatory blending on land use will be substantial. It will have a major effect on greenhouse gas emissions because any conversion of forest lands into agriculture will cause carbon leakage and may undo some of the greenhouse gas reduction objectives the biofuels program is designed to achieve.

5.2. Carbon Taxes and Carbon Cap

Most countries levy a tax on gasoline and diesel, and excise tax reductions are the most widely used instrument to bridge the gap between the price of conventional and that of land-based fuels. However, the level of taxation varies across countries. In the United States, there is a fixed tax credit of $0.45 per gallon of ethanol blended with gasoline and a $1.00 per gallon tax credit for biodiesel (Rajagopal & Zilberman 2007). The excise tax credit may be justified by the presence of environmental externalities that cannot properly be corrected in end-user prices (Kojima et al. 2007). Ryan et al. (2006) estimated that the price difference between conventional and biofuels in Europe is equal to approximately $229 per ton of CO_2 equivalent (2006 prices), which is much higher than the actual price in 2006 of $17 per ton of carbon. However, instead of recommending the use of an excise tax or subsidy, Lasco & Khanna (2009) suggested imposing a differential carbon tax on biofuels on the basis of the carbon intensity. Although a subsidy increases the use of ethanol, which emits less greenhouse gases than does gasoline, the benefits of reduced greenhouse gas emissions are not enough to offset the increase in the demand for driving from lower gas prices.

Energy security is another important driver of biofuels policy. Countries such as the United States have stressed the need to develop the domestic biofuels market so as to reduce their dependence on foreign oil (Taheripour & Tyner 2007). Currently, the United States imports 60% of its oil. The question is how much is the United States willing to pay for this added energy security in terms of higher gasoline prices. If energy security is highly valued, that will translate into a strong incentive program for biofuels production. Carbon taxes that may emerge under a cap and trade program being actively considered in the United States will also encourage the displacement of conventional fuels by land-based fuels. Carbon trading has already been introduced in the European Union, although prices are relatively low in this early phase of trading and setting sectoral targets.

Schneider & McCarl (2003) explored the potential role of biofuels production in a portfolio of climate mitigation options for the United States. The agricultural sector offers a wide range of strategies to mitigate climate change, including biological sequestration from conversion of agricultural land into forests, the adoption of new techniques for soil carbon sequestration, and the displacement of fossil fuels by biofuels. The authors used an optimization model, and for each level of carbon prices, they determined the least costly mitigation strategies. Their results show that biofuels are not viable below a carbon price of $40 per ton. However, for carbon prices above $70, biofuels dominate all other agricultural mitigation strategies.

Reilly & Paltsev (2009) examined the least costly strategy for reaching different carbon-concentration targets (450–750 parts per million). They found that the development of bioelectricity is expected to be insignificant owing to the availability of competitive carbon-free substitutes for electricity (nuclear and solar). However, because other substitutes for petroleum such as fuel cells and hydrogen are not mature enough at this stage, biofuels are the only viable substitute in terms of cost and emissions savings. To meet these carbon targets, biofuels production rises substantially in their model, leading to an increase in world food prices. From 2010 to 2020, world food prices are projected to increase by approximately 10%. When a mandatory blending target is imposed in the European Union and the United States, the increase in prices is expected to be approximately 9% for coarse grains in the United States, 10% for oilseeds in the European Union, and 11% for Brazilian sugarcane.

In a recent study using a Ricardian-Hotelling framework, Chakravorty et al. (2008) analyzed the impact of pollution regulation on the transition to biofuels and on food prices. The demand for a clean environment is expressed in terms of a cap on the carbon stock. The immediate implication of this cap is a rise in energy prices, which speeds up the adoption of biofuels and leads to a rise in food prices. The importance of these effects depends on the level of land scarcity, the demand for food, the level of the regulatory constraint, and the availability of fossil fuels.

