Will Biofuel Mandates Raise Food Prices?

by

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Abstract

Biofuels have received a lot of attention as a substitute for gasoline in transportation. They have also been blamed for recent increases in food prices. Both the United States and the European Union have adopted mandatory blending policies that require a sharp increase in the use of biofuels. In this paper, we examine the effect of these mandates on food prices and carbon emissions. The model we use considers future world population growth and income-driven changes in dietary preferences towards higher meat and dairy consumption as well as heterogenous land quality. We find that food prices increase anyway because of increased demand for food, especially due to the higher consumption of meat products, and scarcity of fertile arable lands. The contribution of the biofuel mandates to food prices is quite small, about 5% at most. However, biofuel mandates actually *increase* global emissions due to land conversion and terms of trade effects, undermining the main reason for imposing the mandates.

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1. Introduction

According to a recent issue of The Economist (2010), "by 2050 world grain output will have to rise by half and meat production must double to meet demand. And that cannot easily happen because growth in grain yields is flattening out, and there is little extra farmland…." This problem of land scarcity is further exacerbated by clean energy policies that promote biofuels such as ethanol from corn and sugarcane. Many countries are actively promoting these renewable fuels to reduce greenhouse gas emissions and as a means of reducing dependence on foreign countries for vital energy supplies. Because of government subsidies, the production of plant-based fuels such as ethanol and biodiesel has grown sharply in recent years.

In the United States, the Renewable Fuel Standard (RFS) mandates the minimum use of 36 billion gallons of ethanol by 2022. Only 9 billion gallons are used at present. The European Union (EU) requires that biofuels must supply at least 10% of transportation fuels by 2020, from a current share of about 2.5%.

Several important issues have arisen with the increased production of biofuels. First, they use scarce land resources. Growth in biofuel production may well result in a large-scale shift in acreage from food to fuel leading to a reduction in food supplies and increased food prices.[2] Moreover, by converting existing grasslands and forests into farmland, especially in developing countries which have a lower cost of production and can therefore compete successfully in a global biofuels market, there may be significant leakage of sequestered carbon into the atmosphere. Deforestation-induced carbon emissions may undermine the central argument for biofuels - that they are a low-carbon alternative to fossil fuels (Fargione *et al*. 2008, Searchinger *et al*. 2008).

In this paper, we examine the effects of biofuel mandates in the US and EU on land allocation and food prices. The model has three unique features. First, consumer preference for food is

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[2] A recent study by the International Food Policy Research Institute (Rosegrant *et al.*, 2008) suggests that an aggressive expansion into biofuels will raise the price of certain food commodities by up to 70% by the year 2020.

driven by per capita income levels, so that rising incomes (as in countries like China and India) imply a higher preference for meat and dairy products which are more land-consuming than cereals and vegetables.[3] Second, cultivable land, which is allocated between food and biofuel production, is limited in its availability. We distinguish between lands of different qualities, which affects how much food or fuel can be produced and in what location. This is important because there is significant heterogeneity in global land quality and most available land is of medium to low quality and located in developing countries.[4] This also helps us estimate emissions from bringing new land under production conditional on their quality.[5] Finally, we model the rising cost of oil because of scarcity, which affects the substitution of gasoline by biofuels over time.

First, we examine the counterfactual - a model with no mandates - to see how expected increases in population and incomes and changes in food preferences will affect demand for food and competition for land. We find, not surprisingly, that the demand for food is expected to rise significantly with continued increases in population, and also because rising incomes will mean a shift in dietary habits towards more meat and dairy consumption. Given that good quality arable land is scarce, these trends will cause a rise in food prices, even *without* renewable fuel mandates.

Next, we impose biofuel mandates that are currently in place in the US and EU. With these mandates, the US which is a major exporter of food to developing countries, experiences a large decline in food exports fall several fold because more domestic land resources are employed to produce energy.[6] This reduction in exports also occurs because subsidies and import tariffs prevent large-scale biofuel imports from lower cost developing countries. The mandates reduce carbon emissions in the regulating countries (US and EU) but lead to a rise in oil consumption in other countries and higher greenhouse gas emissions.

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[3] Per capita consumption of meat and dairy products in the developed world is about four times that in developing countries. Three kg of cereals produces one kg of pork, and eight kg of cereals produces one kg of beef.

[4] A key finding from our paper is that high quality lands have a strong comparative advantage in food production.

[5] Emissions from land conversion differ sharply depending on current use, e.g., cropping forests emits almost twice the amount of carbon than farming pasture.

[6] The United States accounts for 70% of world corn exports, 30-40% of the export market for wheat and soybeans and is a major exporter of many other crops.

The reduction in exports, mainly from the US causes more land conversion for food production in countries such as Brazil, Indonesia and Malaysia, which leads to an increase in indirect (i.e., from land-use changes, not direct combustion) carbon emissions. In the aggregate, emissions actually *increase* because of the mandates. Welfare declines in the developing countries.

Mandates that prescribe the use of newer less land-intensive fuels such as second generation biofuels reduce the pressure on land, and have a muted effect on exports. These new fuels, which are less land-using, slow down the rise in food prices. However, they have a limited effect in curbing global emissions because they also reduce energy prices and lead to increased consumption of fossil fuels.

Sensitivity analysis suggests that estimates of oil reserves have a major impact on biofuels. Lower oil stocks raise energy prices which induce increased biofuel production and land conversion in developing countries. Thus direct (due to combustion) emissions may go down, but indirect emissions increase. When oil prices are assumed to remain constant (at current levels), the result is higher direct emissions from fossil fuel burning but lower indirect emissions from less biofuel use and land conversion. Adoption of high yield crops such as GMOs (Genetically Modified Foods) increase yields and thus reduce pressure on scarce land.

We also consider how the model behaves when food preferences are assumed to be *insensitive* to income changes. The predicted rise in food prices (without the renewable mandates) falls by about a half, suggesting that the preference towards meat and dairy products does indeed contribute significantly to food price increases and land shortages. When the two major emerging economies China and India also impose domestic biofuel mandates, much new land is brought under cultivation, leading to a doubling of indirect carbon emissions. Surprisingly, food price increases are limited even in that situation. In fact, they rise by only 8% compared to the no mandate case.

A key implication of the paper is that biofuel mandates affect aggregate food production marginally, even though they have a major impact on where the food is produced. Mandates imposed by the US and EU, and by other nations, will lead to land conversion and indirect emissions. Mandates also lead to lower oil prices and higher emissions due to leakage. Either way, they have almost no effect in reducing global greenhouse gas emissions, and increase it in some cases.

There are several important studies on the effect of biofuel policies but none explicitly considers changes in dietary preferences, heterogeneous land quality or energy scarcity. Many of them use the well-known trade and general equilibrium model (GTAP) to explore the impact of biofuels production on world agricultural markets, specifically focusing on US/EU mandatory blending and its effects on individual countries (Banse *et al.* 2008, Hertel *et al.* 2008a). In these papers, land quality is explicitly taken into account, but food preferences and scarce energy supplies are not recognized. The static framework adopted does not provide insights on how biofuel standards will affect resource use and emissions over time, as in our case. Schneider and McCarl (2003) focus only on agriculture and adopt a partial equilibrium approach for land allocation between agriculture and forestry. Paltsev and Reilly (2009) build a detailed energy model where land quality is uniform across geographical areas. They also ignore dynamic effects. Rosegrant *et al.* (2008) develop a partial equilibrium model of global agriculture in order to analyze the effects of biofuel mandates on specific crops. They assume a fixed amount of land and find a more pronounced increase in agricultural prices than in our study where land supply is endogenous.

Section 2 describes the basic model structure and assumptions. Section 3 discusses the results of the calibration. In section 4 we perform sensitivity analysis. Section 5 concludes the paper. The Appendix provides the data and parameters used in the model.

2. The Model with Land Quality

The logical structure of the model is simple. The world is divided into several regions (described below) with heterogeneity in land quality endowments, consumption preferences and population growth. Gasoline and biofuels are imperfect substitutes in energy consumption. A social planner imposes a constraint in the form of a minimal amount of biofuels that must be used (US policy) and on the proportion of energy that must be supplied by biofuels (EU policy). Both are imposed simultaneously. Exogenous income and population growth drives up the demand for food, especially meat and dairy products. Rising energy prices and biofuel mandates compete for limited land with the growing demand for meat and vegetables. Land rents rise, leading to shifts in acreage as well as conversion of new marginal lands that are under forest or grass cover. Food and energy production and trade, both in food and fuels, is impacted.

The world is divided into three regions using gross national income per capita data (World Bank 2010a). These are High, Medium and Low Income Countries (HICs, MICs and LICs). Since our study focuses specifically on US and EU mandatory blending policies, the HICs are further divided into three groups - the US, EU and Other HICs. Table 1 shows average per capita income by region. The MICs consist of fast growing economies such as China and India that are likely to account for a significant share of future world energy demand as well as large biofuel producers like Brazil, Indonesia and Malaysia. The LICs are mainly nations from Africa.

Table 1. Classification of regions by income (US$)

Regions	Mean annual gross national income per capita in (2000-2005)	Major countries
US	42,040	-
EU	36,000	-
Other HICs	33,000	Canada, Japan
MICs	936 - 11,455	China, India, Brazil, Indonesia, Malaysia
LICs	below 935	Mostly African countries

Source: World Bank (2010a).

We consider three final consumption goods - namely vegetables, meat and dairy and energy for transportation. Obviously many other products can be included at a more disaggregated level but we want to keep the model tractable so that the effects of biofuels policy on land use are transparent. It is important to distinguish vegetables from meat and dairy because the latter are significantly more land intensive.[7] All three products compete for land that is already under farming as well as marginal lands, which currently sequester carbon through grasslands and forests. Cropping these lands will mean a loss of carbon into the atmosphere and may at least partly, offset the environmental benefits of shifting from fossils to biofuels. According to FAO

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[7] On average, one hectare of land produces either one ton of meat or three tons of vegetables (Bowman 1997). There is a large disparity in meat consumption between developed and developing countries, which is expected to narrow over time as incomes converge. Per capita annual consumption of meat in the former is about 300 kg and only 70 kg in the developing world (FAO 2003). This translates to a per capita land requirement for food of 0.374 ha for OECD countries and 0.071 ha for LICs and MICs.

(2008a), 1.6 billion hectares of marginal lands may be converted to crop production in the future. These lands are mainly located in MICs and LICs.[8]

Energy may be provided by oil as well as biofuels that are land using (often called First Generation biofuels) and newer technologies that are less land-using (Second Generation).[9] The latter aim to convert parts of the plant other than the fruit or grain into fuels.[10] They are speculative and currently cost an order of magnitude more than first gen biofuels, even when the opportunity cost of land is taken into account. Unlike the EU mandate which does not specify the precise biofuel, US regulation imposes a minimum amount of second generation biofuel use by 2022.

