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Do Biofuel Mandates Raise Food Prices?

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by

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Abstract

Biofuels have received a lot of attention as a substitute for gasoline in transportation. They have been blamed universally for recent increases in world food prices. Both the United States and the European Union have adopted mandatory blending policies that require a sharp increase in their use. Many studies have shown that these energy mandates may have a large (30-60%) impact on food prices. We develop a model that takes into account dietary preferences - the fact that with rising incomes, people in the developing world will consume more meat and dairy products, which are land-intensive relative to cereals. On the supply side, we allow for conversion of new lands to farming. We show that about half the increase in food prices can be attributed to population growth and dietary changes, and only the remaining come from biofuel policy. Moreover, with endogenous land supply, food price increases are likely to be much smaller than predicted by other studies. Finally, these biofuel policies do not lead to any reduction in carbon emissions.

Keywords: Clean Energy, Food Demand, Land Quality, Renewable Fuel Standards, Transportation

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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…." These problems of yield stagnation and land scarcity are further exacerbated by clean energy policies that promote biofuels such as ethanol from corn and sugarcane. Many countries have actively embraced these renewable fuels as a means towards reducing greenhouse gas emissions and 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. For instance, about 10% of US gasoline now comes from biofuels and this share is mandated to multiply in the near future.[2]

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, as predicted by many economic studies.[3] 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 current biofuel mandates in the US and EU on world food prices. The model we develop has two unique elements, both of which have been overlooked in previous studies. First, we are able to disentangle the effect of these energy mandates from demand side effects such as population growth and rising incomes (as in countries like China and India) that are likely to lead to an increased consumption of meat and dairy products. Producing

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[2] The European Union (EU) requires that biofuels must supply at least 10% of transportation fuels by 2020, from a current share of about 3%.

[3] The International Food Policy Research Institute (Rosegrant *et al.*, 2008) suggests that US biofuel policy may raise the price of certain food commodities by up to 70% by the year 2020.

meat and dairy products requires more land than growing cereals.[4] Per capita consumption of meat and dairy products in the developed world is about four times that in developing countries. Fig.1 shows the disparity in meat consumption in the United States and China. As incomes in China and other countries rise, the gap in meat and dairy consumption is expected to narrow. Income-induced changes in dietary preferences have been largely ignored in previous studies. We find that food prices will indeed rise, but only about half of that may be due to energy policy.

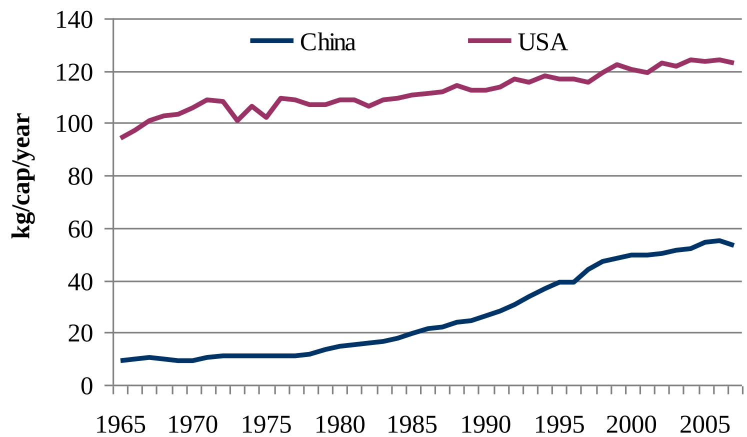


Figure 1. Meat consumption in China and US from 1965 to 2007
Source: FAOSTAT

The second unique feature in our model is the explicit accounting of the endowment of land. We use data that classifies land by quality, location and production cost. The increased demand for food and energy induces new land conversion, especially in the developing countries, where most of the available agricultural land is located. Even though these new lands are of lower quality than the ones already being farmed, we find that our model with endogenous land supply predicts food price increases that are significantly lower than in other studies.

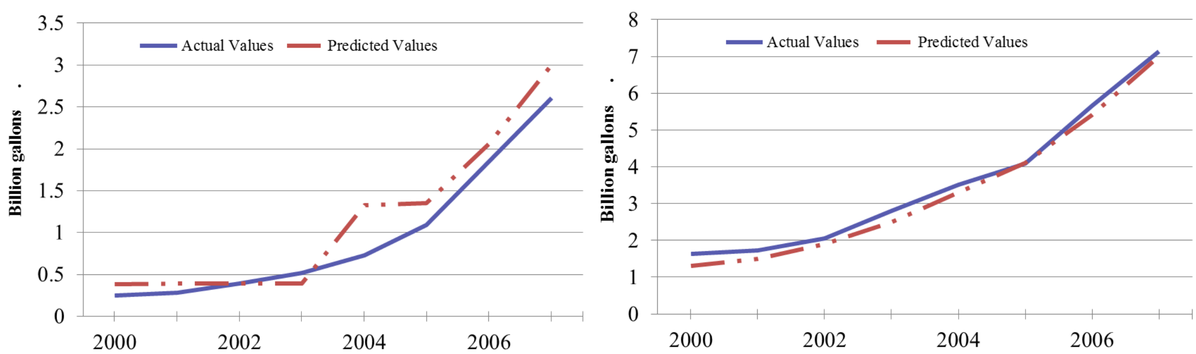
Because new land is available, even biofuel mandates by large developing countries such as China and India (both have active biofuel policies) have only a marginal effect on food prices, which go up by an additional 1%. Of course, this is good news, except that large-scale land conversion leads to an increase in carbon emissions, defeating one of the key objectives of biofuel

[4] For example, eight kilos of cereals produce one kilo of beef and three kilos produce one kg of pork.

policy - reducing greenhouse gas emissions. Global GHG emissions do not go down as a result of biofuel policy, and actually show a small increase.

Unlike many studies which take fossil fuel use as given, we model an explicit crude oil market so that gasoline prices are endogenously determined, with the production cost of oil rising with cumulative extraction. We find that assumptions regarding the scarcity of oil affect the share of biofuels in transportation but surprisingly, do not affect aggregate emissions.

The model was calibrated for the base year 2007. It is not possible to test model predictions over a long time horizon because biofuel mandates have been imposed only recently. However, as shown in Fig.2, the model does track the boom in biofuel use in the US and EU quite closely until the most recent year for which data is available. The difference between observed



(a) EU biofuel consumption (b) US biofuel consumption

Figure 2. Model prediction vs actual biofuel consumption

Source: Consumption figures are from EIA (2011). The jump in panel (a) is due to the imposition of the EU mandate

and projected values is systematically less than 10%. The model also predicts the annual average increase in food prices from 2000 to 2007 at 5%.[5] According to the FAO, food prices grew at an annual rate of 6% during this period.

[5] Our world food price is the average of cereal and meat prices weighted by the share of each commodity in total food consumption. In general, it is hard to accurately predict food prices in the short run, because of weather-related variability (droughts such as the one that occurred in Australia in 2008 or Russia in 2010), currency fluctuations and other macroeconomic phenomena.

