Impacts of US and EU biofuels targets on food production and carbon emissions: Insights from a Hotelling-Ricardian model[1]

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ABSTRACT

We develop and calibrate an empirical model within a Hotelling-Ricardo framework to study the adoption and rate of diffusion of biofuels for transportation use and the implications of this. We include both first and second-generation biofuels. The model is global and considers land allocation (Ricardo) as well as the scarcity of petroleum resources (Hotelling). Within this framework, we analyze the effects of mandatory blending in the United States and the European Union on world agricultural and energy markets, and on carbon emissions. We find that the effect of the mandatory blending policies on food production and food prices is smaller than found in previous studies. Furthermore, by taking into account indirect carbon emissions arising from land conversion, introducing biofuels targets is found to increase carbon emissions at the worldwide level.

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Running Head: Long-Run Effects of Biofuels on Food Production and Carbon Emissions

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1 Introduction

It is well-known that to be able to cut carbon emissions in the near future, clean substitutes to fossil fuels must be found. Biofuels have gained widespread attention over recent years as a promising candidate, especially in the transportation sector. In fact, plant-based fuels such as ethanol and biodiesel have emerged as the only viable substitutes for petroleum-based fuels in transportation. Other candidates, such as fuel cells and hydrogen are currently far from being economically viable. In contrast, several clean alternatives to coal exist for use in the electricity sector, including solar, wind, hydro, and nuclear power. Another argument for increased production of biofuels is energy security. Many countries have a desire for less dependence on foreign countries for vital energy supplies. For instance, to reduce US oil imports, the Renewable Fuel Standards require the use of 36 billion gallons of ethanol by 2022 (DOE 2008).

Several important issues have arisen with the increased production of biofuels. First, this is land-based fuel production. When arable land is a scarce resource that is also crucial in the production of food, the growth in biofuels production may well result in reduced food supply and increased food prices. Furthermore, by converting existing grasslands and forests into farmland, there is a leakage of sequestered carbon into the atmosphere. Deforestation induced carbon emissions can create a so-called carbon debt, which undermines the central argument for biofuels; namely that they reduce carbon emissions compared to fossil fuels (Fargione *et al.* 2008). The aim of this paper is to study the implications of increased use of biofuels, with a particular focus on agricultural production and food prices. We do this by modeling petroleum as a scarce resource in a Hotelling framework, which means that the oil price increases over time. Land, which is allocated to food and biofuels production, is also a scarce resource. Since land quality differs dramatically across geographical areas, land is modeled within a Ricardian framework. The novel feature of the model is that the substitution between petroleum-based fuels and biofuels is induced through prices, which in turn are affected by policies, such as mandatory blending of biofuels. This enables us to better analyze the consequences of biofuels policies on biofuels production, food production and carbon emissions.

The existing economic work on the impact of biofuels on the agricultural sector and induced carbon emissions can broadly be divided into two main categories based on whether the models describe only the agricultural sector or the agricultural sector together with the transportation sector. Schneider and McCarl (2003) focus on the agricultural sector and adopt a partial equilibrium approach of land allocation in the United States between agriculture and forestry. Their study investigates at what carbon prices biofuel is a viable mitigation option. Other papers study the competitiveness of biofuels by looking at the interaction between transportation and agriculture. Reilly and Paltsev (2009) incorporate biomass technologies in a land allocation model within a general equilibrium framework based on the MIT Emissions Predictions and Policy Analysis model (EPPA). Several studies use the trade and general equilibrium model (GTAP) to explore the impact of biofuels production on world agricultural markets specifically focusing on US and EU biofuel policies (Banse *et al.* 2008, Birur *et al.* 2009, Hertel *et al.* 2009). Chakravorty *et al.* (2008) develop a dynamic model of energy choice with competition for land between food production and a clean land-based energy source. They consider resource scarcity and obtain analytical results on the effects of carbon targets on land use. See Chakravorty *et al.* (2009) for a recent survey of the literature.

Our study adds to the above literature in several ways. First, we explicitly take into account resource scarcity by coupling a Hotelling model and a Ricardian model. Existing studies do not explicitly model both petroleum and land scarcity simultaneously. Whereas Schneider and McCarl (2003) explicitly take into account land scarcity without considering an endogenous demand for transportation services, Hertel *et al.* (2009), Reilly and Paltsev (2009) and Birur *et al.* (2009) consider land scarcity, but without considering petroleum scarcity. This is an important extension of the existing work, since both the availability of land and petroleum resources are crucial for understanding the future of transportation energy. Second, while existing studies typically limit the analysis to considering first-generation biofuels, we consider a range of alternative energy sources for transportation over the next century, including both first and second-generation biofuels. The GTAP studies serves as an example of the existing literature (Banse *et al.* 2008, Birur *et al.* 2009, Hertel *et al.* 2009). These studies analyze the impact of mandatory blending of biofuels for first-generation biofuels in the United States and the European Union, but do not consider the potential use of second-generation biofuels. Recent scientific studies suggest that second-generation biofuels will become commercially viable very soon (IEA 2009), and it is therefore important to also include this energy source as a possible alternative to traditional transportation fuels. Furthermore, pro-biofuel policies in the United States require the use of 21 billion gallons of second-generation biofuels (cellulosic ethanol) by 2022. The main advantages of second-generation biofuels are that they are less land-using and less carbon intensive. Consequently, second-generation biofuels may have important implications both for land use, agricultural production and emissions. Our third contribution to the literature is related to the recent finding that when indirect carbon emissions are taken into account in addition to direct emissions, the central argument for using biofuels does not hold anymore: biofuels do not reduce carbon emissions compared to petroleum based fuel sources (Fargione *et al.* 2008, Searchinger *et al.* 2008). The indirect emissions are a result of converting marginal land or forests into farmland for producing biofuel crops, which releases sequestered carbon into the atmosphere. To date, no study has measured the indirect land use effects and the corresponding effect on emissions of biofuels development at the world-wide level. In our model, both direct and indirect carbon emissions are accounted for, and our study therefore gives a better measure of the carbon footprint of biofuels than previous studies.

We find that biofuel policies have less of an impact on food prices than suggested in previous studies. This can be explained by the fact that our model includes non-land using second-generation biofuels, in addition to traditional (land-using) biofuels. Second-generation biofuels do not compete with food for land, hence, using more second-generation biofuels instead of first-generation biofuels reduces the impact of biofuels on food production and food prices. Another interesting finding is the importance of marginal lands both on carbon emissions through indirect carbon emissions from land conversion, and on the increase in food prices. Food prices are found to increase twice as fast over the next couple of decades if marginal lands are not put into agricultural production.

The paper is organized as follows. Section 2 describes the basic model that underlies the empirical model, which is presented in the following section, along with the economic trade-offs we consider in the allocation of land and energy. Section 3 also describes the scenarios considered in the empirical analysis. The simulation results are presented in section 4 along with a sensitivity analysis. The last section concludes the paper.

2 The Basic Model with Land and Petroleum Scarcity

We start out by giving a brief introduction to the basic model underlying our empirical model. This is done by extending the model developed by Chakravorty *et al.* (2008) to include a mandatory blending policy. The implications of such policy are analyzed empirically below and we therefore analyze the implications that can be obtained from the basic model when introducing a mandatory blending constraint.

As in the model by Chakravorty *et al.* (2008), we look at an economy with two goods; a food commodity and transportation energy services, where the latter are provided from oil and biofuels. There are two primary production factors in the model; land and oil. Contrary to the empirical model, land is assumed homogenous in the basic model and the total availability of land is denoted $\bar{L}$, which may be allocated to the production of food or energy crops. The residual land is fallow. A linear relationship is assumed between the input of land and production of energy and food. The other scarce resource in the model is oil. The unit cost of extracting oil is lower than the cost of producing biofuels from land: $c_x < c_b$. The production of energy from the extracted oil (x) and biofuels (b) are treated as perfect substitutes. This is not consistent with existing biofuels, such as E5 or E85, where oil and biofuels are used in fixed proportions to produce energy services. In the empirical model presented below, we relax the assumption of perfect substitution.

The consumption of oil causes carbon emissions whereas land-based fuels are assumed to be carbon neutral in the basic model. In the empirical model, however, land-based fuels are not carbon neutral, but less carbon intensive than petroleum based fuel, which is in line with the recent literature on the topic. The stock of carbon in the atmosphere is assumed to increase with carbon emissions, and decrease at a given diffusion rate over time. The model is analyzed by solving the dynamic optimization problem of the social planner who allocates land to food and fuel production to maximize the net discounted value of the representative consumer's utility, which is derived from consumption of food and transportation services, minus production costs. Chakravorty *et al.* (2008) give the details of the basic model and characterize the solution to the dynamic problem in the unregulated case. They also look at the case of a cap on the carbon stock. We extend their model to analyze another form of regulation; mandatory blending of biofuels.

Biofuels mandatory blending requires that the share of land-based fuels in the energy portfolio should be greater or equal to a certain share s from date T. The effect of this policy can be analyzed by introducing an additional constraint into the optimization problem of the social planner, namely:

$$\frac{L_b}{L_b + x} \geq s \tag{1}$$

Let μ denote the shadow price of the mandatory blending constraint. The current value Lagrangian of the social planner's optimization problem can then be stated as:[3]

$$l = u_f(L_f) + u_e(x + L_b) - c_f L_f - c_b L_b - c_x x - \lambda x + \pi\left[\bar{L} - L_f - L_b\right] + \gamma_b L_b + \gamma_x x + \mu\left(\frac{L_b}{L_b - x} - s\right), \tag{2}$$

where $u_f(\cdot)$ and $u_e(\cdot)$ are utility functions for food and energy, c_f and c_e are the unit costs of producing food and biofuels, L_f and L_b denote land used for food production and biofuel production, λ and π are the shadow values of the petroleum stock and land, and γ_b and γ_g are the shadow values of the non-negativity constraints on land used to produce biofuels and the oil stock.