Main Features of the model

The key elements of the model are summarized below while the precise functional forms and the data used are detailed in the Appendix. Each unit of land is allocated in the model to its highest valued use, in meat and dairy production, vegetable crops or energy. Regional demands for food (vegetables and meat) and energy are modeled by means of Cobb-Douglas demand functions, which are functions of regional per capita income and population. Both world food and energy demand are expected to grow significantly until about 2050, especially in the MICs and LICs (UNDP 2004). By 2050, the current population of six billion people is predicted to reach nine billion. Beyond that time, population growth is expected to slow, with a net increase of one billion people between 2050 and 2100. There will be significant regional disparities in the growth of population which have implications for our model. While the population of high income nations (including the US and EU) is expected to be fairly stable over the next century, the population of middle income countries is expected to rise by about 40% and it is likely to double for lower income countries (UNDP 2004). Demand is also impacted by regional per capita

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[8] The amount of carbon sequestered in marginal lands depends on their current use (grasslands or forests) and on their climatic region. In Brazil, where 25% of global marginal lands are located, about 400 tons of carbon are sequestered per hectare of forestland but only 93 tons in grasslands (Fargione *et al.* 2008). Our model distinguishes between direct carbon emissions from fossil fuel consumption in transportation and indirect carbon emissions induced by the conversion of marginal lands into agriculture.

[9] We transform crude oil into gasoline using a coefficient of transformation equal to 0.3, taken from Chakravorty *et al.* (2009). Since other uses of oil are not explicitly considered, the terms “oil” and “gasoline” are often used interchangeably in the paper where convenient. Gasoline is a fixed share of oil.

[10] Examples include cellulosic material and crop residues.

income, which is projected to increase steadily over time but at a decreasing rate, as assumed in several important studies (e.g., Nordhaus and Boyer 2000). Again, regional disparities are the norm, with the highest growth rates in MICs and LICs.

As incomes rise, we expect to observe increased per capita consumption of meat and dairy products relative to the consumption of vegetables (Delgado *et al.* 1998, Keyzer *et al.* 2005). For example, meat consumption has remained quite flat in the OECD countries (8% growth during the period 1985-99). Vegetable consumption has also been constant during this period (FAO 2003). However in the developing economies of South-East Asia, the growth in per capita income during this time has been accompanied by a doubling of meat intake and nearly flat vegetable consumption. Since meat production is more land-intensive, this would imply a higher demand for land in food production. We model the shift towards animal protein by letting income elasticities vary with per capita income (see Appendix for details). As incomes go up, the income elasticity for food consumption declines in our model.

The regional distribution of land quality is not even, as is evident from Figure 1 which shows land endowments based on climate and soil characteristics. Most good land is located in higher income countries, but Brazil and India also have sizeable endowments of high quality land. There are three categories of land in the model - classes 1, 2 and 3, where class 1 represents the most productive land.[11] Total available land area is the sum of current land under agriculture and marginal land. The initial endowment of agricultural land is 1.5 billion hectares (FAOSTAT). More than half of the agricultural land in the HICs (US, EU and others) is classified as land class 1, while the corresponding shares are only roughly a third for MICs and LICs, respectively, as shown in Table 2. Classes 2 and 3 are defined as marginal lands, which are essentially grasslands and forests, and located in MICs and LICs. The most important country in terms of the endowment of marginal lands is Brazil. It accounts for 25% of all marginal lands in the MICs and also happens to be the biggest producer of biofuels after the US. Note from Table 2 that there are no Class 1 lands remaining for agricultural production. Future expansion must occur only on marginal lands. We assume that the conversion cost of marginal lands to crops is increasing and convex in the aggregate area of land converted in each region (as in Sohngen, Mendelsohn and

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[11] See Appendix for more information on land classification.

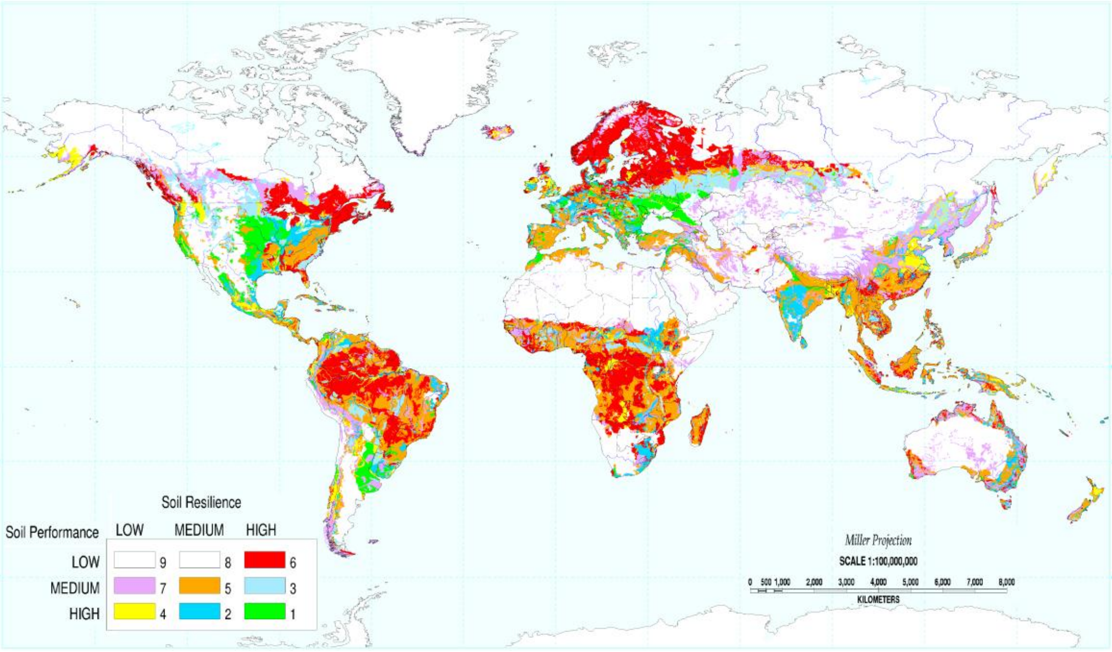

Figure 1. Distribution of land quality

Source: U.S. Department of Agriculture, (Eswaran *et al.* 2003 p.121). *Notes:* Land quality is defined along two dimensions: soil performance and soil resilience. Soil performance refers to the suitability of soil for agricultural production; soil resilience is the ability of land to recover from a state of degradation. Category 1 is the highest quality and 9 the lowest. We aggregate these categories into three classes, 1, 2 and 3.

Table 2. Land under Agriculture, Endowment of Marginal Lands and Yields by Land Class and Region

	Land class	US	EU	Other HICs	MICs	LICs	World
Land already under Agriculture (million ha)	1	100	100	25	300	150	675
	2	40	30	20	250	250	590
	3	30	20	20	240	40	350
Land available for farming (incl. marginal lands) (million ha)	1	0	0	0	0	0	0
	2	0	0	0	300	300	600
	3	0	0	0	500	500	1000
Initial crop yields (tons/ha)	1	4.0	4.0	4.0	3.5	2.5	
	2	2.5	2.0	2.2	2.0	1.5	
	3	1.7	1.7	1.7	1.0	0.7	
Assumed annual growth in yields (% change)	1	0.9%	0.9%	0.9%	1.2%	1.1%	
	2	0.7%	0.7%	0.7%	1.0%	0.8%	
	3	0.6%	0.6%	0.6%	0.8%	0.7%	

Source: Land availability (Eswaran *et al.* 2003); marginal lands (FAO 2008a); agricultural yields (FAOSTAT); average annual growth rates adapted from Rosegrant *et al.* (2001).

Sedjo, 1999).[12] This is because access and other production costs increase with more land conversion.

Food production is assumed to exhibit constant returns to scale for each land class in the model. Hence, regional food supply is just yield times the land area. As shown in Table 2, improvements in agricultural productivity are allowed to vary by region and land category. All regions exhibit increasing productivity over time, mainly because of the adoption of biotechnology (e.g., high-yielding crop varieties), irrigation and pest management. However, the rate of technical progress is higher in MICs and LICs because their current yields (conditional on land class) are low due to a lag in adopting modern farming practices (FAO 2008a). *Ceteris paribus*, the rate of technical progress is also likely to be lower in the lowest land quality. Biophysical limitations such as topography and climate reduce the efficiency of high-yielding technologies and tend to slow their adoption in the low quality lands (Fischer *et al*. 2002). The unit cost of food production in each region is assumed to be increasing and convex. The higher the production of food and biofuels, the more likely that cultivation moves into lower quality lands or those less accessible (van Kooten and Folmer 2004).

Since 99% of transportation is provided by crude oil which is essentially a scarce, nonrenewable resource, it is reasonable to use a Hotelling framework to model energy supply.[13] Oil is converted to gasoline using a fixed coefficient of transformation. Transportation energy is produced from gasoline and biofuels. We define an exogenous world stock of oil and a single integrated "bathtub" world oil market as in Nordhaus (2009). At higher oil prices, new sources such as shale oil reserves become competitive. The stock of oil includes both crude and shale oil stocks. Estimated oil reserves in 2007 serve as the initial stock of oil, which amounts to 179 trillion gallons or 4.26 trillion barrels (WEC 2007). The unit cost of oil depends on the cumulative quantity of oil extracted (Nordhaus and Boyer 2000).

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[12] Their cost figures are for clearing forest land and preparing it for timber plantation, which should be a good approximation for conversion costs for farming. The data is available at http://aede.osu.edu/people/sohngen.1/

[13] Later we check the sensitivity of the results to reduced oil reserves and when crude oil prices are constant over time (i.e., abundant oil at constant unit cost).

Instead of allowing for the production of different types of first gen (generation) fuels for each region, we simplify by considering a representative biofuel for each region. At present, there is only one type of biofuel that dominates in each region, therefore this aggregation is quite reasonable. For example, 94% of production in the US is ethanol from corn, while 76% of EU production is biodiesel from rapeseed. Brazil, the largest ethanol producer among MICs, uses sugarcane. Hence, sugarcane is used as the representative crop for MICs. In the LICs, 90% of biofuels are produced from cassava, although it amounts to less than 1% of global production.[14] The main characteristics of first gen biofuels and the representative crop by region are summarized in Table 3. Production costs depend on the crop used, and processing and energy costs net of the value of by-products are reported.[15] These costs decline by 2% a year (Hamelinck and Fajj 2006) mainly due to a decrease in processing costs.[16] Note the significant difference in yields and costs across crops and land classes.

Table 3. Characteristics of first generation biofuels

	US	**EU**	**Other HICs**	**MICs**	**LICs[4]**
Representative crop					
Crop type	Corn	Rapeseed[3]	Corn	Sugar-cane	Cassava
Proportion[1]	94%	75%	96%	84%	99%
Energy yield per land class[2] (gallons/hectare)					
Land class 1	800	400	800	1,700	600
Land class 2	500	300	500	1,500	400
Land class 3	200	200	200	1,200	300
Cost of production ($/gallon)					
Processing	0.75	0.37	0.80	0.57	0.60
Energy	0.56	0.37	0.60	0.00	0.70
Value of by-products	-0.30	-0.19	-0.30	0.00	0.00
Total	**1.01**	**0.55**	**1.10**	**0.57**	**1.30**

Sources: Breakdown of production costs (FAO 2008a; Eisentraut 2010); energy yields (Rajagopal and Zilberman 2007). *Notes*: 1. Percentage of first-generation biofuels from the representative crop (e.g., corn). 2. Energy yields are expressed as the product of crop yields (FAOSTAT) and a coefficient that converts crop into energy (Rajagopal and Zilberman, 2007). 3. Germany is the largest European biofuel producer. 4. Data availability for LICs is poor. LIC consumption data are from FAO (2008a), production costs are for Chinese cassava (Eisentraut 2010).