There are several important studies on the effect of biofuel policies but none explicitly considers changes in dietary preferences, heterogeneous land quality and energy scarcity. Roberts and Schlenker (2010) use weather-induced yield shocks to estimate the supply and demand for calories and conclude that energy mandates may trigger a rise in world food prices by 20-30%.[6] Hausman, Auffhammer and Berck (2012) use structural vector auto-regression to examine the impact of biofuel production in the U.S. on corn prices. They conclude that one third of corn price increases from during 2006-08 (which rose by 28%) can be attributed to biofuels.[7] Other studies have used 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.* 2010). In these papers, land quality is explicitly taken into account, but changes in food preferences and scarce energy supplies are not modeled. The static framework adopted does not allow for an analysis of long run impacts, as done in this paper.[8] 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. Their results suggest that prices of certain selected crops may rise by up to 70% by 2020.

The main policy implication of the paper is that rising food demands and changing diets may have as much to do with the rise in food prices as biofuel mandates. Moreover, the rise in food prices may be significantly lower because new land can be brought into production. Models that do not account for supply side effects of rising food prices will tend to predict large impacts from these clean energy policies. It is also important to recognize that demand growth and changes in dietary patterns play as important a role in the increase in food prices as energy policy that diverts crops from food to fuel.

[6] They acknowledge that "demand growth has accelerated through demand for meat and other animal-based foods, which are highly income elastic." However, they do not explicitly account for it in their estimation.
[7] Their short-run estimates are consistent with our prediction that in the long-run, the impacts may be significantly lower. This is because higher food prices are likely to trigger supply side responses only with a time lag, especially if significant land conversion were to occur.
[8] Schneider and McCarl (2003) focus 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.

Section 2 describes the underlying model structure and assumptions. Section 3 reports 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 Heterogeneous Land Quality

In this section we discuss the model structure, while relegating some technical details and data to the Appendix. We divide the world into three groups using data on gross national product per capita (World Bank 2010). 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. The five regions are indexed by $n = \{US,\ EU, Other\ HICs, MICs, LICs\}$ where n denotes region.

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	GDP per capita	Major countries
US	46,405	-
EU	30,741	-
Other HICs	36,240	Canada, Japan
MICs	5,708	China, India, Brazil, Indonesia, Malaysia
LICs	1,061	Mostly African countries

Notes: Per capita GDP in 2007 dollars, PPP adjusted. *Source*: World Bank (2010)

We consider three final consumption goods - namely cereals, meat and dairy products and energy for transportation. Cereals include all grains, starch crops, sugar and sweeteners and oil crops. Meat and dairy products include all meat products and dairy such as milk and butter. For convenience, we call this group “meat.” We separate cereals from meat because their consumption is income-sensitive and the latter are more land intensive. Energy for transport comes from gasoline and biofuels, described below. Cereals, meat and biofuels compete for land that is already under farming as well as new land, which is currently under grassland or forest cover.[9]

Regional demands (for cereals, meat and transportation fuel) are modeled by means of Cobb-Douglas demand functions, which are functions of regional per capita income and population. Thus demand D_l for final product l takes the form

$$D_l = A_l P_l^{\alpha_l} w^{\beta_l} N \tag{1}$$

where P_l is the output price of good l in dollars, α_l is the regional own-price elasticity, β_l is the income elasticity for good l which changes exogenously with per capita income reflecting changes in food preferences, w is regional per capita income, N is regional population and A_l is the constant demand parameter calibrated from data. Demand for food products is in billion tons and the demand for fuel is in billion miles.

As incomes rise, we expect to observe increased per capita consumption of meat products relative to the consumption of cereals, as noted in numerous studies (e.g., Delgado *et al.* 1998, Keyzer *et al.* 2005, Regmi *et al*. 2001).[10] We model this shift towards animal protein by using income elasticities for food products that are higher at lower levels of per capita income (as in Keyzer *et al.* 2005). Specifically, income elasticities for the US, EU and other HICs are taken to be stationary in the model since dietary preferences as well as income in these regions are not expected to change significantly in the long run, at least relative to the developing countries. However, they are likely to vary in the MICs and LICs due to the steep increase in per capita incomes. The higher the income, the lower is the income elasticity. All price and income

[9] Obviously many other products can be included in a more disaggregated level but we want to keep the model tractable so that the effects of biofuel policy on land use are transparent.
[10] In recent years, meat consumption has remained quite flat in the OECD countries (a total 8% growth during the period 1985-99). Cereal consumption has also been constant during this period (FAO 2003). However in the developing economies, meat consumption has grown sharply. While population doubled in China between 1961 and 2006, meat consumption grew 33-fold (Roberts and Schlenker, 2010). Since meat production is more land-intensive, this would imply a higher demand for land in food production.

elasticities are specific to each food product (e.g., meat, cereals) and taken from GTAP (Hertel et al., 2008) as described in the Appendix (Tables A1-A3).[11]

We also account for regional disparities in the growth of population. While the population of high income nations (including the US and EU) is expected to be fairly stable over the next century, that of middle income countries is expected to rise by about 40% by 2050 and more than double for lower income countries (United Nations Population Division 2010). Demand is also impacted by regional per capita income, which is assumed to increase steadily over time but at a decreasing rate, as in several studies (e.g., Nordhaus and Boyer 2000). Again, regional differences are the norm, with the highest growth rates in MICs and LICs.[12]

Total available land area is the sum of current land under agriculture and new land that is mostly in pasture and forests. The initial global endowment of agricultural land is 1.5 billion hectares (FAOSTAT). The regional distribution of land quality is not even, as is evident from Figure 3 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 land classes in the model denoted by quality i, where $i = \{1, 2, 3\}$, with class 1 being the most productive land.[13] Initial acreage for each land class can be divided into cultivated land ($\overline{L}_i$) and available land (L_i^s). Land area can be increased by bringing new land under production, mainly located in MICs and LICs. It may be allocated to different uses indexed by j which denote food crops, and first and second generation biofuels. Cropping these lands implies increased carbon emissions.[14]

[11] It is important to recognize that not all developing countries have exhibited as large a growth in meat consumption as China. For example, a third of Indians are vegetarian and a change in their incomes may not lead to dietary effects of the same magnitude. Moreover beef and pork are more land-intensive than chicken, the latter being more popular in countries like India. The distribution of income may also affect this behavior. If it is regressive, the effect on diets may be limited.

[12] Initial population levels and projections for future growth are taken from the United Nations Population Division (2010). Both world food and energy demands are expected to grow significantly until about 2050, especially in the MICs and LICs. By 2050, the current population of 6.8 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.

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

[14] According to FAO (2008a), an additional 1.6 billion hectares of marginal lands could be brought under crop production in the future. This is approximately equal to the total land area already under cultivation.