When the mandatory blending constraint is introduced into the social planner's problem, the first-order conditions for biofuels and petroleum production become:

$$\frac{\partial l}{\partial x} = 0 \quad \Leftrightarrow \quad u_e'\left(x + L_b\right) = c_x + \lambda - \gamma_x + \frac{\mu L_b}{\left(L_b + x\right)^2}, \tag{3}$$

$$\frac{\partial l}{\partial L_f} = 0 \quad \Leftrightarrow \quad u_e'\left(x + L_b\right) = c_b + \pi - \gamma_b + \frac{\mu x}{\left(L_b + x\right)^2}. \tag{4}$$

[3] For additional details, see Chakravorty *et al*. (2008).

Other optimality conditions are identical to those reported by Chakravorty *et al.* (2008) for the basic model.

Assume first that the mandatory blending constraint is not binding (unregulated case) so that $\mu = 0$. The full marginal costs of biofuels and oil are then given as the sum of production cost, the shadow value of the land or oil stock constraint, and the non-negativity constraint on land used in biofuels production or on the oil stock, respectively. The full cost of production is therefore higher than the unit costs of production, c_f and c_e. Producing energy from oil is cheaper than producing energy from biofuels ($c_x < c_b$). However, to determine the optimal fuel source, the full cost of production must be taken into account. The augmented or full unit costs of using these scarce resources are $p_x = c_x + \lambda$ and $p_b = c_b + \pi$, respectively, for oil and land-based fuels. As oil becomes scarcer, its shadow price λ increases driving up the price of energy. At some point the energy price may be high enough to justify producing energy from land fuels. Oil and land fuels are jointly competitive once their full marginal costs are strictly equal: $c_x + \lambda = c_b + \pi$.

Assume now that the mandatory blending constraint is binding ($\mu > 0$). It can be shown that the full unit cost of biofuels is reduced by $\frac{\mu L_b}{(L_b + x)^2}$ compared to the non-regulation case, whereas the full unit cost of oil increases by $\frac{\mu x}{(L_b + x)^2}$. Hence, the shadow value of the mandatory blending constraint can be interpreted as a subsidy on land fuels and a tax on oil. This changes the timing of when land fuels are adopted as well as the time when the oil stock is depleted. Since the full cost of producing biofuels decreases, biofuels become competitive earlier. For oil, on the other hand, the full cost increases, which slows down the extraction of oil and postpones the depletion of the oil stock. This is illustrated in the empirical analysis presented below.

Second-generation biofuels do not require the use of any scarce resource in our model. Hence, the unit cost of production does not need to be augmented with any shadow price in order to obtain the full cost, i.e., the unit production cost is the full unit cost. Introducing second-generation biofuels to the model implies that this technology becomes economically viable when the production cost equals the full production cost of the other fuels that are currently in production, as discussed above.

With this in place, we present the simulation model, which is used to analyze *inter alia* the policy of biofuels mandatory blending.

3 The Simulation Model

In this section we add more structure to the theoretical model outlined above by specifying functional forms and estimating the model based on available data. For a more detailed description of the model, how it is estimated and the data used, see the appendix A.

As mentioned above, two costly substitutes to oil are available, first and second-generation biofuels, the latter being the backstop technology. Feedstock costs comprise more than half the costs of producing first-generation biofuels (FAO 2008).[4] For this reason we use a land-allocation model with endogenous prices based on the Ricardian rent principle coupled with a Hotelling model. The model distinguishes between two aggregate food commodities: vegetarian and animal protein products, and three types of productive land. All types of land can be used as cropland or pastures/forestland (marginal lands). Crop production may be transformed into food, animal feed or energy. Furthermore, the model considers international trade between five regions: the United States, the European Union (EU27), other OECD countries, Medium Income Economies, and Low Income Economies. Medium Income Economies consists of large biofuels producers such as Brazil, Indonesia and Malaysia, as well as China and India; countries that are expected to account for a considerable share of the increased energy demand in the decades to come, and other countries. Low Income Economies are mainly African countries. Another key feature of the model is that it can be used to measure greenhouse gas emissions from transportation by distinguishing between the carbon content of each resource used. Finally, the indirect carbon emissions are taken into account. The main features of the supply side of the model are presented in **Erreur ! Source du renvoi introuvable.**.a and 1.b.

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[4] A feedstock is the raw material or crops used in the biofuels production process.

Despite international trade in agricultural products being highly protected, we assume no barriers to international trade in the model and we treat goods as perfectly homogenous. Food products in the model are aggregate and it is therefore difficult to introduce trade barriers, which are typically specific to each food market (sugar, wheat, etc.). Only final food products are traded in the model. In addition there is trade in primary energy: petroleum, first-generation biofuels and the second-generation biofuels. We have introduced current US and EU trade barriers on biofuels markets in the model. The US bio-ethanol trade policy includes a 2.5% *ad valorem* tariff and a per unit tariff of US$ 0.54 per gallon (Yacobucci and Schnepf, 2007). The European Union trade policy includes a 6.5% *ad valorem* tariff on biofuel imports (Kojima *et al.* 2007).

Regional food demand is modeled as a function of population and per capita income. A boom in world food and energy requirements is expected to occur over the next five decades before the growth levels out. The world population is projected to grow from a current population of about 6 billion people to around 9 billion people by 2050, where it is projected to level out (UNDP 2004). However, there will be significant regional disparities since 80% of the increase in world population will occur in Middle and Low Income Economies, and consequently, these regions are projected to account for the bulk of the increase in food and energy needs. As people become richer, we expect to observe increased consumption of meat and dairy and reduced consumption of vegetarian products. Meat production is more land consuming than the production of vegetarian products (Cranfield *et al.* 1998 and 2003, Delgado *et al.* 1998). In fact, to obtain one kilogram of meat and dairy products, three kilograms of cereals are needed (Bouwman *et al.*, 2005). For this reason we distinguish between two food goods: vegetarian and animal protein products. The shift towards animal protein products is modeled by letting income elasticities be functions of per capita income.[5]

Each of the five regions has an endowment of land and petroleum resources. Middle Income Economies include the Middle-East and are endowed with large petroleum reserves. Agricultural areas and land qualities are also unevenly distributed among regions. Whereas less than one quarter of the world's agricultural area is located in OECD countries (USA, EU and other OECD countries), this region has nearly half of the areas of the highest land quality. We return to agricultural production below, but first we look at how energy supply is modeled.

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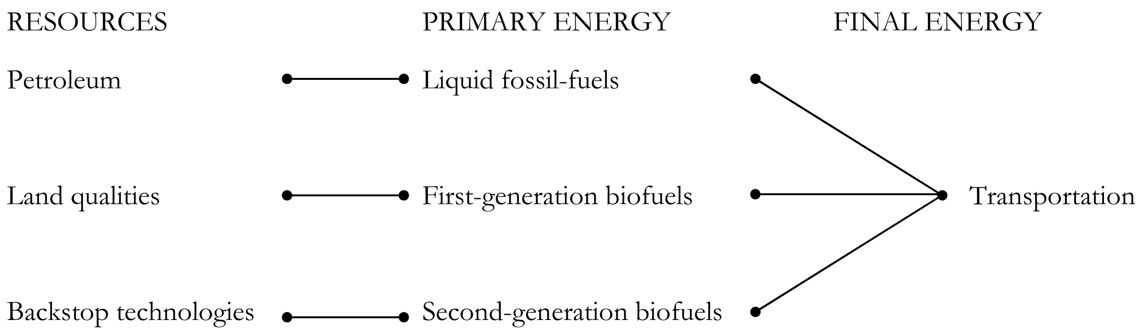
[5] For more details on the specification of the model, see appendix A.

Figure 1.a: Energy production process.



The supply of energy is described in Figure 1.a, which shows the different stages of the energy production process from resource extraction (oil) or land allocation, to final products (energy services for transportation). The scarcity of fossil fuels is implemented by defining an exogenous resource stock for each region, as outlined in the one-region basic model described above. Data on current petroleum stocks have been obtained from the annual survey of the World Energy Council (WEC 2007).[6] With the steady increase in petroleum prices, resource stocks with higher extraction costs, such as oil sands, becomes competitive. Because the least costly stocks are extracted first, extraction costs increase with cumulative extraction. This is implemented in the model by using the functional form of the extraction cost function of Nordhaus and Boyer (2000) and Chakravorty *et al.* (2009). Parameter values are found through calibration using data from Rogner (1997) and the European Commission (2000). Both conventional and non-conventional resources are considered.

Of the substitutes for oil, first-generation biofuels are land using and the energy yields depend upon the feedstock used. Different feedstocks require different climates and land qualities. Consequently, different feedstocks are used in different geographical areas. For instance, in Medium Income

[6] We consider the following types of petroleum reserves: crude oil, oil shale, heavy oil and bituminous sands.