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[14] Reliable data on African production is difficult to obtain. Biofuel production in Africa is negligible in the model, mainly because there is no domestic demand for biofuels and land quality is low.

[15] Only part of the plant (the fruit or the grain) is used to produce first-generation biofuels. The rest of the plant is used to produce other by-products. For instance, crushed bean “cake” (animal feed) and glycerine are by-products of biodiesel. For rapeseed-biodiesel and corn-ethanol, the revenue from the sale of co-products *decreases* their production cost by about a third (FAO 2008a).

[16] Except for cassava, for which we have no data.

We model a US tax credit of 51 cents/gallon, which consists of both state and federal credits (de Gorter and Just 2010). EU states have tax credits on biodiesel ranging from 41-81 cents (Kojima *et al.* 2007). We model an average tax credit of 60 cents for the EU as a whole.

Second gen biofuels can be divided into three categories depending on the fuel source: crops, agricultural and non-agricultural residue. They account for only about 0.1% of total biofuel production. More research is needed to reduce production costs as well as improve fuel performance and reliability of the conversion process. Compared to first gen fuels, they emit less greenhouse gases and are less land consuming.

Since there are several second gen biofuels, we only consider the one that has the highest potential to be commercially viable in the near future, namely cellulosic ethanol in the US and biomass-to-liquid (BTL) fuel in EU (IEA 2009b).[17] Their energy yields are much higher than for first-gen biofuels. In the US, 800 gallons of ethanol (first gen) are obtained by cultivating one hectare of corn, while 2,000 gallons of ethanol (second gen) can be produced from ligno-cellulosic (Khanna 2008). In EU, around 1,000 gallons/ha can be obtained from BTL, whereas only 400 gallons/ha are obtained from first gen biofuels.[18]

Of course, they are also more costly to produce. The full production cost of cellulosic ethanol is $3.5 per gallon while first gen corn ethanol currently costs about $1.01 per gallon and ethanol from sugar cane costs $0.57. The production cost of BTL diesel is $4.5 per gallon - twice that of first gen biodiesel. However, technological progress is expected to gradually narrow these cost differentials and experts predict that by 2030 or so, the per gallon production costs of second gen biofuels and BTL diesel are projected to be $2.08 and $2.27, respectively.[19] Finally, second gen fuels enjoy a subsidy of $1.01 per gallon in the US (Tyner 2009), which is also accounted for in the model.

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[17] Cellulosic ethanol is a substitute for ethanol. It is produced from ligno-cellulosic (a structural material that contains much of the plant) which is transformed into alcohol. Corn stover, switchgrass, miscanthus and woodchips are some examples. Since the whole plant is used, second gen biofuels are more energy efficient. Biomass-to-liquid fuels (BTL) are a substitute for biodiesel produced from biomass, such as short rotation trees, perennial grasses and straw.

[18] That is, when we say second generation biofuels, for the US it means cellulosic ethanol and for EU it implies BTL.

[19] All data on production costs are from IEA (2009b).

The US mandate (EISA 2007) sets the US target for biofuels at 9 billion gallons annually by 2008, increasing to 36 billion gallons by 2022.[20] The bill specifies the use of first and second gen biofuels as shown in Figure 2. The former (corn ethanol) is mandated to increase steadily from the current annual level of 8 to 15 billion gallons by 2015. The bill requires an increase in the consumption of second gen biofuels from near zero currently to 21 billion gallons per year in 2022. In the European Union the mandate (EC 2008) requires a minimum share of biofuels of 10% in transportation fuel by 2020. It aims to achieve annual emissions savings of 600-800 million tons of carbon and an annual reduction in fossil fuel consumption of 70-100K gallons. Unlike the US, the EU has no regulation on the use of second gen fuels.[21]

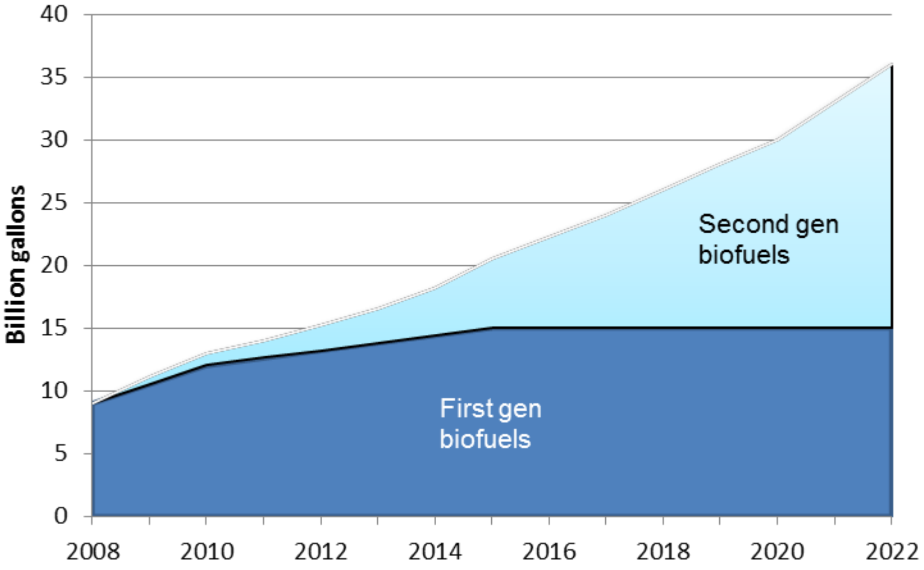

Figure 2. US biofuel mandate

Even though biofuels and gasoline are mixed in fuels such as E5 (5:95 biofuel: gasoline ratio) and E85 (85:15), there is still a large technological potential for displacing fossil fuels in passenger transport (OECD 2008). We thus model the production of energy from gasoline and biofuels which are imperfect substitutes using a CES specification, as in Ando *et al.* (2010). As the

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[20] It is not clear whether the mandates will be imposed beyond 2022 but in our model, we assume that they will be extended until 2050. This assumption does not affect our results much because most of the impacts of the mandates occurs around 2025.

[21] The EU directive also includes minimum greenhouse gas savings for biofuels of at least 35% relative to emissions from fossil fuels by 2013, increasing to 60% by 2018. It recommends that biofuels must not be grown on environmentally sensitive land, including protected areas and land with high biodiversity value or a high carbon stock. These issues are not modeled explicitly in the paper.

relative price of gasoline increases, the fuel composition switches towards using less gasoline. The elasticity of substitution is region-specific and depends upon the technological barriers for displacing gasoline by biofuels in each region. It is higher in the HICs and lowest in the LICs. As in many other studies, first and second gen biofuels are treated as perfect substitutes.

The model accounts for both direct and indirect carbon emissions. While most carbon is released during gasoline consumption, carbon from biofuel use is mainly emitted during production and hence is crop-specific. Considering only direct emissions, displacing gasoline by corn ethanol reduces emissions by 50%, 80% if displaced by sugarcane. Second-generation biofuels reduce carbon by 90% compared to gasoline. Any conversion of marginal lands (land class 2 or 3) for farming releases carbon into the atmosphere.[22] Using Searchinger *et al.* (2008), we assume that the carbon released is 300 and 500 tons of CO_2 per hectare respectively for each of these lands immediately after land conversion. Carbon released from converting pastureland is lower than for converting forestland. Therefore, emissions are lower on class 2 land than on class 3 since the former has more pasture and the latter more forest.

Goods are treated as perfectly homogenous. We assume frictionless trading between countries. In reality, there are significant trade barriers in agriculture, but given the level of aggregation in our model, it is difficult to introduce tariffs, which are mostly commodity-specific (sugar, wheat, etc.). However, we do model US and EU ethanol tariffs. The US ethanol policy includes a 2.5% *ad valorem* tariff and a per unit tariff of $0.54 per gallon (Yacobucci and Schnepf, 2007). EU policy specifies a 6.5% *ad valorem* tariff on biofuel imports (Kojima *et al*. 2007).

Consumers in each region derive utility from transportation energy and food. Consumer and producer surplus is maximized given fixed endowments of crude oil and lands of different quality. The relative prices of biofuels and gasoline determine their share in the total energy mix. Without the mandates, as energy demand increases over time and oil stocks deplete, the price of gasoline increases (at least over an initial time period) inducing substitution into biofuels. The US

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[22] This is a gradual process. For forests it also depends on the final use of forest products. If wood is transformed into wood products, carbon is released gradually over 50 years following land conversion, while it is released immediately if wood is burned (IPCC 2001). We assume that all carbon is released immediately following land-use change, an assumption also made in other well-known studies (e.g., Searchinger, et al 2008).

and EU mandates accelerate this substitution process. However, the demand for food also goes up because of population growth and changes in dietary preferences, and this limits the conversion of especially high quality land from food to energy production. The discount rate is assumed to be 2% as is standard in such analyses (Nordhaus and Boyer 2000). The model is simulated over 200 years (2005-2205) in steps of five, to keep the runs tractable.

3. Simulation Results

We first state the scenarios modeled in the paper and then describe the results. In the *Baseline case* (model BASE), we assume that there are no mandates and both first and second gen fuels are available. This case serves as the counterfactual. The idea is to see how substitution into biofuels takes place in the absence of any regulation. In the *US Regulatory Scenario* (model USREG), US and EU mandatory blending policies, as described earlier, are imposed.[23] We also run a *Flexible Mandate* scenario (model FLEX), in which both first and second gen biofuels can be used to meet mandatory blending specifications, but there is no requirement on the share of second gen fuels. This is mainly to examine whether second generation biofuels (which are less land-intensive) will be produced when they are not explicitly mandated. The major results are as follows:

1. Limited Effect of Biofuel Mandates on Food Prices[24]

Perhaps the most significant finding is that the effect of renewable fuel standards (RFS) on food prices is actually quite modest when second gen fuel requirements are imposed, as in model USREG (see Table 4). Food prices will increase by about 5% in the year 2025 – compare the USREG case with BASE.[25] This is much smaller than what most other studies predict (Banse *et al.* 2008, Reilly and Paltsev 2009), possibly because we have endogenous land allocation in the model and allow for the use of second generation biofuels which are less land-using. Without these new fuels, food price increases are higher (about 30%), see model FLEX for the year 2025.

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[23] Recall that the US mandate stipulates an increase from 8 to 36 billion gallons a year from the year 2022 which must include at least 21 billion gallons of second generation fuels. EU legislation only specifies a minimum share of biofuels in transportation fuel of 10% from year 2020.

[24] Our results are time sensitive but to streamline the discussion, we mostly focus on the year 2025. In the more distant future (say around 2050 and beyond) energy scarcity makes biofuels economical, even without any supporting mandates. Mandates become somewhat redundant by then. Given the lack of space, we do not discuss what happens in 2050 and beyond.

[25] The model is calibrated to track real food prices closely. Vegetable and meat prices in 2005 for the BASE case are $170 and $1,700 per ton. Observed prices were $175 and $1,800 for the period 2005-09 (World Bank 2010b).