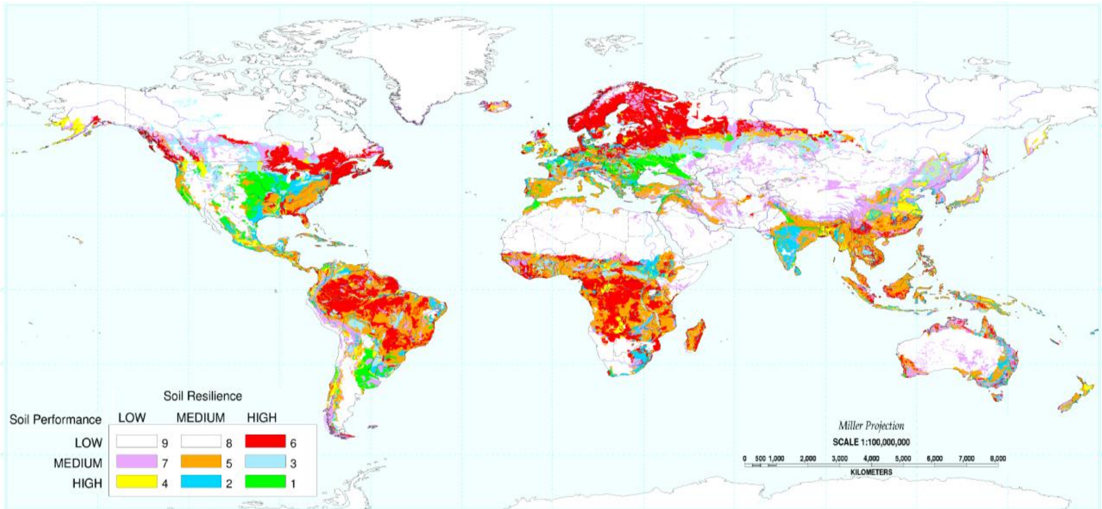


Figure 3. Distribution of land quality

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. In our model, we ignore category 7 through 9 which are unsuitable for agricultural production and aggregate the rest into three classes (categories 1 and 2 become class 1, 2 and 3 become class 2 and 5 and 6 are class 3).[15]

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 roughly a third for MICs and LICs, respectively, as shown in Table 2. Some class 2 and 3 land is cultivated, but most of it is not. They are mostly grasslands

Table 2. Land under agriculture and endowment of available lands

	Land class	US	EU	Other HICs	MICs	LICs	World
Land already under Agriculture (million ha)	1	100	100	25	300	150	675
	2	48	32	20	250	250	590
	3	30	11	20	243	44	350
Land available for farming (incl. marginal lands) (million ha)	1	0	0	0	0	0	0
	2	80	0	0	300	300	680
	3	80	0	0	500	500	1080

Sources: Eswaran *et al.* (2003), FAO (2008a). *Notes:* Land under the US Conservation Reserve Program (CRP) is assumed to be available for crop production. We assume that half of the CRP land is class 2.

[15] Many factors such as irrigation and climate change can affect the distribution of land classes. For instance, investment in irrigation can improve the productivity of land. In northern regions like Canada and Russia higher temperatures may cause an expansion of land suitable for agricultural production; hence, areas of land classes 2 and 3 may widen. The net effect of these factors on the productivity of new land is unclear. These issues are left for future work. However, we do allow for increasing productivity of land over time (see below).

and forests, and located in MICs and LICs. We call these lands "marginal lands." Note from Table 2 that there are no Class 1 lands remaining for agricultural production. Future expansion must occur only on lower quality lands, namely classes 2 and 3. Brazil alone has 25% of all available lands in the MICs and also happens to be the biggest producer of biofuels after the US.

Let $l_i^s(t)$ be the new land converted into agricultural use. We assume that the cost of bringing new land into production is increasing and convex (as in Gouel and Hertel 2006).[16] This is because access costs increase with land conversion. Land conversion costs in time t can be written as

$$C_s(t) = -\phi_1 \ln\left(\frac{L_i^s(0) - \sum_{\theta=0}^{t} l_i^s}{L_i^s(0)} \right) + \phi_2 \qquad (2)$$

where $L_i^s(0)$ is the initial endowment of marginal lands, and ϕ_1 and ϕ_2 are model parameters assumed to be the same across land class but varying by region.

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. Define yield of crop *j* on land class *i* as k_i^j. Then, total production of crop *j* from class *i* is $k_i^j L_i^j$.

Improvements in agricultural productivity are allowed to vary by region and land category (see Appendix). 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 for 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 low quality lands (Fischer *et al*. 2002). The total cost of food or biofuel production in each region is assumed to be increasing and convex. The

[16] This conversion cost has been used by Golub *et al.* (2008) to investigate the effect of carbon sequestration policies on global land use change and greenhouse gas emissions.

higher the production of food and biofuels, the more likely that cultivation moves into lower quality lands (van Kooten and Folmer 2004). Total production cost for product *j* in a given region is defined by

$$C_j(\sum_i k_i^j L_i^j) = \eta_1 \left[\sum_i k_i^j L_i^j \right]^{\eta_2} \tag{3}$$

where $\sum_i k_i^j L_i^j$ is the aggregate output of product *j*, and η_1 and η_2 are regional cost parameters.

Energy in the model is 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). The latter aims to convert parts of the plant other than the fruit or grain into fuels.[17] They currently cost an order of magnitude more than first gen biofuels. Unlike the EU mandate which does not specify the precise biofuel, US regulation imposes a minimum amount of second generation biofuel use by 2022.

Since 95% of global transportation fuel is provided by crude oil which is a nonrenewable resource, it is reasonable to use a Hotelling framework to model energy supply.[18] Transportation energy q_e is produced from gasoline and biofuels in a convex linear combination using a CES specification, as in Ando *et al.* (2010) given by

$$q_e = \lambda \left[\mu_g q_g^{\frac{\rho-1}{\rho}} + (1-\mu_g)(q_{bf} + q_{bs})^{\frac{\rho-1}{\rho}} \right]^{\frac{\rho}{\rho-1}} \tag{4}$$

where λ is a constant, μ_g the share of gasoline in transportation energy, ρ the elasticity of substitution, and q_g, q_{bf} and q_{bs} are the respective input demands for gasoline, first gen (generation) and second gen biofuels. The parameters λ and μ_g are calibrated from observed data. As the relative price of gasoline increases, the fuel composition switches towards using less of

[17] Examples include cellulosic material and crop residues.

[18] 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).

it.[19] 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 higher in the HICs and lowest in the LICs. We use estimates made by Hertel *et al.* (2010). As in many other studies, first and second gen biofuels are treated as perfect substitutes, but with different unit costs (Chen *et al.* 2012).