Countries where first-generation biofuels are produced from sugarcane, about 1,700 gallons of ethanol are produced per hectare of land. In High Income Countries biofuels are produced from corn and the production is 800 gallons per hectare (Senauer 2008). Finally, in Low Income Countries, energy yields for first-generation biofuels are only about 400 gallons per hectare (FAO 2008).[7]

Each region's comparative advantage in the production of biofuels depends on the feedstock used. For instance, ethanol in Brazil is obtained from sugarcane, which can be cultivated on low quality land, whereas in the United States it is produced from corn, which requires higher quality land. The higher the land quality used, the higher the production cost of biofuels. Most food crops require high land quality, which leads to a more aggressive competition between agriculture and energy for land, and, in turn, increases the opportunity cost of land. As described when introducing the basic model above, both energy yields and the opportunity cost of land affects the production cost of biofuels. The cost of producing one gallon of ethanol from sugarcane in Brazil is US$ 0.94, while the cost of producing one gallon of ethanol from corn in the United States is US$ 1.51 (FAO 2008).[8] For further details on production costs per region, see appendix A.

A common feature of second-generation biofuels is that they use little or no land (OECD 2008).[9] Second-generation biofuel technologies that are currently under development may make it possible to use lignocellulosic biomass or wastes in biofuels production. Cellulosic wastes, including waste products from agriculture and forestry, wastes from processing, and organic parts from municipal wastes are potential sources (FAO 2008). The technologies used are still only at the stage of research and development, and their production cost is currently US$ 5 per gallon (IEA 2009). In addition, they may be limited by driving distance once implemented at full scale (Ryan *et al.* 2006). Hence, a capacity constraint which restricts second-generation biofuel development is imposed on these technologies. Due to the assumption of exogenous technical progress, production cost decreases exponentially over time, whereas the production capacity increases exponentially.

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7 Estimate based on first-generation biofuel production from cassava.

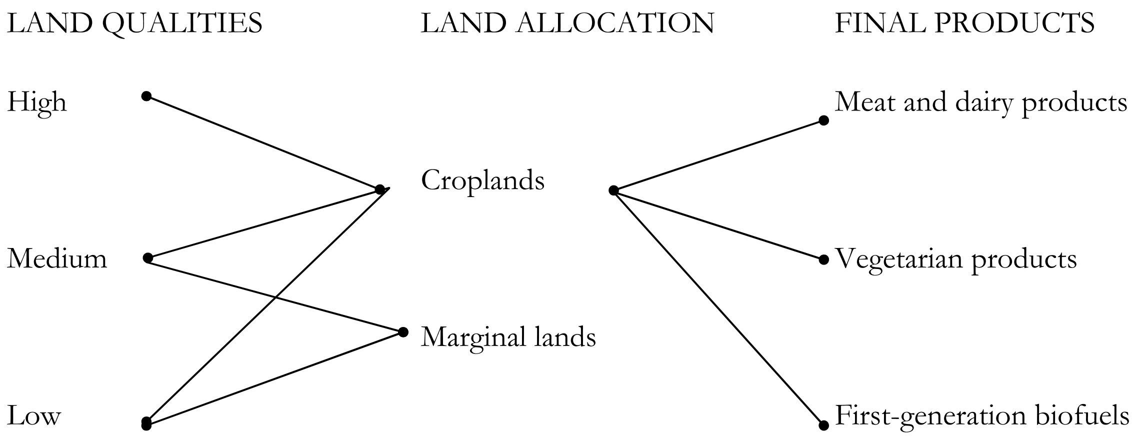
8 These costs include feedstocks, processing and energy costs and is defined based on the cost of land which is endogenous. They are defined net of the co-products value and net of subsidies. In Brazil, there is no subsidy whereas there is a subsidy of US$ 0.51 per gallon in the United States.

9 Second-generation technologies are defined in the appendix.

First-generation biofuels are already mixed with petroleum to meet energy demand in transportation, but there is still scope for displacing fossil fuels in conventional vehicles (OECD 2008). Conventional petrol vehicles are compatible with blends of 10% ethanol (E10). However, flexi-fuel vehicles are designed for blends of 85% ethanol (E85) (Bomb *et al.* 2007). We deal with this by modeling the production of energy from petroleum and bio-oil using a constant elasticity of substitution production function. The elasticity of substitution is a key parameter for predicting future development of land-based fuels as it determines how easy it is to replace fossil fuels by biofuels in response to changes in the relative price between these resources. Since there is also uncertainty about the value of this elasticity, a sensitivity analysis will be carried out. Finally, second-generation biofuels are treated as perfect substitutes for petroleum and first-generation biofuels in the model (Lasco and Khanna 2009).

In addition to modeling energy choices, this study considers GHG emissions by fuel source.[10] Petroleum is the most polluting energy and the emissions occur mainly in the fuel consumption stage. Emissions from biofuels occur primarily in the production process, and the model also takes into account these emissions. On average, each gallon of conventional oil consumed releases 0.0032 tons of carbon (Lasco and Khanna 2009). Emissions can be reduced by shifting towards less polluting resources such as first and second-generation biofuels. Carbon emissions from first-generation biofuels depend on the feedstock used (Peña 2008). Whereas 0.0004 tons of carbon is released to produce one gallon of sugarcane based ethanol, 0.0017 tons of carbon is emitted when ethanol is produced from corn (Lasco and Khanna 2009). In addition, if biofuels production causes conversion of forestlands into agricultural lands sequestered carbon is released into the atmosphere. This so-called carbon debt reduces the carbon benefits of displacing fossil fuels by biofuels (Fargione *et al.* 2008, Searchinger *et al.* 2008). By cultivating tropical forests, about 700 tons of carbon per hectare are released back into the atmosphere. Second-generation biofuels are the least carbon intensive of the fuels we consider, with emissions of 0.0002 tons of carbon per gallon of fuel produced (Lasco and Khanna 2009).

[10] Carbon emissions resulting from conversion of pastureland into cropland are not considered since they are insignificant compared to emissions from fossil fuels and biofuels.



The agricultural supply in the model is outlined in Figure 1.b, which describes the production process of land-based commodities from the allocation of various land classes to the production of final products. We use the land classifications established by the Natural Resources Conservation Service of the United States Department for Agriculture (Wiebe 2003). There are three categories of land in the model; land classes I-III, where I refers to the most productive land.[11] Table 1 depicts the characteristics of each land class in terms of available area and agricultural yields by region. As mentioned above, the distribution of land quality across regions is not even. Half of the agricultural land in OECD countries (USA, EU and other OECD countries) is classified as Land Class I, whereas the corresponding shares are 20% and 18% in Middle and Low Income Countries, respectively. The total area of agricultural land available at the beginning of the study period is 1.5 billion hectares. More than 50% of this area is located in Middle Income Economies, whereas the remaining area is fairly evenly distributed between High and Low Income Economies.

[11] See appendix for more information on land classifications.

Table 1. Agricultural area and yields per regions and per land class.

		Area (billion hectares)	Crop Yields (tons per hectar)
OECD Countries	Class I	0.225	3.50
	Class II	0.095	2.50
	Class III	0.056	1.00
Medium Income Countries	Class I	0.300	2.50
	Class II	0.200	1.75
	Class III	0.195	0.70
Low Income Countries	Class I	0.150	1.75
	Class II	0.250	1.00
	Class III	0.061	0.40

Sources: Land availability (Wiebe 2003), agricultural yields (FAOSTAT).

The recent boom in biofuels production has resulted in significant increases in food prices and accelerated the rate of deforestation in some tropical countries, such as Indonesia and Brazil. According to FAO (2008), there are 1.6 billion hectares of land worldwide that could potentially be brought into cultivation. This land is of low productivity (classes II and III). All uncultivated land is located in Middle and Low Income Economies. Converting forestland into cropland is costly. Since the degree of accessibility to forestland differs, we assume that the conversion cost is increasing and convex in the area of land converted (Sohngen and Mendelsohn 1999). This is based on the assumption that the most easily accessible land is always used first. A complete description of this process, how it is dealt with in the model, and the data used to estimate the model are given in appendix A.

Primary agricultural production exhibits constant returns to scale in the model, and technological progress exogenously enhances land quality.[12] Agricultural yields have doubled over the last four decades with an annual average growth rate of 2.3% since 1961. However, the growth in world agricultural output is projected to fall to 1.5% per year over the next decades, then to 0.9% per year over the subsequent decades (Rosegrant *et al.* 2001, FAO 2008). As agricultural production increases, lower land quality classes are cultivated and more pressure is put on available land resources. Consequently, production costs increase with primary production.

As in the stylized model of Chakravorty *et al.* (2008), the land allocation decision in the empirical model is based on maximization of social surplus, and the optimal mix of petroleum resources and land fuels is driven by their relative price. Consumer and producer prices are found by maximizing social surplus under the various constraints presented above: technological constraints, the dynamics of the exhaustible resource stocks, and land availability. The model is simulated over the next century (2000-2100) in time steps of five years. A real annual discount rate of 2% is assumed.

This concludes our presentation of the simulation model. For details on parameters used in the simulations, the data used to estimate the model, as well as a more detailed description of the empirical model, see the appendix. Below, the empirical model is used to analyze several scenarios, which are introduced next.

3.1 Scenarios

We consider several scenarios that differ along two dimensions: the assumptions made on scarcity rents and the availability of marginal lands, along one dimension, and regulations. The objective is to analyze how biofuels policies in the European Union and the United States affect agricultural production, food prices, land use across regions, and carbon emissions. The different scenarios are summarized in Table 2 and described in more detail below.

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[12] Investment in agriculture is intrinsically linked with food prices. However, due to the lack of econometric studies on the elasticity of agricultural yields to food prices at the worldwide level, we do not consider this feedback effect of food prices on agricultural productivity.