Table 4. Food, biofuels and gasoline prices

		BASE	FLEX	USREG
Weighted world food price ($/ton)	2005	**600**	780 (30%)	726 (21%)
	2025	**864**	**1,133 (31%)**	**911 (5%)**
	2050	605	643 (6%)	**639 (6%)**
World biofuels price ($/gallon)	2005	2.2	2.2 (0%)	2.2 (0%)
	2025	3.1	3.6 (16%)	3.3 (5%)
	2050	1.7	1.8 (6%)	1.7 (0%)
World gasoline price ($/gallon)	2005	1.9	1.9 (0%)	1.9 (-1%)
	2025	2.9	2.9 (-1%)	2.9 (-1%)
	2050	1.9	1.9 (-1%)	1.9 (-1%)

Notes: Weighted food price is the average of vegetable and meat prices weighted by the share of each commodity in total food consumption. The numbers in brackets represent the percentage change of food prices under the mandates compared to the BASE model. Gasoline prices are reported wholesale, without taxes.

Note that food prices decline ultimately towards 2050 as the effect of the mandates wears off. This is mainly because population growth levels off by that time horizon and output increases due to technology improvements in agriculture.

Figure 3 shows the time trend in food prices under the three regimes. Prices increase even in the BASE model which has no biofuel mandate. Although real food prices have declined in the past four decades, the potential for both acreage expansion and intensification of agriculture through

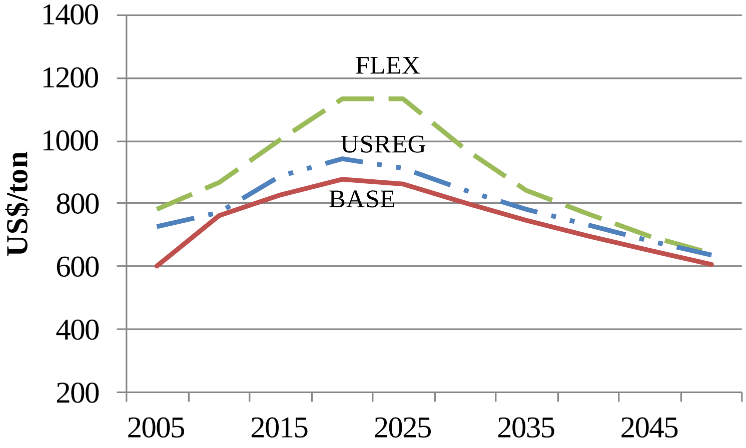

Figure 3. World weighted food prices

Notes: The baseline model is in red and the regulated models are the green and blue lines. The weighted food price is the average of vegetables and meat prices weighted by the share of each commodity in total food consumption.

improved technologies is expected to be lower than in the past (Rosegrant 2001).[26] Second, the substantial increase in food demand in MICs and LICs accompanied by a change in dietary preferences raises the demand for land, which drives up its opportunity cost. Meat consumption in these two regions in the model increases by 25% and 105% between 2005 and 2025, while the consumption of vegetables remains stable. Since more land is used per kilogram of meat produced, the overall effect is increased pressure on land.

Although a 5% increase in food prices may seem small, it may still have major impacts on consumption by the poor and food security in lower income nations where a relatively high share of income is spent on food.[27] The impacts are regressive, with richer regions impacted less and the poorest regions hit the hardest. LICs have higher price elasticities and are therefore more sensitive to increased food prices. For example, US per capita food consumption in 2025 declines due to mandatory blending (USREG) by about 2% and 0.6% for meat and non-meat foods, respectively. The same numbers are much higher for MICs - nearly 15% and 4%.

2. *US food exports reduce sharply: Developing countries must now grow more of their own food, thus inducing conversion of marginal lands*

Both first and second gen biofuels production increases sharply under the US mandate (see Table 5). US food production declines by almost 25% as a result of the energy mandates, as shown in Table 6. US food exports go down by more than 70% (61 to 17 million gallons). This is because land is shifted out of food to produce biofuels for domestic consumption. Imports of first gen biofuels increase almost three fold, even with the import tariff in place. Specifically, US and EU biofuel imports from MIC countries go up by a total of 572 (=521+51) million gallons while MICs export increase only by 320 million gallons. This is because other HIC countries like Canada and Japan import less biofuels due to terms of trade effects.

With regulation, global food production goes down and food prices increase. Food production in the US/EU declines but rises in the MICs. These countries must now produce more food and bring new land under cultivation (Table 7). MICs bring 24 (=967-943) million additional hectares

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[26] From 1960 to 2000, crop yields have more than doubled (FAO 2003). But over the next five decades, agricultural yields are expected to increase by only about 50%, see the data presented earlier in Table 2.

[27] An issue that could be considered in future research.

Table 5. Biofuels production (billion gallons)

		US		EU		MICS	
		BASE	**USREG**	**BASE**	**USREG**	**BASE**	**USREG**
Total biofuels production	2005	8.5	8.5	3.6	3.6	7.7	7.7
	2025	**13.7**	**35.1**	**3.0**	7.5	12.3	11.4
	2050	28.6	35.1	19.3	19.2	37.1	34.6
First gen biofuels production	2005	8.5	**8.5**	3.6	3.6	7.7	7.7
	2025	7.2	**14.1**	3.0	3.6	12.3	11.4
	2050	13.1	14.1	3.8	3.7	37.1	34.6
Second gen biofuels production	2005	0	**0**	0	0	0	0
	2025	6.5	**21.0**	0	3.9	0	0
	2050	15.5	21.0	15.5	15.5	0	0

Notes: Our numbers are calibrated to observed data. From 2005 to 2009, US average biofuels production was 8.3 billion gallons, 3.3 billion for the EU and 7.5 for MICs (FAPRI 2010). Second gen fuel supply was negligible.

Table 6. Trade in food and first gen biofuels and food production

		US		EU		MICs	
		BASE	**USREG**	**BASE**	**USREG**	**BASE**	**USREG**
Net export first gen biofuels (million gallons)	2005	-446	-450	-73	-72	1,396	1,386
	2025	**-379**	**-900**	**-60**	**-111**	**1,869**	**2,189**
	2050	-690	-900	-118	-107	6,710	6,503
Net export food (million tons)	2005	53	53	-53	-52	-220	-220
	2025	**61**	**17**	-38	-47	-264	-215
	2050	73	53	-44	-45	-282	-264
Food production (million tons)	2005	481	481	363	363	1,412	1,412
	2025	**545**	**411**	426	415	1,877	2,000
	2050	580	541	441	443	2,421	2,283

Notes: US and EU import biofuels from MIC nations. The sum of imports from EU and US is not equal to exports from MICs since MICs also export biofuels to other HIC countries. Consumption of biofuels in LIC countries is marginal.

under cultivation. However the table shows that the really big increases in land use occur even without these mandates: in the MICs, 150 million ha (=943-793) are brought under production between 2005-25 without any mandates (see BASE). Most of this additional land is located in three MIC nations – Brazil, Indonesia and Malaysia.

3. Regulation on second generation biofuels has a significant impact in terms of reducing land scarcity and limiting the increase in food prices

The role of second gen biofuels can be seen by comparing the results under FLEX which allows for the composition of first and second gen fuels to be determined endogenously and USREG,

Table 7. Land allocation to food and energy production (in million ha)

		US		EU		MICs	
		BASE	**USREG**	**BASE**	**USREG**	**BASE**	**USREG**
Land under food production	2005	166	166	137	137	786	786
	2025	151	110	132	127	933	958
	2050	108	108	98	101	943	898
Land under biofuels production	2005	12	12	6	6	7	7
	2025	27	68	11	16	10	9
	2050	70	70	45	42	21	20
Total cultivated land	2005	178	178	143	143	**793**	793
	2025	178	178	143	143	**943**	**967**
	2050	178	178	143	143	964	918

Notes: Land allocation in Other HICs and LICs are similar across the different scenarios.

which prescribes a minimum share of the latter (see Table 8). With regulation, second gen biofuel production nearly doubles from 11.4 to 21 billion gallons, suggesting that the mandate does lead to an increased supply of the newer biofuels.

Table 8. Effects of US second generation mandates on biofuels and food production (in year 2025)

		First gen biofuels production	**Second gen biofuels production**	**Net export biofuels**	**Food production**
		billion gallons		million gallons	million tons
US	USREG	14.1	**21.0**	-900	**411**
	FLEX	23.4	**11.4**	-1,232	**444**
MICs	USREG	11.4	0	2,189	2,029
	FLEX	11.9	0	2,501	2,000

Notes: We only report the regions impacted most by second gen biofuel regulation. The numbers do not change significantly for the EU.

Production of first gen fuels declines in the US and import of biofuels also falls. Aggregate food production declines by about 7%, which is somewhat surprising. One may intuitively expect more food to be produced when newer less land-using biofuels are mandated. However, US food exports double under second gen fuels, albeit from a low base. Food is still produced in mostly high quality lands. The combined effect of an increase in food exports and decrease in biofuel imports limits the conversion of marginal lands overseas (MICs and LICs). In summary, regulation of second gen biofuels helps reduce imports, but does not release land for more food production. World biofuels prices fall by about 8% in this case.[28]

4. *Mandates lead to big increases in biofuel production, earlier in time*
Without regulation, biofuel consumption in the EU and US in 2025 is three and 14 billion gallons, and accounts for 4% and 8% of fuel consumption, respectively. This is much lower than what is prescribed by the mandates. Figure 4 shows EU/US consumption with and without the mandates (BASE, USREG). The mandatory blending policy requires an additional 26 billion gallons of biofuels in 2025 compared to the unregulated case, mostly in the US.[29] In the EU, the mandate is binding until 2030 (see panel c). The US target is much more ambitious. It binds until 2050 (see panels a and b). The gap in consumption with and without the mandate is bigger in the US than in the EU.

As seen from Figure 4(a) and 4(c), first gen fuels decline in use without a mandate for several years before becoming economical in response to rising energy prices. After 2025, the use of first gen biofuels increases even without a mandate. In the absence of regulation, the global share of oil steadily decreases from 95% in 2005 to 92% in 2035 and 88% in 2050. The share of biofuels increases, mainly due to a considerable increase in the market share of second gen fuels. Even with no regulation, they are economically viable in the US by 2025. By 2050, they account for about 5% of global transportation energy. The production of first gen fuels, however, does not show nearly the same rapid growth, in spite of regulation, mainly because of competing demands for land (see Fig. 4a and 4c).