5.3. Trade Barriers and Other Market Distortions

Government policies aimed at restricting trade are also of crucial importance to the biofuels industry. Such policies are motivated by a desire for increased energy security and the perceived benefits of supporting heavily subsidized domestic agricultural sectors. Trade policies will have a major impact on where biofuels are produced. For instance, the United States currently imposes a 54 cents per gallon import tariff on ethanol. In addition, the Food Conservation and Energy Act of 2008 provides various incentives to the domestic farm sector to produce first-generation biofuels and for using cellulosic feedstocks (Ando et al. 2009). This includes a differential subsidy for corn ethanol ($0.45 per gallon) and cellulosic ethanol ($1.01 per gallon). Brazil is the main exporter of ethanol into the U.S. market; consequently, lifting this tariff would have a major impact on both U.S. and Brazilian production. U.S. ethanol is economically viable only at crude oil prices exceeding $58 per barrel, whereas Brazilian ethanol is much cheaper. Hence, trade liberalization may result in an increase in exports of ethanol from Brazil to the United States.

The U.S. government protects domestic production by imposing trade barriers and introducing domestic market distortions such as a tax credit to refiners blending ethanol with gasoline. Several studies (Elobeid & Tokgoz 2008, de Gorter & Just 2008, Lasco & Khanna 2009) analyzed the impact of trade liberalization by removing U.S. trade barriers and tax credits in the ethanol market and studying the resulting spillover effects on other markets such as petroleum and agriculture. Removing import tariffs along with the subsidy induces a switch toward gasoline and away from ethanol in fuel composition. de Gorter & Just (2008) estimated that demand for ethanol will decrease by 90%, whereas Lasco & Khanna (2009) and Elobeid & Tokgoz (2008) found a more modest effect of approximately 6% and 2%, respectively. Lasco & Khanna (2009) explained the difference in magnitudes by the various assumptions regarding the elasticity of substitution and the

supply elasticity of gasoline.[3] Because the United States has market power in the world ethanol market, an increase in the world ethanol price causes a reduction in Brazil's ethanol consumption.

International trade in food products is highly protected. An estimated 75% of total agricultural support to OECD countries is provided by market access barriers (Anderson et al. 2006). Liberalization of food markets will impact food and crop prices as well as the competitiveness of biofuels. The European Union and the United States have a range of policies that encourage overproduction of sugar, which in turn leads to a lower world market price of sugar. The sugar market is one of the most distorted agricultural markets, and world prices are estimated to be 40% below the price level that would prevail in a free market (Kojima et al. 2007). These policies have stimulated the production of ethanol in Europe and encouraged Brazil to divert its production of sugar from exports toward ethanol production. Hence, a liberalization of the highly protected European sugar market is likely to result in increased prices of sugar in Europe, which will reduce the competitiveness of European biodiesel.

6. ENVIRONMENTAL IMPACTS OF BIOFUELS PRODUCTION

Contrary to popular impression, biofuels are not carbon neutral. Life Cycle Assessment studies have estimated the amount of carbon emitted by the biofuels production process from "well to wheel" (Rajagopal & Zilberman 2007, Peña 2008). **Table 2** shows the direct emissions savings from using biofuels relative to gasoline measured in CO_2 equivalent. Savings from ethanol produced from sugarcane in Brazil are higher than the savings from corn in the United States. Furthermore, savings from second-generation biofuels tend to be larger than those of first-generation biofuels. Note that the stage at which most of the carbon emissions occur differs between gasoline and biofuels (Peña 2008). Most carbon emissions are released into the atmosphere during the combustion of gasoline, but for biofuels, emissions are generated during the various stages of fuel production. This is important when considering climate policy.

More recent studies have attempted to calculate the overall change in emissions by also accounting for the effects of land-use changes (Fargione et al. 2008, Searchinger et al. 2008). This work aims at recognizing the effects of additional acreage coming from deforested lands or from conversion of grasslands into cropland, which releases stored carbon into the atmosphere. Turning grasslands into croplands is estimated to release between 134 tons of carbon per hectare in the United States and 165 tons per hectare in Brazil (Fargione et al. 2008), whereas conversion of forest can release between 600 and 1000 tons of carbon per hectare (FAO 2008). In a recent study, Fargione et al. (2008) found that the carbon lost by converting rainforests, savannas, or grasslands into land for biofuels production outweighs the carbon savings from substitution of gasoline and diesel by biofuels. Such conversions release 17 to 420 times more carbon, depending on the crop and ecosystem, than the annual savings from replacing fossil fuels. Given such effects, corn-based ethanol, instead of resulting in a 20% reduction in carbon emissions, as previously thought, may double emissions over a 30-year period.