Table 2. Definition of Scenarios

Scenario \ Policy	No regulation	EU mandatory blending	US mandatory blending	EU and US mandatory blending
Finite oil stock, no marginal lands	A.i	A.ii	A.iii	A.iv
Finite oil stock, marginal lands available	B.i	B.ii	B.iii	B.iv
Infinite oil stock, no marginal lands[13]	C.i	-	-	-

A. Standard Hotelling model without marginal lands (forest)

Oil stocks are finite and there are no marginal lands available under this model specification. This means that the scarcity rents of both oil and land are positive. Furthermore, with no marginal lands available, increased production of biofuels requires that land currently devoted to food production will have to be used to produce biofuels crops instead of food.

B. Standard Hotelling model with marginal lands (forest)

In this model, the production of biofuels can take place on marginal lands. The marginal land is forest land, and is consequently not currently used in food production. The conversion of marginal lands into farmland causes sequestered carbon to be released into the atmosphere. The aim of this scenario is twofold. First, it measures the potential role of marginal lands in biofuels expansion. Second, it provides a better estimate of the carbon footprint of biofuels.

C. Without oil scarcity and without marginal lands

[13] We do not consider pro-biofuels policies for model C since this model is only included to analyze the impact of biofuels expansion on food prices and land allocation.

In this model, there are no scarcity rents for oil. This is achieved by assuming an infinite stock of oil. The cost of extracting oil is, however, increasing over time, due to the assumption that the least costly oil fields are put into production first. We also assume that there is no marginal land available. This model is included to eliminate the effect of oil scarcity when analyzing the future of biofuels. With an infinite stock of oil, biofuels are not needed to replace oil as transportation fuels. This scenario allows us to isolate the effects of the boom of biofuels production on food prices and agricultural markets, and on carbon emissions savings induced by the displacement of oil by first and second-generation biofuels.

For each of the three model specifications above (A-C), we analyze the effects of four different policy specifications: (i) no regulation, which is considered the benchmark case, (ii) mandatory blending of biofuels in the European Union, (iii) mandatory blending of biofuels in the United States, and (iv) mandatory blending of biofuels in the European Union and in the United States.

Mandatory blending has recently been suggested implemented by several governments. Governments such as the United States and the European Union have established biofuel mandates to be achieved at target dates. Current regulations in the United States require the use of 36 million gallon of ethanol or biodiesel annually by 2022, of which 16 million by 2022 must be cellulosic ethanol, a second generation biofuel (DOE 2008). Hence, the US mandatory blending policy explicitly distinguishes between first and second-generation biofuels. This is not the case for the proposed EU mandatory blending policy. The European Union currently expects its member states to ensure that biofuels and other renewables have a 5.75% share of transportation fuels by 2010 and 10% by 2020. With an average share of renewables in the EU25 countries of only 2% in 2007 (OECD 2008), there is a long way to go. Since the the European Union Directive does not distinguish between first and second-generation biofuels, we look at two different policy options. In the first case, the share of first-generation biofuels of liquid fuels must exceed 10%, whereas in the second case, second-generation biofuels are used to reach the mandatory blending objective of 10%. Thus, the latter involves the use of both first and second-generation biofuels.

Having introduced the model and the scenarios we will study, we turn to the actual analysis of the different model specifications and scenarios.

4 Model Results

The implementation of biofuels targets in the United States and the European Union raises the following questions: 1) What is the impact on world food prices and on the world agricultural sector? 2) What are the implications for future energy choices? The mandatory blending policies do not explicitly specify if first or second-generation biofuels are to be used. First-generation biofuels are land-using and may significantly affect the world agricultural sector. Second-generation biofuels are, however, still only at the stage of research and development. 3) What are the potential carbon savings from displacing petroleum by biofuels? Although biofuels are not carbon neutral, they are less carbon intensive than petroleum. The carbon savings are related to land-use changes, which induces carbon emissions. 4) What are the costs of these policies? We try to answer these questions below. Our presentation of the results is organized under several important topics: energy choices, the agricultural sector, carbon emissions, and policy implications. However, before we start looking at the results, some important model assumptions are highlighted. This is important in order to better understand the model predictions presented below.

First, food demand and energy needs are projected to be substantial by the mid-century. By 2050, the current population of six billion people will have grown to nine billion people. The population growth then slows down, with an increase of only one billion people between 2050 and 2100. There will also be significant regional disparities in population growth. Whereas High Income Economies' (United-States, European-Union, and other OECD countries) population are predicted to be fairly stable over the next century, Medium Income Economies' population will increase by 41% and Low Income Economies' population will more than double. In addition, world per capita income is predicted to increase steadily over the century, but at a decreasing rate. Again, regional disparities are expected, with highest growth rates in Medium and Low Income Economies. Second, on the supply side, technological change improves land quality and efficiency of first-and-second-generation biofuels. While agricultural expansion on forestlands is likely to play a significant role in meeting food and energy needs, the intensification of land use through improved technologies and management may complement this option (FAO 2008). We do not consider induced-technological change in the model; hence, the intensification of land use in the model is exogenous. The gain in agricultural productivity is expected to be lower in the century to come than in the past; but actual yields are still below their potential in most regions, the gap being larger in Medium and Low

Income Economies (FAO 2008).[14] Technological progress is supposed to fulfil the gap between actual and potential yields over the century.[15]

4.1 Energy choices

In the absence of regulations, petroleum remains the main energy source until well beyond the mid-century in all regions regardless of model specification used (A-C). Focusing first on scenarios A and B, in which oil is scarce, our results show that the world's petroleum stocks are projected to be used until the end of the century, but with a declining share of the total supply of transportation energy. The world share of petroleum in liquid fuels does not vary much across policy scenarios nor model setup (A or B), and is about 97% until 2015 under all scenarios. The share of petroleum then shows a steady decline to about 70% by mid-century and just below 40% by the end of the century. The differences between scenarios are small also when looking at total production of petroleum. Thus, the effect of biofuel policies on petroleum consumption and the share of petroleum in transportation energy is small.

In addition to petroleum, there are two other sources for transportation fuel: first and second-generation biofuels. Although the relative energy share and the production quantity of petroleum are fairly stable across different policy scenarios, first and second-generation biofuel production varies considerable across scenarios. This is because biofuels account for a much smaller share of total transportation energy than petroleum. A one percent increase in the total energy share of biofuels is therefore considerable and may well require a 25% increase in biofuels production. Hence, the effect on world biofuels consumption of introducing mandatory blending in the European Union and the United States is considerable. If biofuels policies are introduced both in the European Union and the United States (A.iv), our results show that world consumption of biofuels is almost doubled by 2020 compared to the policy scenario with no mandatory blending (A.i). Mandatory blending policies affect the price of energy, and, thus, the level of energy consumption.

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[14] In these regions, the development of irrigation technologies, the adoption of high-yielding varieties is expected to improve agricultural productivity.

[15] A direct implication of this option is that technological progress is higher in Medium and Low Income Economies.

Table 3 summarizes the energy choices in 2020 under the different scenarios in the United States, the European Union and in the rest of the world (ROW). Without pro-biofuels policies in any region, the consumption of biofuels in 2020 in the United States and Europe is projected to be 15.8 billion gallons. In the European-Union, the share of biofuels in total transportation does not exceed 2% (see Table 3). If mandatory blending is introduced only in the European Union, the consumption of biofuels in 2020 in this region increases to 35.5 billion gallons (if target is met using second-generation biofuels) or 10.0% of EU fuel consumption. Similar, with mandatory blending in the United States, US biofuel consumption increases to 180 billion gallons or a 21.4% share of total transportation fuels (see Table 3).

The date of adoption of second-generation biofuels differs across regions, with adoption occurring first in OECD and Medium Income Economies due to the relatively lower production costs in these regions. Across all scenarios, the share of second-generation biofuels increases over time from the date of adoption and accounts for almost a quarter of transportation energy by 2050 (scenarios A.ii and B.ii).[16]

As a result of increased consumption of biofuels in the area in which mandatory blending is introduced, the price of biofuels increases relative to petroleum. Consequently, the demand for petroleum increases in the rest of the world at the expense of biofuels. For example, following the introduction of mandatory blending in the United States in the scenario with no marginal lands (A.iii), biofuels account for over 20% of total transportation energy in the United States by 2020, which is more than ten times as much as without a biofuels policy (A.i). At the same time, the share of biofuels in the rest of the world is reduced by about 6%. The overall effect on total fuel consumption is nonetheless that the use of biofuels increases fourfold while petroleum consumption is reduced by 5% in 2020 relative to the base case scenario (A.i). The same substitution effect is observed when looking at the introduction of mandatory blending in the European Union, although the effect is weaker since Europe's share of world energy consumption is lower than that of the United States. This substitution effect explains the carbon leakage that we discuss in more detail below when we look at carbon emissions.

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[16] Since the production capacity of second-generation biofuels within the European Union is constrained, secnd-generation biofuels may need to be imported to reach the target. This is accounted for in the model.

Turning to the effects of introducing mandatory blending in the European Union, we find that it makes a big difference whether the mandatory blending requirement is met by increasing the use of first or second-generation biofuels. This affects the relative shares of first and second-generation biofuels, the timing of when second-generation biofuels are introduced, and trade in biofuels. When the mandatory blending requirement is met by increasing the use of second-generation biofuels, we find that the introduction of second-generation biofuels is brought forward ten years (2020 rather than 2030) in addition to representing a higher share of total fuels. This has important implications for carbon emissions and food prices, as we return to below, since second-generation biofuels require far less land than first-generation biofuels. Finally, EU energy prices show a small increase (2%) in 2020 as a result of the policy (i.e., compared to scenarios A.i and B.i). If, instead, the EU mandatory blending requirement is met by increasing the use of first-generation biofuels, the target is reached by increased domestic production of first-generation biofuels, mainly due to high trade barriers in the European Union. The substitution effect is in this case found to be slightly larger: in the rest of the world petroleum consumption increases slightly more and the reduction in biofuels consumption is bigger as biofuels become relatively more expensive compared to petroleum.