With no regulation, annual world production of biofuels is constant at about 20 billion gallons until 2020, increasing to 54 billion in 2050 (not shown). The stagnation until 2020 is due to a rapid increase in the opportunity cost of land, caused by the growing demand for food. Indeed, land rents double in the US and the EU during this period. Beyond 2020 however, food demand

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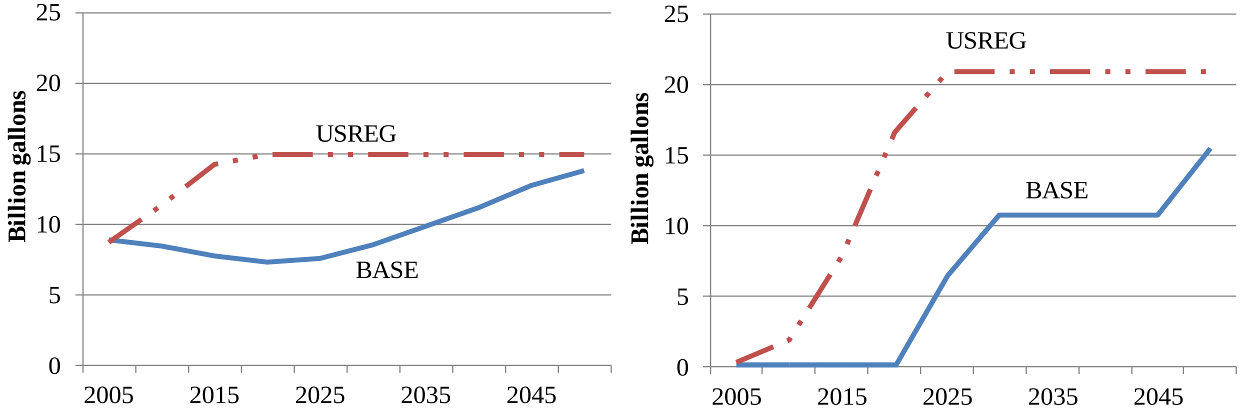
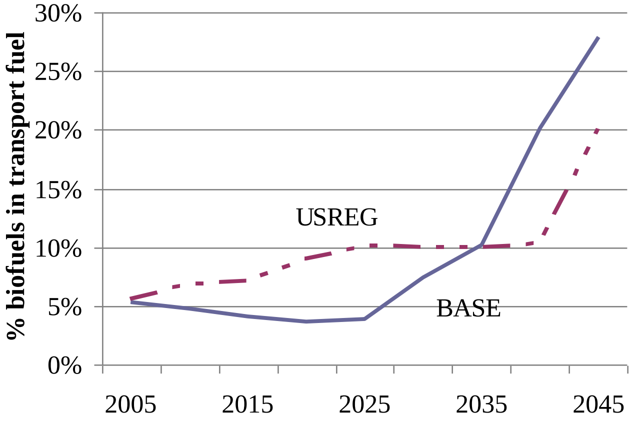
[28] In our BASE model, second gen fuels are used around 2025 (see Table 5), which is much earlier than indicated in other studies (e.g. Peña 2008), and may be due to the fact that we consider the opportunity cost of land, which gives it a cost advantage relative to land-using fuels.
[29] Global biofuels production under the baseline scenario is 29 billion gallons in 2025.



(a) First Gen biofuels use in US (b) Second Gen biofuels use in US



(c) Share of biofuels in transport fuel in EU

Figure 4. US and EU biofuel use (with and without mandates)

Note: The US mandate is more stringent, as can be observed by the vertical distance between the dashed and solid lines. Since the EU mandate is in percent terms, we report percent figures for the EU.

levels off, and so do land rents. However, the scarcity rent of oil continues to increase, making gasoline expensive and biofuels economically feasible (see Fig.4a,b).

5. Mandates reduce global oil prices and lead to terms of trade effects

The major goal of biofuel regulation is to reduce direct emissions from the energy sector. US emissions fall by 8% while those of the EU by about 6% in 2025 (see Table 9). However, our results show that the EU mandate will not achieve their declared carbon savings target of 100 million tons of CO_2 per year by 2020 (Eisentraut 2010). The main reason for this is that the mandated share of biofuels in the EU is not high enough to make a large difference. Beyond 2035 the mandate is no longer binding and the EU actually consumes more oil (and emits more carbon) relative to the model without mandates (BASE).

Table 9. Direct carbon emissions in billion tons of CO_2 (USREG)

	US	EU	World
2005	2.4	1.1	6.2
2025	**2.6 (-9%)**	**1.1 (-6.3%)**	**8.5 (-0.6%)**
2050	2.6	0.8	10.2

Note: Numbers in parenthesis represent the percentage change of carbon emissions compared to BASE model.[30]

Other regions are similarly impacted. The mandates, while increasing the consumption of biofuels in the US/EU, increase oil consumption and reduce biofuel use elsewhere. This occurs because of terms of trade effects - the increased demand for biofuels lowers the world price of oil (see Table 4). In 2025 the price of oil is about 2% lower, while the price of biofuels increases by 5% with mandatory blending. The net effect is that biofuel consumption outside the US and EU goes down by 10% in 2025, most of it in MIC countries (Table 10). Oil consumption goes up by 2%.

Table 10. Food and biofuels consumption

		US		EU		MICS	
		BASE	**USREG**	**BASE**	**USREG**	**BASE**	**USREG**
Food consumption (million tons)	2005	187	186	153	153	126	126
	2025	213	214	162	162	133	132
	2050	225	224	167	165	152	147
First gen biofuels consumption (billion gallons)	2005	8.9	8.9	3.6	3.6	6.3	6.3
	2025	7.6	15.0	3.1	3.7	10.4	9.2
	2050	13.8	15.0	3.9	3.8	30.4	28.1
Second gen biofuels consumption (billion gallons)	2005	0	0	0	0	0	0
	2025	6.5	21.0	0	3.9	0	0
	2050	15.5	21.0	15.5	15.5	0	0
Total biofuels consumption (billion gallons)	2005	8.9	8.9	3.6	3.6	6.3	6.3
	2025	**14.1**	36.0	**3.1**	7.6	**10.4**	**9.2**
	2050	29.3	36.0	19.4	19.3	30.4	28.1

Annual direct emissions of carbon increase by about 6% in the rest of the world.[31] Although the US/EU consume a significant share of global transportation energy - 56% in 2005 which declines

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[30] Observed average carbon emissions for US, EU and World are respectively equal to 2.2, 1.0 and 6.1 tons of CO2 from 2005 to 2009 (IEA, 2010).

[31] Direct emissions from the rest of the world go up from 4.5 billion tons of CO_2 in the BASE model to 4.7 billion tons in the USREG model in 2025.

to 35% in 2050 - the reduced emissions in these regions are not enough to offset the carbon leakage in other regions. Hence, the net effect of mandatory blending policies on global direct emissions is negligible (see Table 9).

In the BASE model, direct emissions from US/EU and other high income countries are expected to be relatively constant over time since energy use is approximately constant (the rate of substitution between gasoline and biofuels is small), while the emissions of other regions show steady growth because of increases in income and population. The majority of the growth in carbon emissions will occur in MICs. Considering only direct carbon emissions, medium income countries (mainly led by China and India) surpass the high income countries and as a group become the largest carbon emitter by 2025. This is because consumption of fuel for transportation is higher in MICs than in the US and EU combined. The results also predict considerable growth in low income regions, but starting from a much smaller base.[32]

6. Indirect carbon emissions increase

Biofuel mandates lead to an *increase* in indirect global emissions (see Figure 5). The mandates cause an increase in total emissions in most years relative to the unregulated (BASE) case, which to a large degree is due to land conversion that releases sequestered carbon into the atmosphere (indirect emissions). Total emissions (direct and indirect) actually increase in the near term (see year 2025 in Figure 5). Currently, carbon emissions from land-use changes account for about 20% of global greenhouse gas emissions, making it the second largest source of emissions after the electricity sector (WRI 2010). Since most indirect carbon emissions are released through the production of first gen biofuels and food, we can compute them from the model. Regardless of whether biofuels mandates are imposed, the increased demand for food causes large-scale land conversion. However, the mandates only accelerate this process, especially for the middle income countries (see Table 7). In 2025, indirect carbon emissions increase by 10% (or 0.6 billion

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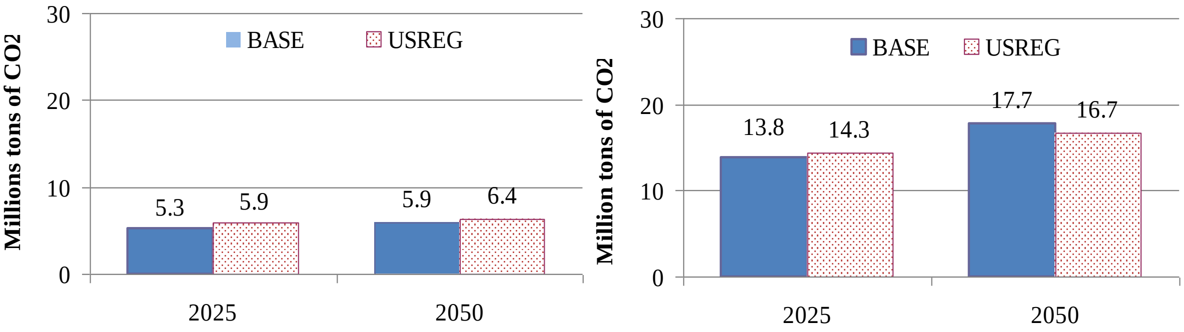
[32] These results are not shown here because of space constraints.



(a) World indirect carbon emissions (b) World total carbon emissions

Figure 5. World indirect and total carbon emissions under BASE and USREG

Note: Total carbon emissions are the sum of direct and indirect carbon emissions.

tons of CO_2). By adding direct and indirect carbon emissions, we immediately see that total carbon emissions increase by about 0.5 billion tons of CO_2 due to mandatory blending in US and EU (see Figure 5).

7. Welfare Declines in other countries

We can compute the regional gains and losses in aggregate consumer and producer surplus as a result of the mandates (Figure 6). Medium income countries experience the largest loss in welfare under mandatory blending, followed by low income nations. This welfare loss (for MICs) amounts to almost half a trillion dollars and increases rapidly until 2020 before declining. EU also experiences a loss in welfare under the mandates compared to the unregulated case, but by a smaller degree because consumers in the EU are less sensitive to a rise in food prices. However, the US experiences a slight *increase* in welfare. These results are primarily driven by changes in surplus from agriculture. The mandates increase biofuel production, which causes an increase in the opportunity cost of land, which in turn drives up the price of agricultural products (both food and energy). This has a significant positive impact on agricultural surplus in the US. Indeed, increased agricultural surplus is one of the stated objectives of the US mandate (De Gorter and Just 2010).