[3]In de Gorter & Just (2008), gasoline and ethanol are perfect substitutes, whereas in Elobeid & Tokgoz (2008), they are perfect complements. Lasco & Khanna (2009) took a middle approach and defined the two as imperfect substitutes.

Table 2 Overview of direct emission savings from biofuels compared with reference fossil-fuel vehicle[a]

Biofuel	Generation	Feedstock	Low	Best estimate	High
Bioethanol	1st	Sugar crops	0.7	1.2	2.2
		Starch crops	0	0.4	0.9
		Brazilian sugarcane	2.4	2.9	3.3
	2nd	Lignocellulosic crops	2.6	2.5	2.4
		Lignocellulosic residues	2.7	2.6	2.5
Biodiesel	1st	Oil seeds	0.5	1.3	1.8

[a]Measurements in tons of CO_2 equivalents per 1000 gallons.
Source: Ryan et al. (2006).

Deforestation is another negative environmental impact that results from the increased production of biofuels (Curran et al. 2004). It also has negative implications for carbon sequestration and the protection of biodiversity. The demand for biofuels has already been cited as a factor responsible for an increase in deforestation. One example is in Indonesia where increased deforestation resulted in a 70% rise in palm oil prices during 2007 (Yacobucci & Schnepf 2007).

Deforestation has negative implications for carbon sequestration and the protection of biodiversity (IIASA 2009). However, these problems may be avoided by using abandoned agricultural lands. Khanna et al. (2009) suggested that land shortages in the United States may be alleviated by bringing into cultivation areas currently protected by the Conservation Reserve Program (35 million acres). A recent study has estimated the potential for bioenergy production at the global scale from using such lands (Campbell 2008). Taking into account the potential for bioenergy, which includes both bioelectricity and biofuels, these results show that approximately 8% of current primary energy demand may be produced on the 400 million ha of abandoned lands.

Several studies have examined the greenhouse gas effects of biofuels policies (Ando et al. 2009, Lasco & Khanna 2009). Lasco & Khanna (2009) compared U.S. carbon emissions under different policy scenarios. If the current U.S. mandate is imposed, the level of carbon emissions is systematically higher than under optimal policy intervention (which internalizes the external effects induced by greenhouse gas emissions). These papers focus on the implications of biofuels policies on the energy markets, abstracting from interactions with other markets, such as agricultural or land markets. Biofuels policies may have implications on land allocation and indirect carbon emissions in land-abundant countries such as Brazil, Indonesia, and Malaysia (IIASA 2009). These studies also neglect the effects of such policies on carbon emissions from the rest of the world. If biofuels mandates are introduced in a country that has market power in the biofuels market (as the United States and the European Union have for ethanol and biodiesel), world biofuels prices may increase. This, in turn, may result in biofuels exports from other countries and increased petroleum consumption in their domestic sectors (carbon leakage). Thompson et al. (2009) found that assumptions about land-use responses in Brazil will have a significant effect on U.S.-Brazil trade in ethanol and ethanol prices in the

United States. That is, these market effects as well as their environmental impacts in terms of deforestation and carbon emissions are highly sensitive to assumptions regarding model parameters.

The production of biomass relies on water resources, which are becoming increasingly scarce in many regions. With more acreage under biofuels, irrigated land areas may expand. This may increase the demand for water and make it more expensive. Increased competition for water may cause a decline in agricultural yields and slow down the growth of food production (Rajagopal & Zilberman 2007). The issue of water availability is all the more important in countries such as India and China that already suffer from water shortages (Berndes 2002, de Fraiture et al. 2008).

7. CONCLUDING REMARKS

The future of the biofuels industry will be an increasingly important issue in the decades to come. The demand for transportation is projected to double by 2030 (IEA 2007). Nuclear power, solar energy, and wind energy can substitute for petroleum and coal to meet demand for electricity and heating. These resources have some advantages: They are largely inexhaustible and carbon neutral. However, the only viable substitute for transportation energy in the near future is first-generation biofuels. The production of this resource is limited by the availability of land, which is also used for food production. Serious concerns have been raised regarding the carbon benefits of biofuels production and use. It is well-known that carbon is released into the atmosphere during the production of biofuel. However, policies that encourage biofuels production may also lead to encroachment into forest lands, thereby speeding up the rate of deforestation, which results in the release of more carbon into the atmosphere. These trends, if significant, may offset the reductions in carbon emissions that the large-scale adoption of biofuels was intended to achieve in the first place.