The difference between scenarios A and B is that marginal land (forests) is only available in the latter. Thus, by comparing the two, we can analyze the impact of using marginal lands to meet the increased demand for land-based fuel and food. World consumption of first-generation biofuels increases steadily until the end of the century under both scenarios. However, when marginal lands are available, first-generation biofuels production shows an increase of 218% from 2005 to 2050 (B.i) while the increase is 173% without marginal lands (A.i). Consequently, the effect of marginal lands on biofuel production is considerable. This also has important implications for carbon emissions and the carbon leakage effect. We discuss that in detail below.

Medium Income Economies play an important role in the market for first-generation biofuels. This region is the world's largest first-generation biofuels consumer and producer, with the United States as the second largest economy.[17] On the supply side, countries such as Brazil, Malaysia and

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[17] Over the base-period, the United-States is the world's largest consumer and producer of first-generation biofuels. However, during the simulation period, this country looses its leadership in favour of Medium Income Countries since most of the rise in energy demand comes from this region, also, this region benefits from a comparative advantage.

Indonesia benefit from a comparative advantage in producing first-generation biofuels on the basis of production costs (models A and B) and land abundance (model B). On the demand side, the largest increase in energy needs will occur in this region where particularly China and India will drive up the demand.

Most existing studies on energy choices focus on long-term substitution in the electricity sector. Hence, there are few other studies to compare our results to. However, according to engineering studies, backstop technologies are expected to be cost competitive from 2040 (Peña, 2008). Our study projects that backstop technologies will be competitive well before this time. This earlier adoption can be explained by the fact that we model land competition between energy and agriculture. With increased competition for land, the opportunity cost of land increases, making first-generation biofuels relatively less competitive over time compared to second-generation biofuels that do not require any land.

Table 3. Energy choices under different scenarios in 2020 in the United States, the European Union, and the rest of the world (ROW).

Energy consumption by source	Petroleum (Billion gallon)			First-generation biofuels (Billion gallon)			Second-generation biofuels (Billion gallon)		
Scenario	USA	EU	ROW	USA	EU	ROW	USA	EU	ROW
A.i	814	358	1,395	16	3	34	0	0	0
A.ii.1	816	334	1,399	14	37	33	0	0	0
A.ii.2	814	319	1,387	15	5	34	0	30	0
A.iii	662	358	1,406	60	3	32	120	0	0
A.vi	662	320	1,408	61	5	32	119	31	0
B.i	813	358	1,396	17	4	37	0	0	0
B.ii.1	815	335	1,400	16	37	35	0	0	0
B.ii.2	814	320	1,398	17	6	36	0	29	0

B.iii	662	358	1,406	61	4	35	119	0	0
B.vi	663	321	1,408	61	6	36	119	29	0

4.2 Agricultural sector

Turning to the agricultural sector, the simulation results show that there will be a substantial increase in the demand for land until 2045. This is due to fast growth in food requirements, particularly in Medium and Low Income Economies. Increased demand for land raises the opportunity cost of land, which increases the price of goods produced with land as an input (biofuels, food). For example, in the base model without marginal lands (A.i), the opportunity costs of land are projected to increase approximately 74% from 2005 to 2050 (all land classes and regions). In addition, the increase in energy needs combined with a steady depletion of petroleum resources increase the demand for petroleum substitutes. Since second-generation biofuels are not economically viable for another couple of decades, the increased demand for substitutes to petroleum increases the demand for first-generation biofuels and thus for land.

Looking at the effect on food prices, the predictions depend on the model specification used.[18] The effect is strongest if there is no marginal land available (model specification A). Even without policies promoting the production and use of biofuels, the price of food increases by 9.0% from 2005 to 2030 (A.i). With no marginal lands and no biofuels policies (A.i), second-generation biofuels come into production in 2030, and soon after the growth in food prices stagnates, before starting to fall in 2045. However, if marginal lands are available, less pressure is put on land resources and the increase in food prices is lower. Our results show that in this case the price of food increases by 4.2% from 2005 to 2030 (B.i), or about half the increase we found when marginal lands are unavailable. Marginal lands are therefore important in meeting the increased demand for food and fuel over the next decades, as the availability of marginal lands is projected to considerably dampen the rapid growth in food prices over the next decades.

[18] In the following, when referring to the food price, we refer to a Laspeyres food price index that was constructed with 2005 as the base period.

To evaluate the impact of biofuel production on food prices we look at scenario C.i, where no biofuels are produced since petroleum stocks are assumed infinite in model specification C. Under this scenario, all available land is used to produce food. Equilibrium food prices are found to increase by 2.8% up until 2030, when food prices level out before they start falling from 2045.

As already noted mandatory blending policies boost the production of biofuels. Since increased production of first-generation biofuels means that more land must be used to produce fuel, this shifts the opportunity cost of land upwards, which in turn leads to increased food prices. Looking at the results from the different simulation scenarios, the general finding is that the introduction of biofuels policies has a limited effect on food prices. There are some differences in the impact on food prices between the different scenarios, though, which we discuss in the following.

We start out by looking at the effect of introducing mandatory blending in the European Union. There is a noticeable difference in the effect of mandatory blending depending on whether the biofuels target is met by increasing the production of first or second-generation biofuels. Second-generation biofuels are non-land using; consequently, food prices are unaffected when the biofuels target is met by relying only on this technology. If, instead, first-generation biofuels are used to reach the target, food prices over the period 2020-2040 are projected to be about 0.6% (A.ii) or 0.4% (B.ii) higher than under the unregulated scenarios (A.i and B.i), depending on whether or not marginal lands are available.[19]

Similar patterns are observed when analyzing the implications of introducing mandatory blending policies in the United States. The increase in first-generation biofuels production relative to the unregulated case results in an increase in food prices in 2020 of 0.8% (A.iii) and 0.2% (B.iii) depending on whether marginal land is available, compared to the baseline scenarios (A.i and B.i). The largest effect on food prices is observed when mandatory blending is introduced both in Europe and in the United States, since this involves a larger total production of biofuels. However, if second-generation biofuels are used to cover the additional demand for biofuels in the European Union as a result of the EU policy, the impact on food prices is basically the same as what we found when a biofuels target is only introduced in the United States (policy scenario iii).

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[19] This is calculated as the difference in food price index between the scenario with biofuel policy (A.ii or B.ii) and the unregulated case (A.i or B.i) relative to the food price in the base scenario (A.i and B.i) for specific years.

The United States accounts for a significant share of the world's transportation energy market. Nonetheless we find that introducing a biofuels target in the United States does not have much of a impact on food prices, not even compared to the impact of an EU biofuels target. This is because non-land using second-generation biofuels are important in meeting the US biofuels target; approximately half the biofuels consumed to meet the target are second generation. We conclude that introducing biofuels policy in Europe and/or the United States is expected to have only a minor impact on world food prices because of the introduction of second-generation biofuels.

In addition, mandatory blending has effects on international trade. For example, mandatory blending policies in the United States cause US agricultural exports to decrease because agricultural land traditionally used to produce food is put into production of biofuel crops. This mainly affects Medium Income Economies who would otherwise import agricultural products from the United States. The same is observed when looking at the implications of an EU biofuels target on trade. This is important for understanding the consequences of mandatory blending on indirect carbon emissions, as is discussed below.

Given our projections that biofuels policies will have only a limited impact on total food production and the food price index, we do not expect these policies to significantly affect food consumption. However, the increasing food prices and lower food production may have certain implications for food consumption across regions. Comparing the policy scenarios where mandatory blending is imposed (policies ii-iv) to the unregulated case (policy i), we find that daily food consumption in OECD countries (United States, European Union and other Rich Income Economies) is projected to be less affected by mandatory blending policies than food consumption in Medium and Low Income Economies. However, the differences are small. There are two reasons why Low and Medium Income Economies have the largest decline in food consumption. First, price elasticities for food products are higher in these regions than in Rich Income Economies. Second, the implementation of biofuels targets in Europe and the United States is projected to shift domestic agricultural output from food export to domestic energy crops.

Several other studies have looked at how biofuels and mandatory blending affect food prices and food consumption. Our predicted increase in world food prices as a result of mandatory blending in the European Union is systematically lower than what is found in other studies. For instance, Banse *et al.* (2008) project a decrease in cereals and sugar prices from 2001 to 2020 of 7-8% in absence of any regulation, while they project an increase of 2% in oilseeds prices when a mandatory blending is imposed in the European Union. The corresponding predictions without any regulation is a decrease in cereals and sugar prices of 12% and a decrease in oilseeds prices of 7% from 2001 to 2020. Our predictions are quite different. First, even in the absence of regulations, food prices are increasing over the period 2005-2020. In scenario B.i (with marginal lands), world food prices are projected to increase by 3.9%. Second, world food prices rise by 4.3% when the EU target is met by first-generation biofuels and by 4.9% when the EU target is meat by either first or second generation biofuels. The increase in food prices is lower than what is found in the study by Banse *et al.* because we consider non-land using second-generation biofuels in addition to first-generation biofuels.

4.3 Carbon emissions

In this section we look at the potential for reducing carbon emissions by displacing petroleum by biofuels. The empirical model allows us to distinguish between direct and indirect carbon emissions. Recall that direct emissions are emissions directly related to the production of first-and-second-generation biofuels and consumption of petroleum. Indirect emissions are those from converting marginal lands (grasslands and forestlands) into farmland, which causes sequestered carbon to be released into the atmosphere. Consequently, indirect emissions are only present in the model where marginal lands are available (B). Finally, notice that carbon emissions are closely linked to energy choices, which we discussed above.