The global welfare effect of introducing mandatory blending is obviously negative. In the MICs and LICs - countries where a large share of income is allocated to food consumption, consumers are more sensitive to changes in food prices. As a result, in these countries, the loss in the welfare of food consumers exceeds the gain to food producers (from higher food prices). Note however,

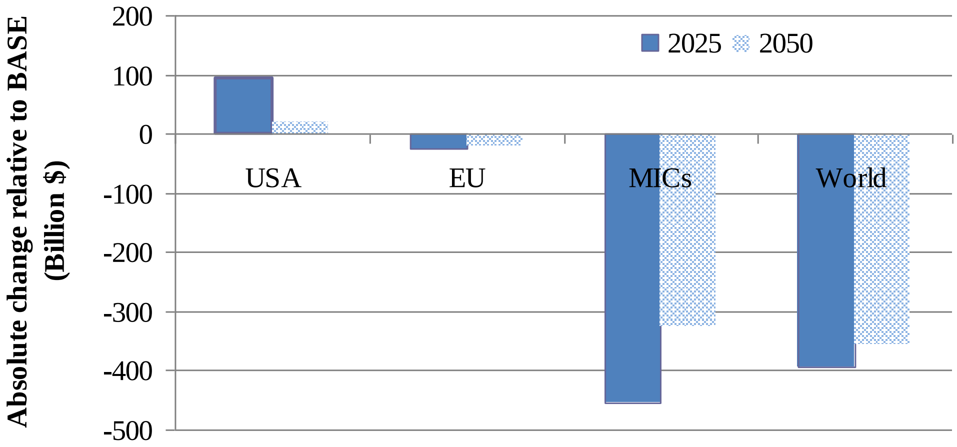


Figure 6. Welfare impacts of US and EU mandates: Absolute change in total surplus compared to baseline

Note: Biofuel mandates impact the welfare of MICs and LICs the most. HICs including the US experience slight improvement in welfare relative to the unregulated scenario.

that we do not include the benefits from reduced carbon emissions in the mandated nations, and given that greenhouse gases are global pollutants, it is not clear whether any benefits accrue to the countries imposing mandates. On the other hand, higher emissions in other nations due to the terms of trade effects will cause environmental damages which will reduce aggregate welfare, regionally and globally as well.

8. The US Mandate is stricter than that of the EU

The associated shadow prices of the mandates yield the subsidy needed to meet biofuel targets in the regulated countries.[33] The subsidy is only positive when the policy constraint is binding (see Figure 7). The US subsidy is 1-2 orders of magnitude higher than in the EU. The subsidy required to meet the second gen requirement is higher than the first gen subsidy, which can be explained by a relatively high production cost of second gen biofuels technologies still in their infancy. Prior to 2015, the requirement on second gen biofuels consumption is relatively small and therefore less costly to impose.[34]

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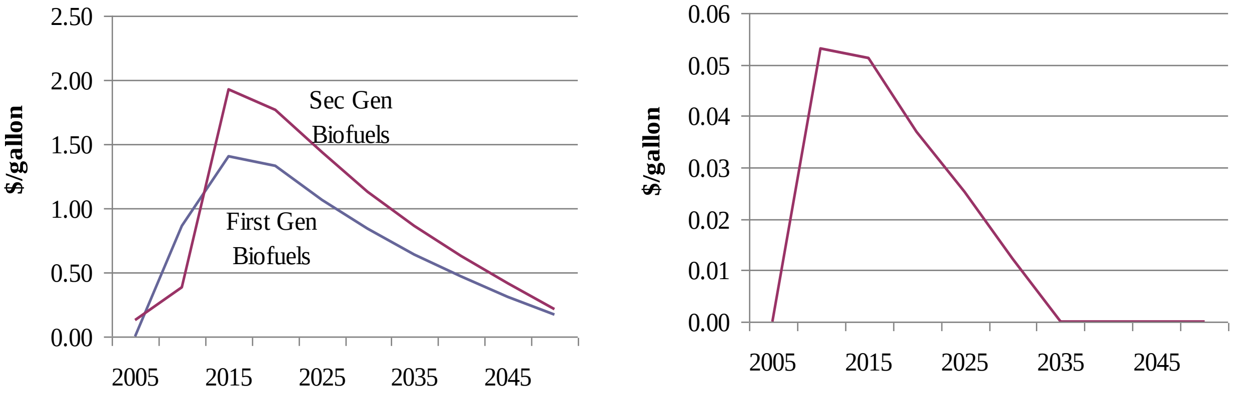
[33] This subsidy would be in addition to the current tax credits described earlier in the paper.

[34] Banse *et al*. (2008) calculated the subsidy required to meet the EU biofuel mandate and report numbers for Sweden and the U.K. They found that in 2020 the subsidy would range from 30% of production costs in Sweden to almost 60% in the United Kingdom. In our case, US subsidies are $1.33 and $1.76 per gallon for first and second-generation biofuels, respectively, while the EU biofuels subsidy is $0.04 per gallon. Based on a current production cost for



(a) US subsidy for first and second gen biofuels

(b) EU subsidy

Figure 7. Implicit biofuel subsidies in the US and the EU ($/gallon)

Note: Since EU mandate does not differentiate between first and sec gen use, the subsidy is given to any type of biofuels. US subsidies are several times that in the EU.

4. Model Sensitivity to Parameter Values

There is uncertainty regarding the values of several key parameters used in the empirical analysis. These include the stock of oil and its cost of extraction, the conversion cost of marginal lands, the production cost for second gen biofuels and yield parameters for crops. In this section we investigate the sensitivity of our results to changes in these parameters. In addition, we analyze the implications of lifting the current trade restrictions in the US and EU.[35]

Our strategy is to study the model with full regulation (model USREG) with the following changes: (1) a 20% lower initial stock of oil (2) 50% lower conversion cost for marginal lands (3) no trade restrictions on biofuels (free trade) (4) reduction in the initial cost of second gen biofuels and (5) a 15% increase in agricultural yields because of adoption of biotechnology.[36]

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second gen fuels of about $4 per gallon, the subsidy represents about 33% of total production cost in the US and only about 1% in the EU. Hence, the implicit biofuel subsidies we calculate for the EU are considerably lower than their findings. This difference may be explained by the fact that Banse et al. do not model second- generation fuels. However, Ando *et al.* (2010) report per gallon subsidies of $1.67 for corn ethanol and $2.23 for cellulosic ethanol, similar to our figures ($1.40 and $1.95, respectively).

[35] Because of a lack of space, we are unable to show all our sensitivity results. We discuss only the most significant ones.

[36] An increase in the cost of extraction of oil is not considered, but would have a similar effect as a reduction in the initial stock of oil since both would raise energy prices. Preliminary runs suggest that the model is not very sensitive to an increase in the cost of extraction of oil.

There is considerable uncertainty concerning the production costs of second gen biofuels. IEA (2009b) has developed a set of cost projections based on the potential market penetration of second gen biofuels where the cost and its rate of decline over time depend on crop prices, economies of scale from large plants, integration of new technologies and the effects of experience and learning. For production costs in the benchmark models we have used their conservative estimates. In the sensitivity analysis we apply their optimistic projections which yield costs that are lower by about 15% for both the US and EU. We model the adoption of genetically modified foods that may raise agricultural yields through introduction of new cropping varieties that are plant and disease resistant and do well in arid environments (OECD 2009).[37] Biotechnologies are currently adopted by the world's largest agricultural producers except the EU and occupy about 10% of global crop area.[38] We assume a reasonable across-the-board increase in agricultural yields of 15% relative to the previous models described earlier.[39] To keep it simple, this increase in yields is assumed to be uniform across land classes and across regions. In addition, it equally affects food and first-and-second generation biofuels.

The results are summarized in Table 11 while the impact on carbon emissions is reported in Table 12. Lower oil reserves raise energy prices, which in turn lead to higher food prices since land is shifted out from food to energy production (Table 11). Lower oil use also reduces direct emissions (see Table 12). However, less oil use and higher oil prices induce more biofuel production, which leads to more marginal lands being brought under cultivation. This increases indirect emissions, mainly in other countries (see Table 12).

A reduction in the conversion cost of new land leads to more marginal land being converted for agricultural production in the MICs, which have surplus land endowments. First gen biofuels from countries such as Brazil, Malaysia and Indonesia become competitive in the US and EU

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[37] The adoption of Genetically Modified Organisms (GMOs) can help biofuel production by increasing the production of biomass per unit of land but also by improving the conversion of biomass to first or second gen biofuels (FAO 2008b).

[38] The US leads in the adoption of biotechnologies, followed by Brazil, Argentina and to a lesser extent India and China.

[39] According to CBI (2008), adoption of GMOs contributed to a 15% increase in US crops yields during 2002-07. Due to a lack of data for other countries, we apply this rate of increase across the board.

market. This releases land for food production in both countries leading to a rise in food exports from the US and EU, as shown in Table 11.

Table 11. Sensitivity analysis: Effect of changes in model parameters on the model with US/EU Mandates (year 2025)

	USREG	**Lower oil reserves**	**Lower land conversion cost**	**No biofuel trade barriers**	**Lower cost of second gen fuels**	**Higher adoption of biotech**
Food price (US$/ton)	911	951	880	896	886	805
Biofuel price ($/gal)	3.30	3.45	3.18	3.24	3.25	2.92
Gasoline price($/gal)	2.87	3.92	2.88	2.86	2.85	2.81
Net Exports						
US food (mil tons)	**17**	18	32	19	18	**42**
US biofuels (mil gal)	**-900**	-940	-1,350	**-2,160**	-1,048	-720
EU biofuels (mil gal)	-111	-131	-276	-473	-112	-95
Food production (million tons)						
US	411	412	413	416	412	459
MICs	2,000	1,965	2,050	2,026	2,060	2,128
Biofuels production (billion gallons)						
US	35.1	35.1	34.6	33.8	34.9	35.3
EU	7.5	18.1	7.4	7.3	7.5	7.8
MICs	**11.4**	**14.4**	12.7	13.1	11.8	**14.1**
First gen biofuels consumption (billion gallons)						
US	15.0	15.0	15.0	15.0	15.0	15.0
EU	3.7	2.8	3.7	3.7	3.7	4.0
MICs	9.2	9.7	8.9	7.8	9.4	9.4
Second gen biofuels consumption (billion gallons)						
US	21.0	21.0	21.0	21.0	21.0	21.0
EU	3.9	15.4	3.9	3.9	3.9	3.9
Aggregate acreage used (million hectares)						
World	**1,807**	1,815	1,845	**1,940**	**1,941**	1,777

Notes: mil=millions, gal=gallons. The benchmark model USREG is shown in the left hand column.

Free trade enables MICs to produce more biofuels. More food production occurs in the high quality lands in the mandated countries. Indirect emissions increase in the MIC nations because of increased biofuel production.

The decrease in the cost of second gen biofuels helps reduce energy prices, which in turn induces more food production and less energy production in the US. More biofuels are imported from MICs, leading to increased land clearing for agriculture. This result is somewhat surprising since *ex ante*, one may think that the lower cost of second generation biofuels will lead to lower overall emissions. Due to a decrease in the cost of second gen biofuels, the scarcity rent of oil declines.[40] This causes fuel composition to switch towards more oil and less biofuels in MICs and LICs where second gen biofuels technologies are not available. Indirect carbon emissions almost double as shown in Table 12. Total emissions increase sharply.

Table 12. Sensitivity analysis: Impact of US and EU mandates on carbon emissions (year 2025) in billion tons of CO_2

	USREG	Lower oil reserves	Lower land conversion cost	No biofuel trade barriers	Lower cost of second gen fuels	Higher adoption of biotech
Direct emissions						
US	2.6	2.3	2.6	2.6	2.6	2.5
EU	1.1	0.7	1.1	1.1	1.1	1.2
World	8.5	7.0	7.9	8.5	8.5	8.5
Indirect Emissions	5.9	6.0	7.6	11.8	11.9	3.6
Total Global Emissions	**14.3**	12.3	15.5	**20.3**	**20.4**	12.2

Exogenous improvements in biotechnology reduce food prices by about 12% compared to the USREG model. The demand for land declines. Because of increased food production, US food exports rise by about 150% in 2025 compared to the regulated model. Less land is required to produce the regulated level of biofuels. Indirect emissions decline significantly in this case. In summary, the only parameters that have a major effect in increasing aggregate emissions are the removal of trade barriers and lower cost of second gen fuels.