Even in the absence of regulation to encourage the production of biofuels, the supply of biofuels is expected to lead to rising food prices. Models show that corn and oil seed prices may increase by 65–75% by the year 2020. However, when more advanced second-generation biofuels that use less land are introduced, these figures decline to 45–50%.

Many policies have been introduced with the aim of increasing the production and use of biofuels. Mandatory blending requirements have been implemented in the United States and various E.U. countries. These policies are projected to induce substantial increases in world biofuels production in the near future. They are also expected to adversely impact agricultural production in the rest of the world because these domestic biofuels targets can be met only through large-scale imports from land-abundant countries such as Brazil that enjoy a comparative advantage in producing low-cost biofuels from sugarcane. Trade in biofuels may induce significant land-use changes and deforestation in the developing countries. However, protectionist policies in the developed economies will likely reduce these adverse environmental impacts. More economic studies need to be done to take into account the increase in the carbon footprint of biofuels because of land-use changes, which may, according to some estimates, release much larger amounts of carbon into the atmosphere than the carbon savings from the displacement of petroleum by biofuels.

Relative to other climate mitigation options for the agricultural sector, the substitution of fossil fuels by biofuels is still expensive. Modeling studies suggest that displacing fossil fuels by biofuels can be a competitive climate mitigation strategy if the price of the carbon

is above $70 per ton. Next-generation biofuels may be superior in terms of their land-use requirements, but they may also be more costly to produce.

From the point of view of economic research, the issue of fuel versus food is a promising one. The allocation of land away from food to the production of biofuels will depend on an array of factors, some of which exhibit a significant degree of uncertainty. First, although current biofuel technologies are land intensive, newer generation biofuels may use land more efficiently. Therefore, the impact of biofuel supply on food production may be limited. Second, protectionist policies that limit imports of clean energy based on trade and national security considerations may have a positive environmental effect by limiting land conversion and deforestation in developing countries that have a cost advantage in the supply of biofuels. Third, the price of nonrenewable resources such as crude oil will determine how quickly consumers switch to the cleaner alternative. This shift will also be determined by government cap and trade programs and investment decisions such as those providing subsidies and tax credits to fueling stations that cater to flexible-fuel vehicles. Understanding the effects of these policies will require economic models that build on the limited number of important existing studies and that integrate approaches from agriculture and resource economics as well as industrial organization.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

The authors thank the Canada Research Chair program, the Social Science and Humanities Research Council (SSHRC) of Canada, and the Center for Applied Business Research in Energy and the Environment (CABREE) at the University of Alberta for generous financial support. They also thank David Zilberman for valuable comments and suggestions, which improved the paper significantly.

LITERATURE CITED

Adams DM, Alig RJ, Callaway JM, McCarl BA, Winnett SM. 1996. *The forest and agricultural sector optimization model (FASOM): model structure and policy applications*. Res. Pap. PNW-RP-495, US Dep. Agric., For. Serv., Pac. Northwest Res. Stn.

Anderson K, Martin W, Valenzuela E. 2006. The relative importance of agricultural subsidies and market access. *World Trade Rev.* 5(3):357–76

Ando AW, Khanna M, Taheripour F. 2009. *Market and social welfare effects of the renewable fuels standard*. See Khanna et al. 2009. In press

Banse M, van Meijl H, Tabeau A, Woltjer G. 2008. *Impact of EU biofuel policies on world agriculture and food markets*. Eur. J. Agric. Econ. Pap. 6476, 107th Semin., Sevilla, Spain

Berndes G. 2002. Bioenergy and water—the implications of large-scale bioenergy production for water use and supply. *Glob. Environ. Change* 12:253–71

Birur DK, Hertel TW, Tyner WE. 2008. *Impact of biofuel production on world agricultural markets: a computable general equilibrium analysis*. GTAP Work. Pap. 53, Purdue Univ.

Bureau JC, Guyomard H, Jacquet F, Tréguer D. 2009. *European biofuel policy: How far will public support go*? See Khanna et al. 2009. In press

Burniaux J, Truong T. 2002. *GTAP-E: an energy-environmental version of the GTAP model*. GTAP Tech. Pap. 16., Cent. Glob. Trade Anal., Purdue Univ.