We define an exogenous world stock of oil and a single integrated "bathtub" world oil market as in Nordhaus (2009).[20] Both conventional and unconventional oils (e.g., shale) are included. At higher oil prices, the latter become competitive. According to IEA (2011), around 60% of crude oil is used by the transportation sector. From the estimated oil reserves in 2010, we compute the initial stock of oil available for transportation as 153 trillion gallons (3.6 trillion barrels, WEC 2010). The unit cost of oil depends on the cumulative quantity of oil extracted (as in Nordhaus and Boyer 2000) and can be written as

$$C_{oil}(x(t)) = \varphi_1 + \varphi_2 \left(\frac{\sum_{\theta=0}^{t} x(\theta)}{\bar{X}} \right)^{\varphi_3} \qquad (5)$$

where $x(t)$ is oil used in period t, $\sum_{\theta=0}^{t} x(\theta)$ is cumulative oil extracted and $\bar{X}$ is the initial stock of crude oil. Oil is then transformed into gasoline or diesel. For each region, we consider a representative fuel: gasoline for the US and diesel for the EU.[21]

We simplify by considering a representative first generation biofuel for each region. This assumption is reasonable because there is only one type of biofuel that dominates in each region. 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

[19] This specification captures the fact that there is a large technological potential for displacing fossil fuels in passenger transport through blended gasolines such as E85 (85:15 biofuel:gasoline ratio), see OECD (2008).
[20] We transform crude oil into gasoline using a coefficient of transformation equal to 0.3, taken from Chakravorty *et al.* (2010). Thus gasoline is a fixed share of oil. Since other uses of oil are not explicitly considered, the terms "oil" and "gasoline" are often used interchangeably in the paper where convenient.
[21] In the US, gasoline represents more than three-quarters of transport fuel use while diesel accounts for about 60% in the EU (Earth Trends 2011). The coefficients of transformation of oil into gasoline and into diesel are reported in the Appendix.

produced from cassava, although it amounts to less than 1% of global production. Table 3 shows the representative crop for each region and its production cost. Note the significant difference in costs across crops. These costs are assumed to decline by around 1% a year (Hamelinck and Faijj 2006) mainly due to a decrease in processing costs.[22]

Table 3. Unit costs of first generation biofuels[23]

	US	**EU**	**Other HICs**	**MICs**	**LICs**
Representative crop	Corn (94%)	Rapeseed (76%)	Corn (96%)	Sugar-cane (84%)	Cassava (99%)
Unit cost of production ($/gallon)	1.01	0.55	1.10	0.94	1.30

Sources: Production costs (FAO 2008a; Eisentraut 2010); *Notes*: The numbers in parentheses represent the percentage of first-generation biofuels produced from the representative crop (e.g., corn).

We model a US tax credit of 46 cents/gallon, which consists of both state and federal credits (de Gorter and Just 2010) which is removed in the model in year 2010, as done in other studies (Chen *et al.* 2012). EU states have tax credits on biodiesel ranging from 41-81 cents (Kojima *et al.* 2007). We include 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 currently account for only about 0.1% of total biofuel production although the market share may increase with a reduction in production costs and improved fuel performance and reliability of the conversion process. Compared to first gen fuels, they emit less greenhouse gases and are less land consuming.

Among several second gen biofuels, we model 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). 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

[22] Except for cassava, for which we have no data.
[23] These costs are inclusive of the value of by-products, since only part of the plant (the fruit or the grain) is used to produce first-generation biofuels. For instance, crushed bean “cake” (animal feed) and glycerine are by-products of biodiesel that can be sold separately.

EU, around 1,000 gallons/ha can be obtained from BTL, but only 400 gallons/ha are obtained from first gen biofuels.[24]

Second gen fuels are also more costly to produce. The production cost of cellulosic ethanol is $1.75 per gallon while first gen corn ethanol currently costs about $1.01 per gallon and ethanol from sugar cane costs $0.90. The production cost of BTL diesel is $2.25 per gallon - twice that of first gen biodiesel. However, technological progress is expected to gradually narrow these cost differentials and by 2030 or so, the per gallon production costs of second gen biofuels and BTL diesel are projected to be $1.09 and $1.40, respectively.[25] 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.

The US mandate (Energy Independence Security Act, 2007) sets the US target for biofuels at 9 billion gallons annually by 2008, increasing to 36 billion gallons by 2022.[26] The bill specifies the use of first and second gen biofuels as shown in Figure 4. The former (corn ethanol) is mandated

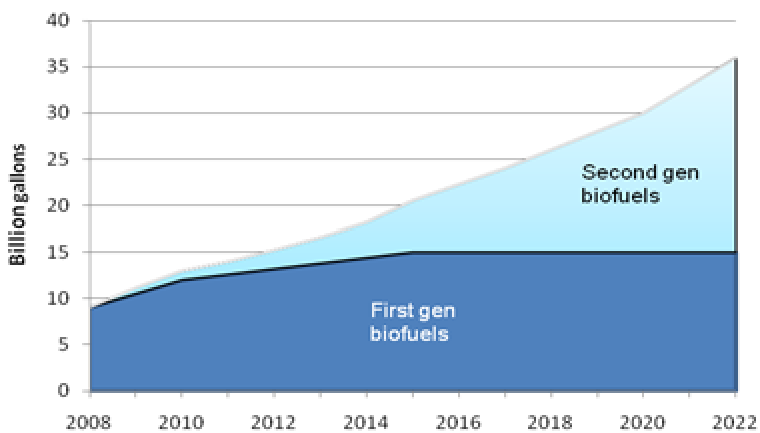


Figure 4. US biofuel mandate

to increase steadily from the current annual level of 11 to 15 billion gallons by 2015. The bill requires an increase in the consumption of second gen biofuels from near zero to 21 billion

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[24] By second generation biofuels, we mean cellulosic ethanol in the US and BTL in the EU.
[25] All data on production costs are from IEA (2009b). Second generation biofuels costs are assumed to decrease by 2% per year (IEA 2009b).
[26] 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. In fact ethanol use in the US is close to hitting the 10% “blending wall” imposed by Clean Air regulations which must be relaxed for further increases in biofuel consumption.

gallons per year in 2022. In the EU the mandate (European Commission 2009) requires a minimum share of biofuels of 10% in transportation fuel by 2020. Unlike the US, the EU has no regulation on the use of second gen fuels.[27]

The model distinguishes between direct carbon emissions from fossil fuel consumption in transportation and indirect carbon emissions induced by the conversion of new land into agriculture. 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 35%; 70% if displaced by ethanol from sugarcane. Second-generation biofuels reduce carbon by 80% compared to gasoline (Chen *et al.* 2012). Conversion of land (land class 2 or 3) for farming also releases carbon into the atmosphere.[28] Using Searchinger *et al.* (2008), we assume that the carbon released is 300 and 500 tons of CO_2 per hectare respectively for land classes 2 and 3, immediately after land conversion. Carbon released from clearing pastureland is lower than for forests. 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 in crude oil and food commodities between countries. In reality, there are significant trade barriers in agriculture, but given the level of aggregation in our model, it is difficult to model agricultural tariffs, which are mostly commodity-specific (sugar, wheat, etc.). However, we do model US and EU tariffs on biofuels. The US ethanol policy includes a per unit tariff of $0.54 per gallon and a 2.5% *ad valorem* tariff (Yacobucci and Schnepf, 2007). The EU specifies a 6.5% *ad valorem* tariff on biofuel imports (Kojima *et al*. 2007). After 2012, US trade tariffs are removed from the model (The Economist 2012).

We maximize the consumer plus producer surplus given regional demand functions for food and energy (denoted by subscript l) where energy may be supplied by gasoline, and first and second

[27] US and EU mandates introduce other minor criteria that we do not model. For instance, the EU mandate specifies that biofuel should not be produced on lands with significant biodiversity.
[28] This is a gradual process. For forests it may also depend on the final use of forest products. However, 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).