Aggregate discounted net surplus is found to be rather insensitive to changes in model assumptions. This is evident from Table 13, which shows sensitivity results for the discounted surplus and biofuel subsidies. However, the implicit biofuel subsidies are far more sensitive. They are most sensitive to change in the initial oil reserves and higher yields from biotechnologies. A reduction in the initial oil reserve causes a 26% and 70% reduction, respectively, in the US subsidy on first and second generation biofuels. A lower oil stock increases the price of gasoline and improves the competitiveness of biofuels. Hence, the subsidy needed to meet the mandate is lower. An increase in agricultural yields due to improvements in biotechnology causes a 25-35%

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[40] This is analogous to a decline in the backstop price in a nonrenewable resource model.

reduction in the subsidy on first and second gen biofuels. Increase in agricultural yields reduces the shadow price of land, which increases the competitiveness of first gen biofuels.

Table 13. Sensitivity analysis: Impact of US and EU mandates in 2025 on net discounted surplus and biofuels subsidy

	USREG	**Lower oil reserves**	**Lower land conversion cost**	**No biofuel trade barriers**	**Lower cost of second gen fuels**	**Higher adoption of biotech**
Net discounted surplus (billion$)						
US	508.4	508.2	508.4	508.4	508.5	508.4
EU	112.1	111.9	112.1	112.1	112.1	112.1
MICs	85.1	84.0	85.2	85.1	85.1	85.9
World	741.2	739.5	741.4	741.3	741.3	742.0
Biofuels subsidy ($/gallon)						
US first gen	**1.06**	**0.78**	0.91	0.91	1.02	**0.67**
US second gen	**1.43**	**0.43**	1.55	1.35	1.15	**1.07**

Changes in the values of the parameters have a major impact in increasing biofuels production in the MICs, even more than on domestic production in the US and EU. Lower initial oil reserves and increased agricultural yields, both raise MIC biofuels production by about 25% (Table 11). The reason MICs are impacted is because they have surplus cultivable land. The US and EU do not. Relative changes in food and fuel prices, and land rents affect imports to the US and EU, mainly from the MICs. They do not affect domestic consumption in the US/EU in a big way.

Additional Runs

It may be useful to comment on how the BASE model (the one without regulation) itself changes due to the changes in the above parameters. The most important observation is that when the conversion cost of new land decreases, direct emissions decline, because more biofuel is used. Less food is consumed but greater biofuel use leads to more land conversion. Other factors, such as removal of trade barriers and decrease in the cost of second generation fuels, have similar qualitative effects on the model without regulation, but less in magnitude.[41]

We also consider the case of China and India, the two most populous countries, imposing domestic biofuel mandates.[42] In this scenario, we assume that these two nations impose a mandate

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[41] Detailed results for this case are not shown but can be obtained from the authors.

requiring the share of biofuels in transportation to be at least 10% by 2025. Imposing these mandates increases biofuels consumption in the MICs from 10 billion gallons under USREG to 24 billion. But terms of trade effects in the MICs is smaller now because the major countries use more biofuels. Global oil consumption goes down by less than 1%, with little change in direct carbon emissions in the MICs. What is interesting is that instead of moving land away from food to fuel production, farmers from MICs which are land abundant bring new lands under cultivation (another 140 million hectares). This is a nearly six fold increase in land conversion – the original increase in MIC land use was only 24 million hectares (see Table 7). As a result, indirect carbon emissions almost double to 12 million tons of CO_2. But world food prices still rise by only 2%.

We also run simulations to estimate the effects of two key assumptions in the model. First, we suppose that the price of oil remains constant over the entire time period at $79/barrel, the initial crude oil price in our model. Without a mandate, world use of biofuels decreases because of constant oil prices. US biofuel use drops from 7.2 to under 3 billion gallons. Second gen fuels are never adopted. Because of the mandate, indirect carbon emissions increase by more than 60% compared to the BASE model (both with cheap oil). About 50 million hectares of new land is brought under cultivation because of the mandates. This is double the acreage when oil price were assumed to rise competitively. This is because with cheap oil, biofuel use is low without mandates and increases sharply with them. Now, imposing the mandate has a bigger effect on food prices, which increase by 12% - recall that food prices increased by about 5% when oil prices were allowed to increase competitively. This is because the mandates induce higher land conversion to energy and less to food. The subsidy required to meet the US targets are almost twice higher than under the USREG model.

Second, we examine what happens when food preferences are assumed to be constant, i.e., there is no income-driven preference for meat and dairy products. We fix income elasticities for meat and vegetable products in the MICs and LICs at levels similar to US and EU. This means that people in developing countries have the same preference towards meat and vegetables as in developed nations. As a result, their meat consumption increases much less rapidly with income

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[42] The number of vehicles in China is expected to increase from 30 to 225 million by the year 2025, and in India from 15 to 125 million (IEA 2009). Currently, biofuels supply less than 1% of transportation fuels in these countries. There is some evidence that both countries have considered imposing biofuel mandates (Eisenstraut, 2010).

than before. To compare, note that per capita meat consumption goes up from 75 to 95 kg during 2005-25 when preferences change endogenously as in all the earlier runs. When preferences are kept fixed, they only rise to 81kg. Food prices increase over time by 28% in the same period, compared to 44% in the BASE model (see Table 4). Since land rents fall, more biofuels are produced – three billion gallons more than in the BASE case. Food prices increase by only 1% compared to no regulation. To meet their biofuel targets, US and EU import less biofuels from MIC countries. MIC nations convert less land to farming.

5. Concluding Remarks

We model the effect of biofuel mandates in the US and EU by combining three elements which have not been considered in previous studies - income-driven dietary preferences, differences in land quality and a limited endowment of oil. Our results are quite different from previous studies. We find that food price increases will come primarily from population growth and dietary changes towards meat and dairy products. Biofuels add another element to the mix, but not enough to be cast a "villain" as has been done in the popular media (e.g., New York Times 2008) and in several previous studies which show large impacts of the mandates on food prices (Banse *et al.* 2008; Rosegrant *et al.* 2008).[43]

Our framework with endogenous land allocation suggests that because of yield differences, the good quality land is best used for food production. Biofuel mandates mostly help accelerate conversion of medium quality lands which are currently under grasslands and forest cover, and largely located in developing countries. Sensitivity analysis shows that even when the big countries such as China and India adopt mandates, the additional supply comes from new land conversion, not by displacing food production. This trend is robust across many different scenarios. The good news is that the impact on food prices is likely to be small. The bad news is that the effect of the mandates on indirect carbon emissions may be large and likely to offset any emission declines from replacing gasoline in transportation, an outcome widely feared by the policy community (Searchinger *et al.*, 2008).

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[43] In general, it is difficult to compare outcomes from different models, but Rosegrant et al. (2008) predict prices of specific crops such as oilseeds, maize and sugar rising by 10-25% in 2020 which is significantly higher than in our case. Reilly and Paltsev (2009) predict aggregate biofuel use of 75 million gallons by 2025 which is much higher than our estimate of 22 billion. In their case, land quality is assumed constant, which may lead to higher output estimates since going down the land quality ladder will reduce the biofuel supplies.

Another key insight from the model is the effect of oil supplies. Abundant oil will mean lower impacts on food production, less land conversion but more direct carbon emissions from combustion. Scarce oil will imply biofuels become more competitive, hence bigger effects on food prices, more land conversion and larger indirect emissions from land-use changes. In one case, direct emissions go up, in the other case, indirect emissions increase. Either way, biofuel mandates are not likely to reduce carbon emissions significantly.

The model is simple and can be extended in many directions. From the sensitivity analysis, it seems that energy prices have a major impact on biofuels supply. Thus more work needs to be done in studying the effect of energy price changes, especially at the level of individual behavior, e.g., the choice of fuel-efficient cars. High oil prices may lead to new discoveries and therefore reduce substitution to biofuels. Learning effects, that are a result of market share, especially for new technologies like second generation biofuels, may be quite significant. Newer technologies for hybrid and alternate fuel vehicles may mean increased efficiency in the transportation sector which in turn will impact biofuel use. Finally it is not clear how other countries will react to these biofuel mandates in terms of their own energy and agricultural policies. Although we consider the case of China and India imposing mandates of their own, these strategic effects could be modeled explicitly in future work. Alternatively, the international climate negotiations may lead to a price on carbon, which will then imply that countries that encroach upon grass and forest cover to grow energy crops will have to face higher abatement costs. This may reduce biofuel production and indirect carbon emissions.

A major issue not addressed directly in this paper is how food price increases may affect the poor. These increases, even if modest may have major impacts in terms of increasing poverty and malnutrition in the low and medium income economies. This issue needs to be addressed further in future research.

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APPENDIX: DETAILS OF THE EMPIRICAL MODEL

Here we describe the empirical model in more detail. Notice that all variables are functions of time, but for convenience we omit the time index when necessary. The model has been calibrated for five year intervals starting from year 2005. The five regions, US, EU, other HICs, MICs and LICs are indexed by $r = \{US,\ EU, Other\ HICs, MICs, LICs\ \}$ where *r* denotes region. The regional index is omitted whenever convenient.

Demand Regional demand D_l for each final product l (vegetables, meat and dairy and transportation fuel) takes the form, $D_l = A_l P_l^{\alpha_l} w^{\beta_l} N$, where P_l is the output price in dollars, α_l is the regional own-price elasticity, β_l is the regional income elasticity, w is regional per capita income, *N* is regional population and A_l is the constant demand parameter calibrated from the data.[44] Per capita income increases exogenously over time at a decreasing rate (Nordhaus and Boyer 2000). Initial population levels and projections for future population growth are taken from UNDP (2004).

Demand parameters and related data are presented in Tables A1, A2 and A3. Income elasticities for the US, EU and other HICs are stationary since dietary preferences as well as income in these regions are not expected to change significantly in the long run. However, they will vary in the MICs and LICs due to an increase in per capita incomes. To take into account changes in dietary preferences, the income elasticity for each food product (meat and dairy, and vegetables) varies over time, but decreases with per capita income (Keyzer *et al.* 2005).

Energy Primary energy is provided by three resources - gasoline, first gen and second gen biofuels indexed by $\{g, bf, bs\}$. Each region is endowed with an initial stock of oil $\bar{X}$. Data on stocks is taken from the World Energy Council (WEC 2007) and reported in Table A4. Oil is also an input in sectors other than transportation, such as in chemicals and heating (IEA 2009a). Studies (IEA 2009a) suggest that 50% of oil consumption is in transportation. So we only consider 50% of total oil reserves as the resource stock available for transportation.[45,46]

Let $x(t)$ be the amount of oil used globally at period *t*. Then, the change in the remaining oil stock is given by $X(t+1) - X(t) = -x(t)$. To take into account the heterogeneity of oil reserves, extraction costs in period T depend on the cumulative quantity of oil extracted. Hence, unit extraction costs can be expressed

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[44] Demand for vegetables and for meat and dairy are assumed independent as in GTAP models (see Hertel *et al.* (2008a). Demand for food products (vegetable, meat and dairy) and fuel is in billion tons and billion gallons, respectively.