In absence of any biofuels regulation, OECD countries remain the largest carbon emitter until 2020 (A.i and B.i). During this period the OECD is also the largest energy consumer. However, due to rapid increase in energy consumption in Medium Income Countries, that region takes over as the largest carbon emitter from 2020 onward. Although less polluting resources (first-and-second-generation biofuels) are gradually substituting polluting resources (petroleum), the increase in total carbon emissions is still considerable. The most rapid growth in emissions occurs before 2025 in both scenarios (A.i and B.i), with an average annual growth over the period of 1.3% (A.i) and 3.9% (B.i), depending on whether marginal lands are available. Increased use of first-generation biofuels causes land-use changes that release carbon into the atmosphere. Under scenario B.i, grasslands and forestlands are converted into farmlands, with most of the conversion occurring between 2020 and 2050. Due to land-use changes in Medium and Low Income Economies, indirect carbon emissions are actually higher than direct carbon emissions over the period when most the land conversion occurs in these regions.

When a biofuel target is imposed in the European Union and in the United States, carbon emissions from these economies are expected to decrease. There is, however, a carbon leakage effect in other regions. This happens as a result of the aforementioned substitution effect when other regions increasing their use of petroleum based fuels as biofuels become relatively more expensive following the introduction of mandatory blending in the European Union and/or the United States. If mandatory blending is introduced both in the United States and the European Union, US and EU carbon emissions are projected to go down 10% and 7% from 2015 until 2025, respectively, compared to an increase of 6% and 3%, respectively, over the same period without mandatory blending (models A and B). Thus, mandatory blending clearly reduces carbon emissions in the regions introducing the policies.

However, since mandatory blending in one region raises the worldwide price of biofuels relative to petroleum, the demand for petroleum in other regions increases at the expense of biofuels. This has important implications for emissions. Increased emissions associated with this substitution effect are commonly referred to as carbon leakage. To find the carbon leakage effect of the biofuels policies, we look at the development in total emissions in the rest of the world with and without mandatory blending in the United States and Europe. The extent of the carbon leakage effect depends critically on whether there is marginal land available that can be put into production. This is because the increased production of biofuels results in marginal lands being converted into farmland (model B), an activity that causes large carbon emissions when sequestered carbon is released into the atmosphere. Without any marginal lands (model A), total emissions in all regions apart from the United States and the European Union increases 26.5% from 2015 to 2025 in the unregulated case (A.i) compared to a 26.6% increase in the scenario with biofuels policies (A.iv). Thus, the carbon leakage effect is negligible without marginal lands.

If, however, marginal lands are available (model B), the story is quite different. In this case total emissions in all regions apart from the United States and the European Union increase 280% in the unregulated case (B.i), compared to 304% when biofuels targets are imposed in the United States and Europe (B.iv). This represents an increase in carbon emissions in the rest of the world in 2025 of 7.3% (or about 1 billion tons of carbon) as a consequence of the mandatory blending policies in the United States and the European Union. Out of the 7.3% increase in carbon emissions, 7.0% are due to changes in land use (indirect emissions) while only 0.3% are due to increases in direct carbon emissions.

For any local environmental policy to have a reducing effect on total emissions and not only on local emissions, the direct emissions reductions must more than offset the carbon leakage effect. However, in this case our results suggests that the effect of mandatory policies (policy scenarios ii-iv) on total emissions is small and in some cases even negative, as the carbon leakage effect is larger than the direct emissions savings in the European Union and the United States. The carbon leakage effect is strongest if there is marginal land available, since in this case the indirect emissions from land conversion must also be taken into account. The effects of the various policy scenarios on carbon emissions are summarized in Table 4. Policies ii.1 and ii.2 refer to mandatory blending in the European Union satisfied by increasing the use of first and second-generation biofuels, respectively.

Table 4. Carbon emissions 2015-2025: change compared to base case scenarios (A.i and B.i)

	US	**EU**	**R.O.W.**	**Total**	**US**	**EU**	**R.O.W.**	**Total**
	Scenario A.ii.1				Scenario B.ii.1			
2015	0.12%	0.17%	0.29%	0.21%	0.09%	0.14%	0.20%	0.16%
2020	0.17%	-1.61%	0.27%	-0.02%	0.15%	-1.37%	6.50%	4.13%
2025	0.20%	-1.93%	0.31%	-0.02%	0.14%	-1.10%	2.16%	1.67%
	Scenario A.ii.2				Scenario B.ii.2			
2015	0.05%	0.10%	0.15%	0.11%	0.04%	0.08%	0.12%	0.08%
2020	0.11%	-9.80%	0.22%	-1.21%	0.08%	-9.59%	1.56%	0.02%
2025	0.10%	-9.79%	0.17%	-1.16%	0.08%	-9.37%	0.12%	-0.47%
	Scenario A.iii				Scenario B.iii			

2015	0.30%	0.41%	0.69%	0.52%	0.30%	0.40%	0.66%	0.50%
2020	-14.66%	0.44%	0.72%	-4.20%	-14.62%	0.43%	19.38%	9.13%
2025	-15.37%	0.41%	0.71%	-4.22%	-15.16%	0.39%	7.11%	3.53%
	Scenario A.iv				Scenario B.iv			
2015	0.39%	0.53%	0.87%	0.66%	0.35%	0.48%	0.82%	0.61%
2020	-14.60%	-9.63%	0.87%	-5.51%	-14.53%	-9.32%	20.97%	9.15%
2025	-15.24%	-9.44%	0.92%	-5.35%	-15.09%	-9.07%	7.30%	3.11%

Under scenario C.i biofuels are never used since petroleum reserves are unlimited. This case is not very realistic but can be used to illustrate the effect on emissions of substituting petroleum with biofuels in transportation fuels. Over the whole century, total emissions are 508% and 171% larger under scenario C.i than under scenarios A.i and B.i, respectively. This amounts to 524 and 396 billion tons of additional carbon being emitted over the century, respectively, compared to scenarios A.i and B.i. Hence, considerable emissions savings are realized when displacing petroleum by biofuels.

4.4 Implications for biofuels policies

Despite the recent increase in petroleum prices combined with technological improvements in biofuels production, government intervention is needed to promote the market introduction of biofuels. Our model can be used to calculate the subsidy needed to meet the biofuels targets in the European Union and in the United States. This is calculated from the shadow value of the biofuels target constraint (cf. theoretical model) in the optimization problem of the social planner. Consequently, the subsidy is only positive when the policy constraint is binding. The value of the implicit subsidy is expressed in dollars per gallon. This subsidy reaches its highest level between 2020 and 2040 in scenario A.ii (EU target reached only with first-generation biofuels), during which time the subsidy should be about US$ 0.5 per gallon. Banse *et al.* (2008) calculated the internal subsidy to meet the European Directive on Biofuel. They found that in 2020, the subsidy would range from 30% of production costs in Sweden to almost 60% in the United Kingdom. If mandatory blending is introduced both in the United States and the European Union (A.iv), subsidies for second-generation biofuels are US$ 1.2 per gallon in the United States and US$ 0.2 per gallon in the European Union. Based on the currently production cost of second-generation biofuels of about US$ 4 per gallon, the subsidy represents 30% of total production cost in the United States and 5% in the European Union. Hence, the implicit biofuels subsidies we calculate for the European Union are considerable lower than the implicit subsidies reported by Banse *et al.* (2008).

The relatively high cost of introducing biofuels policies must be taken into account when evaluating whether the biofuels targets are worthwhile. Our results indicate that the effect on total world level emissions of carbon is limited, and even negative if the policies cause more marginal lands to be put into crop production. Reduced local emissions are therefore offset by increased direct emissions elsewhere and indirect emissions from land-use changes. Hence, little is gained in terms of emission reductions. The other main reason for introducing a biofuels target is to reduce a region's dependency on foreign countries to cover its energy needs. We found that a biofuels target can significantly reduce the dependency on foreign oil. Consequently, the relatively high cost of introducing the policies must be justified by the gains that are mainly in terms of increased energy security. There could also be gains in terms of learning by doing effects when using new technologies. However, such effects are not accounted for in our analysis.

4.5 Sensitivity analysis

There is uncertainty regarding the values of several key parameters used in the empirical analysis. These parameters include production costs of second-generation biofuels, the stock of petroleum resources, and the elasticity of substitution between first-generation biofuels and petroleum. To investigate the consequences of changing these values, three additional scenarios are designed. Scenario B.i (with marginal lands and no biofuels regulations) is considered the baseline scenario. In the first sensitivity analysis scenario, the initial value of the production cost of second-generation biofuels is US$ 3.5 per gallon or 30% lower than in the baseline scenario.[20] The rate of technical progress is the same as in the baseline scenario: production costs decrease by 30% by 2030. In the second scenario, we analyze the implications of the initial stock of petroleum being 20% higher than in the baseline scenario. Finally, in the third scenario, we look at the effect of lowering the elasticity of substitution between first-generation biofuels and petroleum. We assume the elasticity is uniform across the different regions and close to unity. The results from the scenarios are summarized in Table 5. All results are reported as the percentage change from the baseline scenario (B.i). We report the value of the variables at the world-wide level in 2020 and 2050.

Table 5. World biofuels consumption and world carbon emissions: percentage change compared to base scenario (B.i).