Campbell JE, Lobell DB, Genova RC, Field CB. 2008. The global potential of bioenergy on abandoned agriculture lands. *Environ. Sci. Technol.* 42:5791–94

Chakravorty U, Magné B, Moreaux M. 2008. A dynamic model of food and clean energy. *J. Econ. Dyn. Control* 32:1181–203

Cranfield JAL, Hertel TW, Eales JS, Oreckel PV. 1998. Changes in the structure of global food demand. *Am. J. Agric. Econ.* 80(5):1042–50

Curran L, Trigg N, McDonald AK, Astiani D, Hardiono YM, et al. 2004. Lowland forest loss in protected areas of Indonesian Borneo. *Science* 313(5660):1000–3

de Fraiture C, Giordano M, Liao Y. 2008. Biofuels and implications for water use: blue impact of green energy. *Water Policy* 10(Suppl. 1):67–81

de Gorter H, Just DR. 2008. The economics of the US ethanol import tariff with a blend mandate and tax credit. *J. Agric. Food Organ.* 6(6):1–21

de Gorter H, Just DR. 2009a. The welfare economics of a biofuel tax credit and the interaction effects with price contingent farm subsidies. *Am. J. Agric. Econ.* 91(2):477–88

de Gorter H, Just DR. 2009b. The welfare economics of biofuel tax credits and mandates. See Khanna et al. 2009. In press

Delgado C, Rosegrant M, Steinfeld H, Henui S, Courbois C. 1999. *Livestock to 2020. The next food revolution*. Discuss. Pap. 28, Int. Food Policy Res. Inst., Food Organ. Agric. Int. Livest. Res. Inst.

Elobeid A, Tokgoz S. 2008. Removing distortions in the U.S ethanol market: What does it imply for the United States and Brazil? *Am. J. Agric. Econ.* 90(4):918–33

FAO. 2007. *The State of Food and Agriculture: Paying Farmers for Environmental Services*. Rome: Food Agric. Organ.

FAO. 2008. *The State of Food and Agriculture: Prospects and Perspectives. Biofuels: Risks*. Rome: Food Agric. Organ.

FAPRI. 2007. *US and World Agricultural Outlook*. Ames, IA: Food Agric. Policy Res. Inst., Iowa State Univ./Univ. Mo.-Columbia

Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P. 2008. Land clearing and the biofuel carbon debt. *Science* 319:1235–38

Hayami Y, Ruttan VW. 1971. Induced innovation and agricultural development. Staff Pap. Ser. 71, Dep. Agric. Appl. Econ., Univ. Minn., St-Paul

Hamelinck CN, Faaij A. 2006. Outlook for advanced biofuels. *Energy Policy* 34(17): 3268–83

Hertel TW. 1997. *Global Trade Analysis: Modeling and Applications*. Cambridge, UK: Cambridge Univ. Press

Hertel TW, Rose S, Tol RSJ, eds. 2009a. *Economic Analysis of Land Use in Global Change Policy*. New York: Routledge

Hertel TW, Tyner WE, Birur D. 2009b. Biofuels for all? Understanding the global impacts of multinational mandates. In *Economic Analysis of Land-Use in Global Climate Change Policy*, ed. TW Hertel, S Rose, RSJ Tol. New York: Routledge

Hochman G, Sexton SE, Zilberman D. 2008. The economics of biofuel policy and biotechnology. *J. Agric. Food Ind. Organ.* 6(8):1–22

IIASA. 2009. *Biofuels and Food Security: Implications of an Accelerated Biofuels Production*. Vienna: Int. Inst. Appl. Syst. Anal.

IEA. 2006. *World Outlook 2006*. Paris: Int. Energy Agency

IEA. 2007. *World Outlook 2007*. Paris: Int. Energy Agency

IEA. 2009. *From 1st to 2nd Generation Technologies*. Paris: Int. Energy Agency

Keeney R, Hertel TW. 2008. *The indirect land-use impacts of U.S. biofuels policies: the importance of acreage, yield and bilateral trade response*. GTAP Work. Pap. 52, Purdue Univ.