C_j), the cost of land conversion (C_s) and crude oil supply (C_{oil}). The choice variables are the consumption of crude oil (x), land of quality i allocated to each use j (L_i^j) and new land brought under cultivation (l_i^s). Endowments include the initial stock of crude oil and land of quality i. The maximization problem where we hide the time and region subscripts (respectively, t and n) can be written as[29]

$$\underset{x, L_i^j, l_i^s}{Max} \sum_{t=0}^{\infty} \left\{ \frac{1}{(1+r)^t} \left[\sum_n \left[\sum_l \int_0^q D_l^{-1} d\theta - \sum_j C_j (\sum_i k_i^j L_i^j) - C_s (\sum_i l_i^s) \right] - C_{oil}(x)x \right] \right\} . \qquad (6)$$

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 energy 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 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 (2007-2207) 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 energy 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 clean energy regulation. In the *Regulatory Scenario* (model REG), US/EU mandatory blending policies, as described earlier, are imposed. The key results are as follows: [30]

[29] The complete set of model equations is available from the authors.

[30] Our results are time sensitive but to streamline the discussion, we mostly focus on the year 2022. In the more distant future (say around 2050 and beyond), rising energy prices and a slowdown in demand growth 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.

1. Limited effect of biofuel mandates on food prices

We find that the effect of the mandates on food prices is quite modest (see REG in Table 4). With no energy mandates, food prices rise by about 15%, which is purely from changes in population and consumption patterns (see BASE). [31] With energy mandates, they go up by 32% (see REG). Thus the additional increase in 2022 from energy regulation is about 17%.[32] This is much smaller than what most other studies predict (Banse *et al.* 2008, Rosegrant *et al.* 2008, Roberts and Schlenker 2010).[33]

Table 4. World food, biofuel and gasoline prices (in 2007 Dollars)

		BASE	REG
Weighted food price ($/ton)	2007	557	564
	2022	639(15%)	746(32%)
Biofuel price ($/gallon)	2007	2.14	2.18
	2022	1.97	2.19
Crude oil price ($/barrel)	2007	105	106
	2022	121	119

Notes: Weighted food price is the average of cereal and meat prices weighted by the share of each commodity in total food consumption. The numbers in brackets represent the percentage change in prices between 2007-22. Our predictions for crude oil prices are quite close to US Department of Energy (EIA 2010, p 28) projections of $115/barrel in 2022.

Figure 5 shows the time trend in food prices under the two regimes. Note that prices increase both with and without regulation.[34] The substantial increase in food demand in MICs and LICs

[31] The model is calibrated to track real food prices in 2007. Cereal and meat prices for that year for the BASE case are $218 and $1,964 per ton. Observed prices in 2007 were $250 and $2,262, respectively (World Bank 2010). The small difference can be explained by our calibration method which is based on quantities not prices.

[32] Since the model is dynamic, the initial conditions are endogenous, hence the starting prices in 2007 are not exactly equal (Table 4).

[33] 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 20-70% in 2020 which are, in general, significantly higher than in our case. Roberts and Schlenker (2010) project that 5% of world caloric production would be used for ethanol production due to the U.S. mandate. As a result, world food prices in their model rise by 30%. These studies assume energy equivalence between gasoline and biofuels, i.e., one gallon of gasoline is equivalent to one gallon of biofuel. We account for the fact that one gallon of ethanol yields about a third less energy than gasoline, as in Chen *et al.* (2012).

[34] Although real food prices have declined in the past four decades, the potential for both acreage expansion and intensification of agriculture through improved technologies is expected to be lower than in the past (Ruttan 2002). From 1960 to 2000, crop yields have more than doubled (FAO 2003). But over the next five decades, yields are expected to increase by only about 50%, see the data presented in the Appendix (see Table A6). However, yields may also respond to higher food prices, an effect we do not capture here. Although that will imply an even smaller impact of energy mandates on food prices.

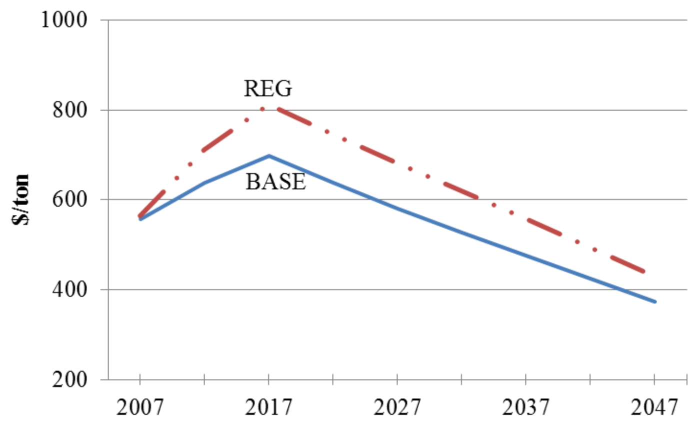


Figure 5. World weighted food prices

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

accompanied by a change in dietary preferences raises the demand for land, which drives up its opportunity cost. Without energy regulation, meat consumption in these two regions increases by 8% (for MICs) and 34% (for LICs) between 2007 and 2022, with the latter starting from a smaller base. The consumption of cereals remains stable. Since more land is used per kilogram of meat produced, the overall effect is increased pressure on land. Food prices decline ultimately towards 2050 as the effects of the mandates wear off. This is mainly because population growth levels off by that time horizon and yield increases due to technological improvements in agriculture.

2. *Demand growth causes most of the land conversion, nearly all of it in developing countries.* Table 5 shows that the really big increases in land use occur even without mandates: in the MICs, 119 million ha (=912-793) are brought under production between 2007-22 without any mandates (see BASE). This is about two thirds of all cultivated land currently in production in the US. Most of this land conversion occurs in three MIC nations – Brazil, Indonesia and Malaysia. No new land (including CRP) are brought under cultivation in the US due to higher conversion costs than in MICs. With the mandates, MICs bring another 74 (=986-912) million hectares under farming. Food production in the US/EU declines but rises in the MICs.