	Lower second-generation biofuels production cost		Higher stock of petroleum		Elasticity of substitution	
	2020	2050	2020	2050	2020	2050
Petroleum consumption	-13%	-2.7%	+14.0%	+13.0%	-1.1%	-0.6%
First-generation biofuels consumption	-15%	-3.0%	-14.0%	-13.0%	+250%	+200%
Second-generation biofuels consumption	0.0%[21]	+2.5%	0.0%[22]	0.0%	0.0%[23]	0.0%
Carbon emissions:						
- Direct	-7.0%	-2.0%	+6.5%	+9.3%	2.2%	1.6%
- Indirect	0.0%	0.0%	0.0%	-6.0%	0.0%	+2.0%

[20] IEA (2009) defines two scenarios; optimistic and pessimistic. Under the pessimistic scenario, production costs of second-generation biofuels amount to US$ 5 per gallon and is expected to decrease by 30% until 2030. These numbers have been used in the baseline scenario. Under the optimistic scenario, production costs of second-generation biofuels amounts to US$ 3.5.
[21] Second-generation biofuels are adopted in 2020 in this scenario.
[22] Second-generation biofuels are adopted ten years later than in the baseline scenario.
[23] The date of adoption of second-generation biofuels is not affected by a change in the value of the elasticity of substitution.

When production costs of second-generation biofuels are reduced, the competitiveness of second-generation biofuels is improved and they are adopted ten years earlier than under the baseline scenario. As a result, petroleum and first-generation biofuels consumption fall leading to a decline in direct carbon emissions.

If the petroleum stock is higher than what we assumed in the empirical analysis above, the price of petroleum is reduced relative to the price of biofuels. Consequently, fuel composition shifts away from first-generation biofuels towards petroleum. Furthermore, the adoption of second-generation biofuels is delayed by ten years relative to the baseline scenario, because the relatively lower price of transportation energy means that it takes longer before second-generation biofuels become cost competitive. With an increased consumption of the most carbon intensive resource, direct carbon emissions rise. However, indirect carbon emissions decrease in response to a decline in first-generation biofuels production, which limits the effect on total emissions somewhat.

Finally, by assuming a lower elasticity of substitution between first-generation biofuels and petroleum, the consumption of first-generation biofuels increases at the expense of petroleum. As a result, both direct and indirect carbon emissions increase. The relative increase in consumption of first-generation biofuels is seen to be considerable when the elasticity of substitution is reduced, but the impact on other predictions reported in the table is still small. The other scenarios we consider in the sensitivity analysis also yield results that are relatively similar to the baseline scenario, which suggest that our main empirical findings are robust: none of our main conclusions changes even if important model parameters are changed considerably.

5 Conclusion

The purpose of the study was to analyze future long term energy choices for transportation and the impact of biofuels policies on energy and food markets. This was done by developing and calibrating a model based on a Ricardian model of land use coupled with an extended Hotelling model of fossil fuel production. With the depletion of petroleum, the price of petroleum increases and makes biofuels economically viable. At the same time there is an increase in food needs in Medium and Low Income Economies. The increase in food demands and an expected shift from vegetarian towards meat and dairy products are expected to result in substantial increases in the demand for and opportunity cost of land. This puts pressure both on food and biofuels prices. In this context of land and petroleum scarcity, second-generation biofuels, which is the technology we consider as the backstop, are projected to be adopted in 2030 if there are no biofuels policies (scenarios A.i and B.i); earlier when biofuels targets are implemented. Second-generation biofuels are first adopted by OECD countries. By 2055, 30% of transportation energy will be provided by alternative renewable energy (first-and-second-generation biofuels). However, despite the shift towards cleaner energy sources, transportation is projected to release substantial amounts of carbon into the atmosphere over the next five decades. We find that world emissions of carbon will increase by 180% from 2005 until 2055. Carbon emissions in Medium and Low Income Economies are projected to exhibit that fastest growth.

Our results emphasize that the availability of marginal lands is crucial for the development in food prices. If marginal lands cannot be put into production, we observe that the food price increases twice as fast over the period 2005-2030 than if marginal lands can be converted into farmlands. Hence, marginal lands are projected to play an important role in dampening the expected increase in food prices. Biofuels policies are, on the contrary, not expected to have any big impact on food prices. The policies affect food prices, but the increase in the food price index when introducing biofuels targets in the European Union and the United States is, at most, projected to be moderate. This is in contrast to what has been reported in previous studies. The difference compared to our results can be explained by non-land using second-generation biofuels. Contrary to previous studies that have focused exclusively on first-generation biofuels, we also model the production and use of second-generation biofuels. Since first-generation biofuels require land, increased production of these biofuels increases the opportunity cost of land, which, in turn, increases the price of food. With second-generation biofuels, this negative effect on food prices through land competition between food and fuel does not occur.

Biofuels policies significantly affect energy choices across regions as well as carbon emissions. Introducing a biofuels target in one region has considerable impact on energy choice in this region, but also in other regions through the increase in the price of biofuels relative to petroleum. This is the carbon leakage effect. Still, introducing biofuels policies tend to reduce total world emissions. However, if marginal lands are available, biofuels policies have the additional effect of causing more land to be converted into farmland, which releases sequestered carbon into the atmosphere; indirect carbon emissions. Taking indirect emissions into account, the total effect of mandatory blending in Europe and/or the United States on world carbon emissions is increased emissions.

Compared to the previous literature, we find that the backstop technology, second-generation biofuels, becomes economically viable earlier. Our analysis suggests that second-generation biofuels become cost competitive around 2030. In contrast, Peña (2008) conclude that the backstop will not be competitive until 2040. The difference can be explained by the fact that we explicitly take into account the competition for scarce land resources between food and fuel. Increased competition for land causes the opportunity cost of land to increase and increases the competitiveness of second-generation biofuels relative to land-using first-generation biofuels.

There are several ways to extend the current work. First, results from the different scenarios highlight an increasing trend in food prices or, at the very least, a slowdown in the rate of decrease of food prices. Over recent decades, investment in R&D in agriculture has dwindled. Empirical work suggests that the level of agricultural productivity is related to food prices; the higher the food prices, the higher the level of R&D investment, and the higher is the agricultural productivity. This could be implemented in our model by making agricultural productivity a function of food prices. Second, most countries impose several forms of trade restrictions on both feedstock and biofuels with preferential waivers of tariffs and quotas for certain countries. Modeling the impacts of global trade in biofuels for the environment and especially for climate would be a possible area of future research. Finally, the model can be extended by making learning-by-doing effects in the use of second-generation biofuels endogenous. In the current model, the efficiency improvement in this technology over time is exogenous, which may bias our results toward under estimating the benefits of using the backstop technology.

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Appendix A: EMPIRICAL MODEL

A detailed representation of the empirical model illustrated in **Erreur ! Source du renvoi introuvable.** is presented below. There are two final food products in the model; a vegetarian product and a meat and dairy product. In addition fuels for transportation are supplied. Energy services for transportation may be provided by a blend of oil and first or second-generation biofuels. Land resources, which are categorized by land quality, may be allocated to pastures or to crops. Whereas pastures are exclusively used to produce meat and dairy products, crops may be allocated to feed production used in the meat and dairy production, the production of food crops, or to produce energy crops. The model accounts for direct and indirect carbon emissions. Finally, both food products and the three energy resources (oil, first-generation biofuels and second-generation biofuels) are traded between five regions; the United States, the European Union, other OECD countries, Medium Income Economies, and Low Income Economies. The model is described in more detail in the following. Notice that all variables are functions of time, but for convenience we omit the time index where this does not cause confusion. The model has been calibrated over the five year period 2000-2005.

A.1 Regions

The world is divided into five regions, USA, European Union, other OECD countries Medium and Low Income Economies. USA and European Union are characterized as two explicit regions since our study focus on the impact of US and EU mandatory blending policies on world agricultural and energy markets as well as on carbon emissions. Medium and Low Income countries are categorized according to their 2007 gross national income (GNI) per capita based on the World Bank Atlas Method. Table A. 1 shows the annual average GNI per capita. The level or range over the reference period (2000-2005) is shown in the second column while the third column shows the representative countries within each region.

Table A. 1: Classification of model regions

Regions	Annual average GNI per capita (2000-2005)	Main countries
United States	42,040	-
European Union	36,000	-
Other OECD countries	33,000	
Medium Income Economies	US$ 936 - 11,455	Brazil, Indonesia, Malaysia China , India
Low Income Economies	Below US $ 935	Africa

Regional GNI per capita increases exogenously over time at a decreasing rate. Initial population levels and projections for future population growth are extracted from *World Population in 2030* (UNDP 2004).

A.2 Demand function

Domestic demand for each final product takes the following form:

$$d_f^r = A_f^r \cdot P_f^{\alpha_f^r} \cdot y^{\beta_r} \cdot N \ ,$$

where $f = \{processed\ crops,\ meat\ and\ dairy,\ transportation\}$ and $r = \{rich, medium, low\}$, and where d_f^r is regional demand expressed in billion tons, P_f is the price of commodity f in US$, α_f^r is the regional own-price elasticity of product f, β_f^r is the regional income elasticity for product f, y^r is the regional per capita income and N is the regional population. A_f^r is the constant demand parameter calibrated from the data. To take into account changes in dietary habits, the income elasticity is not fixed over time, but changes with per capita income.

A.3 Energy sector

Primary energy may be provided by three different resources: oil, first-generation biofuels and second-generation biofuels. Primary energy resources are indexed by k.