[45] By keeping the share of oil in transportation fixed, we ignore possible changes in the share of petroleum that goes to the transportation sector. It is not clear *ex ante* how the share of oil in transportation will change as the price of oil increases, and the answer may depend on the availability of substitutes in transport and other uses.

[46] In the paper, we discuss the effect of an exogenous change in oil reserves on our results.

Table A1. Population and per capita income in 2005 and 2050

	Population (millions)		**Per capita income** (2005$/capita)	
Region	2005	2050	2005	2050
US	280	312	42,040	57,767
EU	460	523	36,000	49,468
Other HICs	180	201	34,000	46,720
MICs	4,555	6,381	7,050	25,000
LICs	760	1,778	1,500	7,000
World	6,235	9,185	--	--

Source: Population data is taken from UNDP (2004) and per capita income from Nordhaus and Boyer (2000).

Table A2. Initial demand elasticities: price and income, by region and product

Region	**Elasticity**	**Vegetables**	**Meat and dairy**	**Fuel**
US	Price	- 0.05	- 0.50	- 0.30
	Income	+ 0.06	+ 0.61	+ 0.90
EU	Price	- 0.11	- 0.55	- 0.40
	Income	+ 0.13	+ 0.51	+ 0.95
Other HICs	Price	- 0.10	- 0.60	- 0.45
	Income	+ 0.14	+ 0.57	+ 1.00
MICs	Price	- 0.37	- 0.80	- 0.70
	Income	+ 0.30	+ 0.90	+ 1.20
LICs	Price	- 0.40	- 0.90	- 0.70
	Income	+ 0.40	+ 1.20	+ 1.30

Source: Hertel *et al.* (2008b)

Table A3. Changes in income elasticities for food products

Region	**Year**	**Vegetables**	**Meat and dairy**
US	2005	+ 0.06	+ 0.61
	2050	+ 0.05	+ 0.59
EU	2005	+ 0.09	+ 0.51
	2050	+ 0.06	+ 0.49
Other HICs	2005	+ 0.07	+ 0.57
	2050	+ 0.06	+ 0.55
MICs	2005	+ 0.30	+ 0.90
	2050	+ 0.20	+ 0.70
LICs	2005	+ 0.40	+ 1.20
	2050	+ 0.30	+ 0.90

Source: GTAP database. *Note:* Income and price elasticities for vegetables and meat and dairy products vary with per capita income every model period of 5 years (Keyzer *et al.* 2005).

following Nordhaus and Boyer 2000 as: $C(x(T)) = \phi_1 + \phi_2 \left(\frac{\sum_0^T x(t)}{\bar{X}} \right)^{\phi_3}$ where $x(T)$ is the amount of oil used at period *T* and $\sum_0^T x(t)$ is the cumulative amount of oil extracted from during [0,T] . The inequality $\sum_{0}^{T} x(t) \leq \overline{X}$, must hold, that is, cumulative production until time T cannot exceed the initial oil stock. The parameter ϕ_1 is the extraction cost over the base period, and ϕ_2 and ϕ_3 are calibrated parameters reported in Table A4. Oil is converted into gasoline using a constant coefficient of 0.3 and a cost of conversion of $0.5/gallon. Due to technological progress, the latter cost is projected to decrease annually by 1.5%.

Table A4. Extraction cost parameters for oil

Available stock (trillion barrels)	**Extraction cost parameters** ($US/bbl)		
	ϕ_1	ϕ_2	ϕ_3
4.26	20	100	5

Source: Available stock (WEC 2007); Extraction cost parameters (Chakravorty *et al.* 2009)

Energy supply Transportation energy is domestically produced from gasoline and biofuels in a convex linear combination given by $\lambda\left[\theta_g q_g^{\frac{\rho-1}{\rho}} + (1-\theta_g)(q_{bf} + q_{bs})^{\frac{\rho-1}{\rho}}\right]^{\frac{1}{\rho-1}}$, where λ is a constant, θ_g the share of gasoline, ρ the elasticity of substitution, and q_g , q_{bf} and q_{bs} are the respective input demands for gasoline, first gen and second gen biofuels. The first two parameters are calibrated from observed data.[47] In Table A5 we provide the calibrated values of λ and θ_g. The elasticity of substitution is region-specific and depends upon the technological barriers for displacing gasoline by first gen fuels in each region. It is 2 for HICs, 1.85 for MICs and 1.5 for LICs (Hertel *et al*. 2008a).

Land Quality The USDA database divides the global land area into nine land categories based on climate and soil properties (Eswaran *et al.* 2003) labeled I to IX (see Figure 1). They are classified according to their suitability for agricultural production, category I being the most productive. Land classes unsuitable for agricultural production, i.e., categories VII to IX are disregarded in our study. We aggregate the remaining six (I through VI) based on their characteristics. Category I and II are grouped and referred to as

Table A5. Energy supply parameters by region

	Constant, λ	**Gasoline share, θ_g**	**Biofuel share, *1-* θ_g**
USA	0.967	0.96	0.04
EU	0.945	0.97	0.03
Other HICs	1.085	0.97	0.03

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[47] We calculate the constant parameters of the CES production function by using the observed fuel production, gasoline and biofuel demands and shares over the base period as in Rutherford (2002).

MICs	1.061	0.96	0.04
LICS	1.097	0.98	0.02

Source: Resource shares are computed for the calibration year 2005 (FAO 2008a). Constant parameters are calibrated using Rutherford (2002).

land class 1in our study, III and IV as class 2, and V and VI as class 3. We thus have three land classes indexed $i = \{1, 2, 3\}$. Land class 1 benefits from a long growing season and soil of high quality, class 2 has a shorter growing season due to water stress or excessive temperature variance. Class 3 is of the lowest quality.

Initial acreage available for each land class can be divided into cultivated lands ($\overline{L_i}$) and marginal lands (L_i^s). Cultivated lands may be allocated to different uses indexed by *j* which denote food crops, first-gen or second-gen biofuels. Cultivated land area can be increased by bringing marginal lands under production. Let $l_i^s(t)$ be the new land (cultivated or marginal) converted into agricultural use at period *t*. As in Sohngen, Mendelsohn and Sedjo (1999), the cost of bringing one hectare of marginal land into production is an increasing and convex function of the aggregate land area in each region. It is defined by $\varphi_1 \sum_i l_i^s(t)^{\varphi_2}$ where φ_1 and φ_2 equal 30 and 1.5, respectively. They are assumed to be the same across land class and region.[48] Then, we have $L_i^s(t+1) - L_i^s(t) = -l_i^s(t)$. In period *T*, the land available for agricultural production is given by $\overline{L_i} + \sum_{t=0}^{T} l_i^s(t)$. Finally, the land allocation constraint is defined by $\overline{L_i} + \sum_{t=0}^{T} l_i^s(t) - \sum_j L_i^j \geq 0$, where L_i^j is the acreage from land class *i* allocated to use *j*. The Lagrange multiplier associated with this constraint is the implicit land rent. Total supply is the product of land supplied times its yield. Define crop yield on land class i by k_i^j, as reported in Table 2. Then, the total production from class *i* for use *j* is $k_i^j L_i^j$. Total primary production cost with respect to use *j* in a region is defined by $C_j(\sum_j k_i^j L_i^j) = \eta_1 \left[\sum_j k_i^j L_i^j \right]^{\eta_2}$, where $\sum_j k_i^j L_i^j$ is the total level of production in use *j*, and η_1 and η_2 are regional cost parameters. The parameters are calibrated against observed data and reported in Table A6.

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[48] We examine the sensitivity of the results to a 50% reduction in the land conversion cost, i.e., we reduce the value of φ_1 by half and keep φ_2 constant.

Table A6. Crop production cost parameters by region

	US	EU	Other HICs	MICs	LICs
η_1	1.51	1.61	1.55	0.37	0.80
η_2	1.50	1.55	1.50	1.60	1.70

Source: Cost parameters calibrated using observed data.

Food crops have two uses in our model, either to produce food (i.e., vegetables) or animal feed that is transformed into meat and dairy. We assume that one ton of primary crop produces 0.85 tons of final food products (FAOSTAT). It is assumed uniform across regions. The quantity of meat and dairy produced from one ton of crops is referred to as *the feed ratio*. It is region-specific and adapted from Bouwman (1997). We use a feed ratio of 0.4 for developed countries (US, EU and Other HICs) and 0.25 for developing countries (MICs and LICs) to account for higher conversion efficiencies in the former.

Carbon emissions The model tracks direct as well as indirect carbon emissions. Emissions from gasoline are the same across regions, but emissions from first and second gen biofuels are region-specific and depend on the crop used. Emissions from gasoline occur at the consumption stage, while emissions from biofuels occur at the production stage. Let z_g represent the amount of carbon (measured in tons of CO_2) released per unit of gasoline consumed, and z_{bf} and z_{bs} are emissions per unit first and second gen biofuels. The figures used are shown in Table A7. Finally, indirect carbon emissions are generated by conversion of marginal lands, namely forests and grasslands into food or energy crops. The sequestered carbon is released back into the atmosphere. Let z_i^s be the amount of carbon released in any region per unit of land of class *i* brought into production. Then, aggregate indirect carbon emissions are given by $z_i^s l_i^s$.

Indirect emissions depend on whether forests or grasslands are being converted for farming - one hectare of forest releases 604 tons of CO_2 vs 75 tons for grasslands (Searchinger *et al.* 2008).[49] For each land class and region, we weight the acreage converted by the share of marginal lands allocated to each use (grasslands or forests). For instance, in the MICs, 55% of land class 2 is under pasture (45% under forest), thus indirect emissions from converting one hectare of land class 2 are 313 tons of CO_2 per hectare.[50] Land class 3 has 84% forest, so emissions are 519 tons/ha. The corresponding figures for LICs are 323 tons (land class 2) and 530 tons (class 3).

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[49] Losses from converting forests and grasslands are assumed to be the same in MICs and LICs. Carbon is sequestered in the soil and vegetation. About a quarter of the carbon is lost from the soil and the rest from vegetation. Detailed assumptions behind these numbers are available in the supplementary materials to his paper available at: http://www.sciencemag.org/content/suppl/2008/02/06/1151861.DC1/Searchinger.SOM.pdf.

[50] By using this method, we assume that the share of marginal lands under forests and grasslands is constant. In our model, the area of marginal lands converted into croplands is endogenous; however, we cannot determine if forests or grasslands have been converted.

Table A7. Carbon emissions from gasoline and representative biofuels

	Gasoline	Corn ethanol	Rapeseed biodiesel	Sugar-cane ethanol	Cassava ethanol
Carbon emissions (tons of CO_2/gallon)	0.0117	0.0062	0.0062	0.0014	0.0062
Emissions reduction relative to gasoline	-	53%	53%	80%	53%

Source: Gasoline, corn ethanol and sugar-cane ethanol numbers are from Farell (2006), rapeseed biodiesel from IEA (2009b) and cassava ethanol from FAO (2008a).