Fig.6 shows land use for food and fuel. Note that in the US about 60 million ha – a third of all

Table 5. Land allocation to food and energy production (in million ha)

		US		EU		MICs	
		BASE	REG	BASE	REG	BASE	REG
Land under food production	2007	166	167	138	136	789	789
	2022	166	107	137	129	905	980
Land under biofuel production	2007	12	11	5	7	4	4
	2022	12	71	6	14	7	6
Total cultivated land	2007	178	178	143	143	793	793
	2022	178	178	143	143	912	986

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

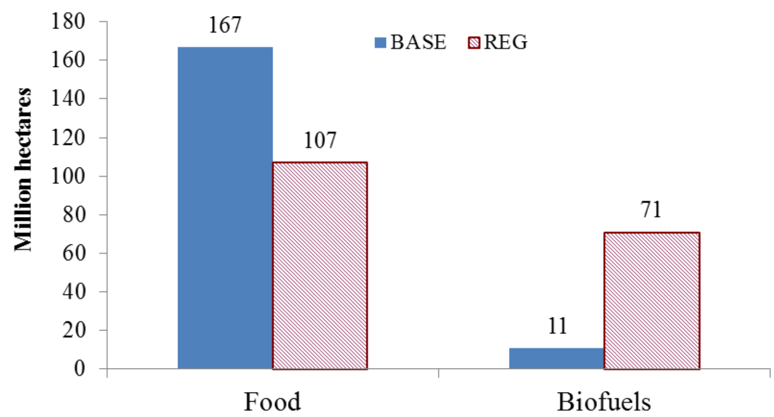


Fig. 6(a). Land allocation in US: land is shifted out from food to fuel

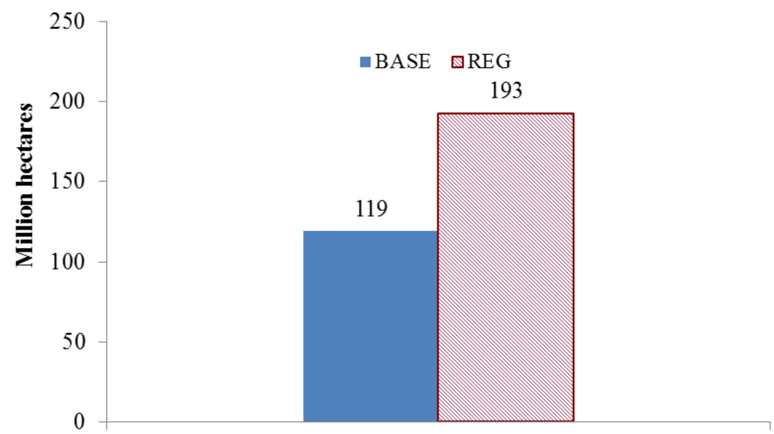


Fig. 6(b) Land conversion in MICs

Figure 6. Land allocation under Base and REG (year 2022)

Note: An area larger than current US farmland is cleared in the MICs but most of it is due to demand growth not energy policy farmland – is moved from food to fuel production. But no new land is added (Fig.6a).[35] However, the MICs convert a significant amount of land, irrespective of the energy mandates (Fig.6b).[36]

Both first and second gen biofuel production increases sharply under the US mandate (see Table 6). US food production declines by almost 27% as a result of the energy mandates (not shown). US food exports go down by more than 80% (from 75 to 13 million gallons). This is because land is shifted out of food to produce biofuels for domestic consumption. Imports of first gen biofuels increases more than double (see Fig.7).

Table 6. Biofuel production (billion gallons)

	Year	US		EU		MICs	
		BASE	**REG**	**BASE**	**REG**	**BASE**	**REG**
Total biofuels	2007	8.1	8.2	2.3	3.1	7.4	7.3
	2022	6.5	34.8	2.0	5.4	12.2	10.9
First gen biofuels	2007	8.1	8.2	2.3	3.1	7.4	7.3
	2022	7.3	13.8	0.1	1.5	12.2	10.9
Second gen biofuels	2007	0	0	0	0	0	0
	2022	0	21.0	1.9	3.9	0	0

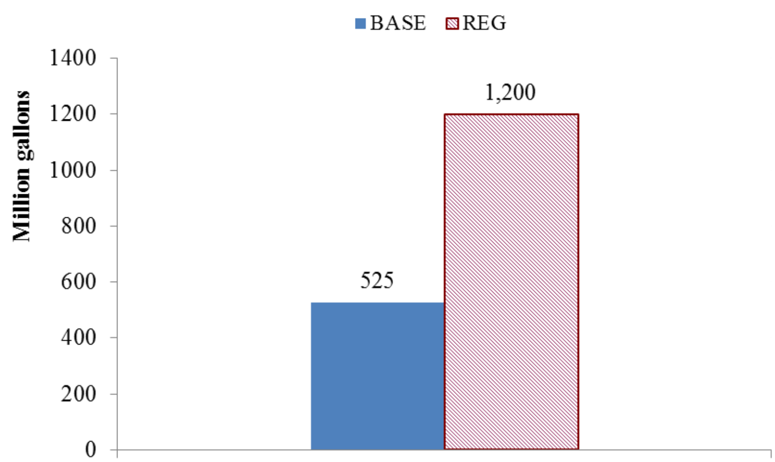


Figure 7. US biofuel imports with and without the energy mandate

[35] We allow for the conversion of CRP lands in the US, but they are unable to compete with lands in the MICs which are lower cost.
[36] We do not show the EU case because it does not change appreciably.

3. *Mandates lead to big increases in biofuel production, earlier in time*

Without regulation, biofuel consumption in the EU and US in 2022 is around 2 and 7 billion gallons, and accounts for 3% and 5.5% of fuel consumption, respectively. This is much lower than what is prescribed by the mandates. Figure 8 shows consumption with and without the mandates (BASE, REG). The mandatory blending policy requires an additional 30 billion gallons of biofuels in 2022 compared to the unregulated case, mostly in the US.[37] 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 Fig. 8(a) and 8(c), first gen fuels decline in use without a mandate for several years before becoming economical in response to rising energy prices. After 2030, the use of first gen biofuels increases even without a mandate. In the absence of regulation, the global share of oil in transport steadily decreases from 95% in 2007 to 84% in 2050. The share of biofuels increases, mainly due to an increase in the market share of first gen fuels. With no regulation, second gen biofuels are not economically viable by 2022 in the US whereas they are adopted by 2017 in the EU. This is due to lower processing costs in the EU. The production of first gen fuels, however, does show a more rapid growth after 2030, mainly because of a reduced demand for land (see Fig. 8a and 8c).

With no regulation, annual world production of biofuels is constant at about 20 billion gallons until 2020, increasing to 96 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 EU during this period. Beyond 2020 however, food demand 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.8).

4. Mandates reduce crude oil prices and cause significant leakage and direct emissions

The primary goal of biofuel regulation is to reduce direct emissions from the energy sector. US emissions fall by less than 1% and EU emissions by about 1.5% (see Table 7). The switch

[37] Global biofuels production under the baseline scenario is 18 billion gallons in 2022.