Khanna M. 2008. Cellulosic biofuels: Are they economically viable and environmentally sustainable? *Choices* 23(3):16–21

Khanna M. 2009. *Transition to a bioeconomy: environmental and rural development impacts*. Proc. Farm Found./USDA Conf., St. Louis, Mo. http://www.farmfoundation.org
Khanna M, Hochman G, Rajgopal D, Sexton SE, Zilberman D. 2009. Sustainability of food, energy and environment with biofuels. *CAB Rev. Perspect. Agric. Vet. Sci. Nutr. Nat. Resour.* 4(28): In press
Khanna M, Scheffran J, Zilberman D, eds. 2009. *Handbook of Biofuels Economics and Policy*. New York: Springer. In press
Kojima M, Mitchell D, Ward W. 2007. *Considering Trade Policy for Liquid Biofuels*. Washington, DC: World Bank Energy Syst. Manag. Assist. Program
Lasco C, Khanna M. 2009. US-Brazil trade in biofuels: determinants, constraints and implications for trade policy. See Khanna et al. 2009. In press
Lee H-L, Hertel TW, Sohngen B, Ramankutty N. 2005. *Towards an integrated land-use database for assessing the potential for greenhouse gas mitigation*. GTAP Tech. Pap. 25, Cent. Glob. Trade Anal., Purdue Univ.
Martin A. 2008. Fuel choices, food prices and finger-pointing. *New York Times*, Mar. 15, pp. B1, B6
McDougall RM, Golub A. 2008. *A revised energy-environmental version of the GTAP model*. GTAP Tech. Pap., Cent. Glob. Trade Anal., Purdue Univ.
Msangi S, Sulser T, Rosegrant M, Valmonte-Santos R, Ringler C. 2007. *Global Scenarios for Biofuels: Impacts and Implications*. Washington, DC: Int. Food Policy Res. Inst.
OECD. 2008. Economic assessment of support biofuels policies. *Organ. Econ. Coop. Dev. Draft Rep.*, Paris
Paltsev S, Reilly J, Jacoby H, Eckaus R, McFarland J, et al. 2005, The MIT Emissions Predictions and Policy Analysis (EPPA) model: Version 4. *MIT Rep. 125*, Joint Program Sci. Policy Glob. Change, Cambridge, MA. http://web.mit.edu/globalchange/www/MITJPSPGC_Rpt125.pdf
Peña N. 2008. *Biofuels for transportation: a climate perspective*. Solut. White Pap., Pew Cent. Clim. Change
Rajagopal D, Zilberman D. 2007. *Review of environmental, economic, and policy aspects of biofuels*. Policy Res. Work. Pap. 4341, World Bank
Reilly J, Paltsev S. 2009. Biomass energy and competition for land. See Hertel et al. 2009a, ch. 8
Ryan L, Convery F, Ferreira S. 2006. Stimulating the use of biofuels in the European Union: implications for climate change policy. *Energy Policy* 34:3184–94
Schneider UA, McCarl B. 2003. Economic potential of biomass based fuels for greenhouse gas emission mitigation. *Environ. Resour. Econ.* 24:291–312
Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid J, et al. 2008. Use of U.S. croplands for biofuels increases greenhouse gas through emissions from land-use change. *Science* 319:1238–40
Seauner B. 2008. Food market effects of a global resource shift toward bioenergy. *Am. J. Agric. Econ.* 90(5):1226–32
Taheripour F, Tyner W. 2007. *Ethanol subsidies: Who gets the benefits*? Work. Pap., Purdue Univ.
The Economist. 2007. Food prices: cheap no more. *Economist*, Dec. 6, http://www.economist.com/printedition/displayStory.cfm?Story_ID=10250420
Thompson W, Meyer S, Westhoff P. 2009. *Potential for uncertainty about indirect effects of ethanol on land-use in the case of Brazil*. Work. Pap., Univ. Mo., Columbia
Wiebe K, ed. 2003. *Land Quality, Agricultural Productivity, and Food Security*. Cheltenham, UK/Northampton, MA: Edward Elgar
Yacobucci BD, Schnepf R. 2007. Ethanol and biofuels: agriculture, infrastructure, and market constraints related to expanded production. *CRS Rep. RL33928*, Natl. Counc. Sci. Environ., Washington, DC

Annual Review of
Resource Economics

Volume 1, 2009

Contents

Resource Dynamics

Ecology and Space

Technology and Innovation

Errata

An online log of corrections to *Annual Review of Resource Economics* articles may be found at http://resource.AnnualReviews.org