Each region is endowed with an initial stock of petroleum denoted by $\bar{S}^r$. Data on stock availability are extracted from the annual survey of the World Energy Council (WEC 2007). Petroleum is an input in several sectors in addition to transportation, such as the chemical industry and heat generation (IEA 2007, IFP 2007). The French Institute for Petroleum study indicates that 50% of extracted petroleum is used in transportation (IFP 2007). As a result, we only consider 50% of total petroleum reserves as the resource stock available for transportation.[24] To take into account the heterogeneity of petroleum reserves, regional extraction costs depend on the cumulative amount of petroleum extracted at date T. Thus, extraction costs can be expressed as follows (Nordhaus and Boyer 2000):

$$C_T^r(s_T^r) = \xi_1^r + \xi_e^r . \left(\sum_{t=0}^{T} s_t^r \Big/ \bar{S}^r \right)^{\xi^r}$$

where s_T^r is the amount of petroleum extracted at date T in region r and $\sum_{t=0}^{T} s_t^r$ is the cumulative amount of petroleum extracted at date T. The following inequality must hold: $\sum_{t=0}^{T} s_t^r \leq \bar{S}^r$. The parameter ξ_1^r is the extraction cost over the base period, and ξ_2^r and ξ_3^r are regional parameters.

[24] This assumption may be criticized since the bulk of increase in energy demand will come from transportation (IEA, 2007). Thus, this share is expected to increase.

The parameters are calibrated using data from the SAUNER model database (European Commission 2000) and reported in Table A.2. Then, petroleum is converted into gasoline or diesel, the coefficient of conversion is uniform across the different region as well as the conversion cost. Thanks to technical progress, conversion cost decreases by 5% every five years.

Table A. 2. Petroleum stock characteristics

	Available stock (billion gallons)	**Extraction cost parameter**		
		ξ_1	ξ_2	ξ_3
USA	42,769	0.01817	100	5
EU	10,461	0.01817	100	5
Other OECD countries	56,974	0.01817	100	5
Medium Income Economies	62,160	0.01817	100	5
Low Income Economies	12,894	0.01817	100	5

Sources: Resources stock (WEC, 2007), extraction costs (European Commission, 2000; Chakravorty *et al.* 2009).

First-generation biofuels

There are two main types of land-based fuels: bio-diesel and bio-ethanol. Currently, ethanol production represents 90% of first-generation biofuels at the world level. A representative feedstock is assigned to each region based on current production. First-generation biofuels in the United States are mainly produced from corn. In the Europe Union, the representative feedstocks are sugar beet and rapeseed. Brazil is the largest producer among Medium Income Economies; hence, sugar cane is used as the representative feedstock in this region. In Low Income Economies, first-generation biofuels are produced from cassava although current production levels are relatively low (FAO 2008). The next step is to combine this with information on crop yields and the coefficient of transformation of crop into energy, obtained from FAO (2008). Finally, conversion cost of primary crop into final energy is extracted from Rajagopal and Zilberman (2007). Conversion costs from feedstock to biofuels are assumed to decrease by 5% every five years. Information on first-generation biofuels is summarized in Table A. 3.

Table A. 3. First-generation biofuels characteristics

	Representative feedstock	Conversion coefficient (gallon/ton)	Cost of conversion[25] (US$/gallon)	Subsidy (US$/gallon)
USA	Corn	105	1.52	0.51
EU	Sugar beet, rapeseed	305	1.04	0.6
Other OECD countries	Corn, wheat	100	1.52	
Medium Income Economies	Sugarcane	405	1.04	0
Low Income Economies	Cassava	100	1.52	0

Sources: Conversion coefficient (FAO 2008), cost of conversion (Rajagopal and Zilberman 2007), subsidy (Von Lampe 2006).

Second-generation biofuels

OECD (2008) distinguishes between three categories of second-generation biofuels based on what the fuel is produced from: dedicated crops, agricultural residues and non-agricultural residues.

First, dedicated crops that provide cellulose for ethanol or biomass for Fischer-Tropsch synthesis fuel are often, but not always, produced on land that can be alternatively used for food or feed production, and hence have the potential to negatively impact the supply of these products. However, for simplicity and without loss of generality, we adopt the same specification as in the OECD model and assume that this group is non-land using (OECD 2008). Then, agricultural

[25] The cost of conversion is defined based on the cost of land, which is endogenous in the model.

residues such as straw or stover can be used to produce ethanol via gasification or other biofuels such as Fischer-Trospch. Finally, biofuels from non-agricultural residues include biodiesel from cooking oil, synthesis from municipal wastes or algae, ethanol from forest residues, and wood chips, and other forms of organic matter that have no link to agricultural production.

Despite the diversity of these technologies, all second-generation biofuels are treated as one in the model. The initial cost, which is an aggregate cost, amounts to US$ 5 per gallon (Ryan *et al.* 2006). In addition, since these technologies are still at the stage of research and development, a capacity constraint is imposed.

Energy production is represented as the sum of i) a convex linear combination of petroleum and one land-based fuel and ii) a backstop:

$$\left[\sum_{k,k\neq\text{second-generation biofuels}} \theta_k^r.\left(q_k^r\right)^{\rho-1/\rho}\right]^{1/\rho-1} + q^r_{\text{second-generation biofuels}}$$

where θ_k^r is the share of resource *k*, which is calibrated from observed data, ρ is the elasticity of substitution, and q_k^r is the input demand for resource *k*. The elasticity of substitution is region specific and depends upon the technological barriers in each region. In High Income Economies, this value reaches 2. In Medium Income Economies, it is 1.85 and finally, and in Low Income Economies the value is 1.5.

Land classes

USDA's database divides the global land surface into nine land classes based on climate and soil properties (Wiebe 2003). Land types are classified according to their suitability for agricultural production. Since we only consider productive land, land classes unsuitable for agricultural production, i.e., land classes VII to IX, are disregarded in the study. Then, the six remaining land classes are aggregated based on their characteristics. The USDA land classes I and II are grouped and referred to as land class I in our study, USDA land classes III and IV are grouped and referred to as land class II, and, finally, USDA land classes V and VI are grouped and renamed land class III.

Hence, we end up with three land classes that we index using i = {*I, II, III*}. Land class I benefits from a long growing season and soil of good quality, land class II has a shorter growing season due to water stresses or too high or too low temperatures. Land class III is of the lowest quality. Each land class may be allocated to cropland or pastures. Let *u* denote the land-use index, where u = {*crop, pastures*}.

Total supply from a specific use is represented by a Leontieff production function; it is the product of land supply and yield, as in most partial equilibrium model. Let us denote by $k_{i,u}^r$ the agricultural yield on land class i allocated to use u in region r. Data on initial crop yields are extracted from FAOSTAT. Exogenous technical progress is assumed to improve land quality. However, annual growth rates will be steadily declining over the century (FAO 2005, 2008; Rosegrant *et al.* 2001). Hence, world primary crop yields are expected to increase by 50% and 75%, respectively, over the next five decades and the century (Rosegrant *et al.* 2001).

Total primary production cost with respect to use u in region r is defined by:

$$C_u^r(\sum_i k_{i,u}^r.L_{i,u}^r) = \eta_{1,u}^r \left(\sum_i k_{i,u}^r.L_{i,u}^r \right)^{\eta_{2,u}^r} \qquad \forall u, \forall r \, ,$$

where $\sum_i k_{i,u}^r \cdot L_{i,u}^r$ is the total level of production in region r for use u, $\eta_{1,u}^r$ *and* $\eta_{2,u}^r$ are specific regional parameters with respect to use u. They are calibrated using so-called Positive Mathematical Programming (Howitt 1995). Primary production costs can be extracted from GTAP and they are defined from the cost of land for different products and for different regions.

Finally, an additional 1,600 million hectares of lands would be potentially suitable for crop production (FAO 2008), most of which is found in Latin America and Africa (see Table A. 4 below). [26] This land is located in Medium and Low Income Economies and belongs to land classes II and III.

[26] Protected forestlands have been excluded (FAO 2008).

Table A. 4. Marginal lands availability by land class and region (in million hectares)

	Class I	Class II	Class III
United States	No land available	No land available	No land available
European Union	No land available	No land available	No land available
Other OECD countries	No land available	No land available	No land available
Medium Income Economies	No land available	300	500
Low Income Economies	No land available	200	600

Source: FAO (2008)

A.4 Carbon emissions

The model accounts for direct and indirect carbon emissions.

Direct carbon emissions

The carbon emissions combined with the production and use of the three energy sources differ. The stage at which carbon emissions occur also differs between energy sources. Whereas the majority of carbon emissions related to petroleum are released in the atmosphere during the consumption phase, the majority of carbon related to biofuels is emitted into the atmosphere during the production stage. Table A.5 shows the carbon contents of the different energy sources. The carbon content of petroleum is independent of where it is consumed, while the carbon content of first and second-generation biofuels differs across regions. As an example, the production of sugar-based ethanol is less carbon intensive than corn ethanol.

Table A.5: Carbon contents of the different resources (tons of carbon per gallon).

	Petroleum	First-generation biofuels	Second-generation biofuels
USA	0.0032	0.0017	0.0002
EU	0.0032	0.0017	0.0002
Other OECD countries	0.0032	0.0017	0.0002
Medium Income Economies	0.0032	0.0004	0.0002
Low Income Economies	0.0032	0.0017	0.0002

Sources: Farell (2006) and Lasco and Khanna (2009).

Indirect carbon emissions

Biofuels offer carbon savings depending on how they are produced. Converting forest or grasslands in to farmland to produce food or energy crops releases sequestered carbon back into the atmosphere. This is referred to as indirect carbon emissions. Table A.6 reports the amount of carbon released in the atmosphere after land conversion.

Table A.6: Amount of carbon released in the atmosphere after land conversion (tons of carbon per hectare).

	Class I	Class II	Class III
USA, EU and Other OECD countries	No land available	No land available	No land available
Medium-income countries	No land available	300	500
Low-income countries	No land available	300	500

Sources: Searchinger *et al.* (2008).