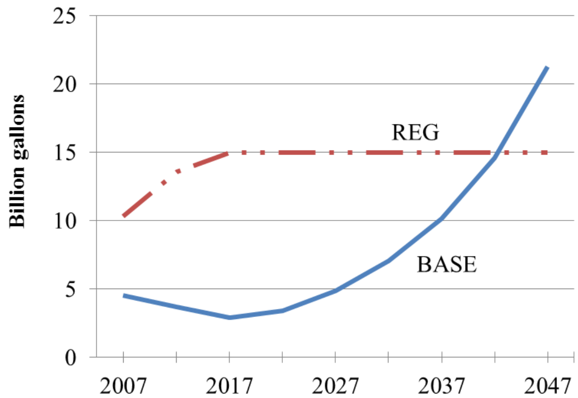


Fig. 8(a) US first gen biofuel use

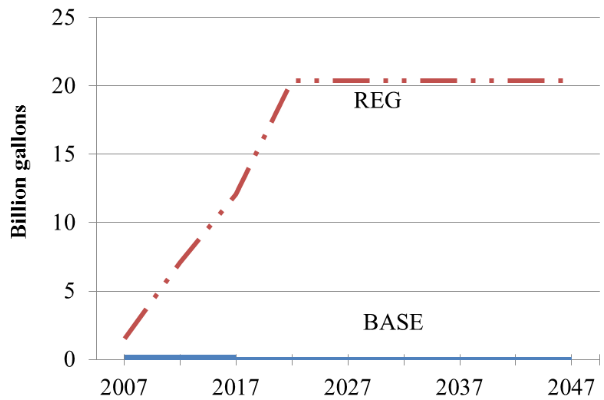


Fig. 8(b) US second gen biofuel use

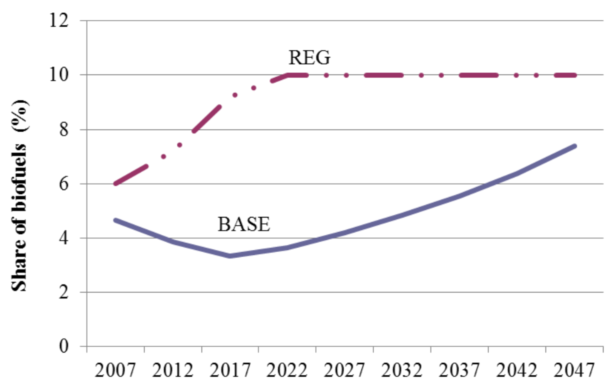


Fig. 8(c) Share of biofuels in transport in EU

Figure 8. US and EU biofuel use (with and without mandates)

Notes: 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 it.

Table 7. Direct carbon emissions in billion tons of CO_2 (REG)

	US	EU	World
2007	1.85	0.83	5.1
2022	1.95 (-0.9%)	0.81(-1.5%)	6.30 (-0.5%)

Note: Numbers in parenthesis represent the percentage change of carbon emissions compared to BASE model, which is not shown here.[38]

towards the less carbon intensive energy is partially offset by the rise in the demand for the blended fuel.

[38] Observed average carbon emissions for previous years are close to our model predictions: they equal 1.7, 0.9 and 5.8 tons of CO2 for the US, EU and World in 2007 (IEA, 2009c).

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 subsidy for biofuels lowers the world price of oil (see Table 4). In 2022 the price of oil is about 1% lower, while the price of biofuels increases by 11% with mandatory blending. The net effect is that biofuel consumption outside the US and EU goes down by 20% in 2022, most of it in MIC countries. Oil use in the rest of the world goes up by 1%.[39]

Annual direct emissions of carbon decrease by less than 1% in the rest of the world. Although the US/EU consume a significant share of global transportation energy - 53% in 2007 which declines to 28% in 2050 – the decline in emissions because of regulation is mostly offset by spatial leakage. The net effect of mandatory blending policies on global direct emissions is small (Table 7).

5. Indirect carbon emissions increase

Biofuel mandates lead to an *increase* in indirect global emissions (see Fig. 9). The mandates increase total emissions in most years relative to the unregulated (BASE) case, which to a large degree is due to land conversion. Total emissions (direct and indirect) also increase in the near term (see Figure 9).

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 biofuel mandates are imposed, the increased demand for food causes large-scale land conversion. The mandates accelerate this process. In 2022, indirect carbon emissions increase by 60% (or 4.4 billion tons of CO_2). As a result, total carbon emissions in non-regulated countries increase by the same amount, which is much larger than the annual savings from regulation in the mandated countries (0.01 billion tons). In aggregate, carbon emissions increase by about 4.4 billion tons of CO_2 due to mandatory blending (see Fig. 9).

[39] We only discuss spatial leakage while other models have studied inter-temporal leakage (e.g., see Fischer and Salant, 2011) and inter-sectoral leakage (Fullerton and Heutel, 2010).

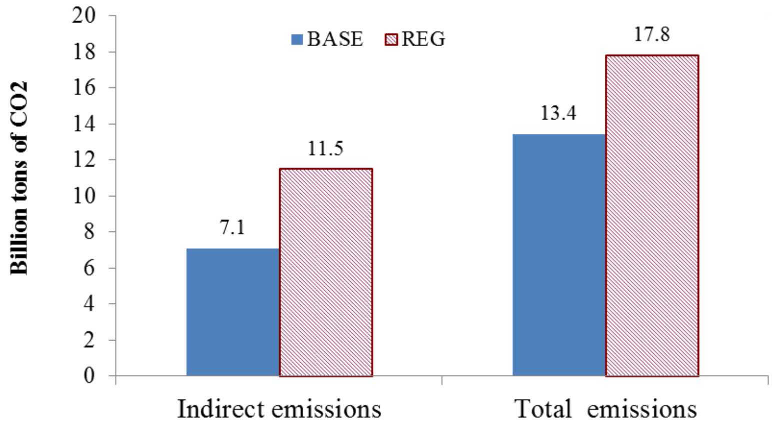


Figure 9. Biofuel mandates do not reduce carbon emissions
Total emissions are the sum of direct and indirect emissions.

6. Welfare declines in the non-regulated countries

We can compute the regional gains and losses in aggregate consumer and producer surplus as a result of the mandates (Figure 10). Medium and low income countries experience the largest loss in welfare with mandatory blending. This welfare loss (for MICs and LICs) amounts to 11 trillion dollars annually and increases rapidly until 2022 before declining. 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 surplus in the US agricultural sector, which is one of the stated goals of the mandate (de Gorter and Just 2010).

The global welfare effects of introducing mandatory blending is clearly 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, the loss in welfare of food consumers exceeds the gain to food producers (from higher food prices). Note however, 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 directly to the countries imposing mandates. On the other hand, higher emissions in other nations due to terms of trade effects will cause environmental damages that will likely reduce aggregate welfare.

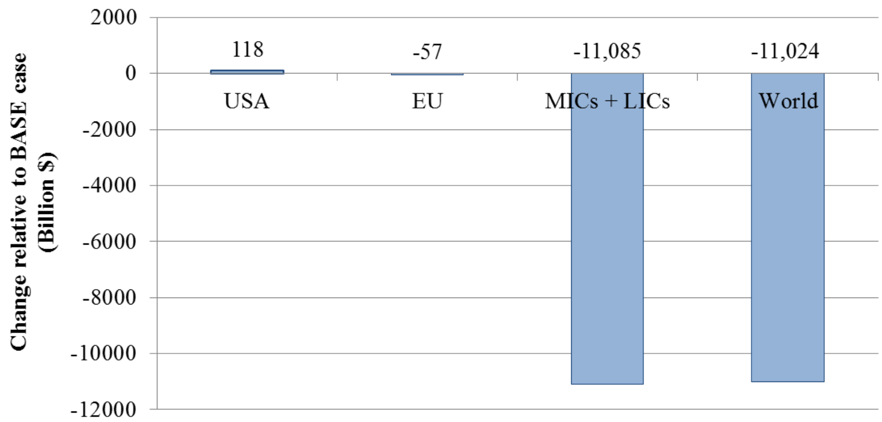
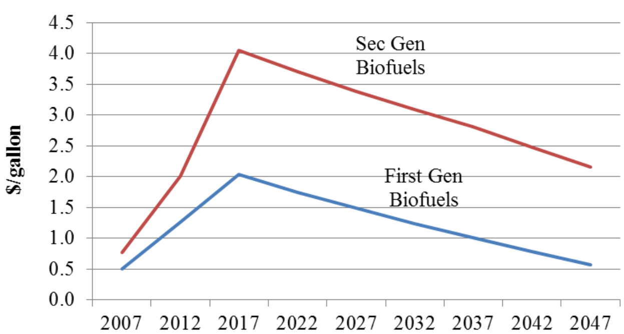


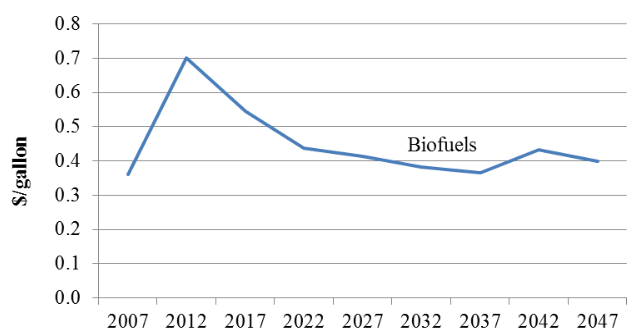
Figure 10. Welfare impacts of US and EU mandates relative to No Mandate (year 2022)
Notes: 1) Surplus is the sum of consumer and producer surplus net of subsidies; 2) Biofuel mandates impact the welfare of MICs and LICs the most.

7. 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. The subsidy is only positive when the policy constraint is binding (see Figure 11). The US subsidy is an order 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 the relatively high production cost of second gen biofuel technologies still in their infancy. Prior to 2015, the requirement on second gen biofuel consumption is relatively small and therefore less costly to impose.[40]



(a)US subsidy



(b)EU subsidy

Figure 11. Implicit biofuel subsidies: US subsidies are much larger than in EU
Since the EU mandate does not differentiate between first and sec gen use, the subsidy is given to all biofuels.

[40] These estimates are close to that of other studies such as Ando *et al.* (2010).

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, and yield parameters for crops. In this section we investigate the sensitivity of our results to changes in these parameters.[41] We also impose biofuel mandates in two of the largest energy consuming nations, China and India, to check how food prices may be impacted. Finally, we check how assumptions regarding the scarcity of crude oil and income-based dietary preferences affect our analysis.

Our strategy is to study the model with full regulation (model REG) with the following changes: (1) a 20% lower initial stock of oil (2) 50% lower conversion cost for marginal lands and (3) a 15% increase in agricultural yields because of adoption of biotechnology.[42] For (3), 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).[43] Biotechnologies are currently adopted by the world's largest agricultural producers except the EU and occupy about 10% of global crop area.[44] We assume a reasonable across-the-board increase in agricultural yields of 15% relative to the models described earlier.[45] 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 both types of biofuels.

The results are summarized in Table 8 while the impact on carbon emissions is reported in Table 9. Lower oil reserves raise energy prices, which in turn lead to higher food prices since more land is shifted out from food to energy production (Table 8). Lower oil use also reduces direct

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

[42] 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.

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

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

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

emissions (see Table 9). However, less oil use and higher oil prices induce more biofuel production, which leads to more land being brought under cultivation. The rise in land rents causes a rise in food prices which reduces food demand. This leads to lower land conversion. Overall, indirect carbon emissions decrease (see Table 9).

Table 8. Sensitivity analysis: Effect of changes in model parameters on the model with mandates (year 2022)

	REG	Lower oil reserves	Lower land conversion cost	Higher adoption of biotech
Food price (US$/ton)	746	758	683	482
Biofuel price ($/gal)	2.19	2.21	2.06	1.66
Gasoline price($/gal)	2.52	3.76	2.64	2.61
Net Exports				
US food (mil tons)	13	14	11	32
US biofuels (mil gal)	-1,200	-1,230	-1,350	-975
EU biofuels (mil gal)	- 82	- 24	- 99	-255
Aggregate acreage used (mil hectares)				
World	1,826	1,814	1,904	1,718

Note: gal=gallons. The benchmark model REG is shown in the left hand column.

Table 9. Sensitivity analysis: Impact of energy mandates on carbon emissions (year 2022, billion tons of CO_2)

	REG	Lower oil reserves	Lower land conversion cost	Higher adoption of biotech
Direct emissions				
US	1.95	1.57	1.96	1.97
EU	0.81	0.63	0.82	0.87
World	6.30	5.15	6.31	6.44
Indirect Emissions	11.50	10.90	16.29	5.12
Total Emissions	17.80	16.05	22.60	11.56

A reduction in the conversion cost of new land leads to more land being converted for agricultural production in the MICs. First gen biofuels from the MICs become competitive in the US and EU markets. 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 8.

Exogenous improvements in biotechnology have a major impact, reducing food prices by about 35% compared to the REG model. The demand for land declines. Because of increased food production, US food exports more than double. Less land is required to produce the regulated level of biofuels. Indirect emissions decline significantly in this case. In summary, lower conversion costs increase emissions and adoption of biotechnology reduces them.

Chinese and Indian Mandates, Scarcity of Oil and Dietary Preferences

It may be useful to comment on how the BASE model (the one without regulation) itself responds to 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 phave similar qualitative effects on the model without regulation, but less in magnitude.[46]

Mandates in China and India

We also consider the case of China and India, the two most populous countries, imposing domestic biofuel mandates.[47] In this scenario, we assume that these two nations impose a mandate requiring the share of biofuels in transportation to rise linearly to at least 10% by 2022. Imposing these mandates increases biofuel consumption in the MICs from 10 billion gallons under REG to 24 billion. But terms of trade effects are smaller now because these two large 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 land under cultivation (another 10 million hectares). As a result, indirect emissions rise to 13 million tons. But world food prices still rise by only 1% beyond the impacts from US and EU mandates.

Constant Oil Prices

We 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 $105/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 to 2 billion gallons. Second gen fuels are never adopted. Because of the

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

[47] 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 2009a). Currently, biofuels supply less than 1% of transportation fuel in these countries. Both countries are actively promoting biofuels – India has an ambitious target of 20% of the transport fuel mix (Swarup 2011, Eisenstraut, 2010).

mandate, indirect carbon emissions increase by around 60% compared to the BASE model (both with cheap oil). About 80 million hectares of new land is brought under cultivation because of energy regulation. This is 10 million hectares more than when oil prices rise competitively. 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 30% - recall that food prices increased by about 17% when oil prices were allowed to increase competitively. The mandates induce higher land conversion to energy and less to food. The subsidy required to meet the US targets is almost 1.5 times larger than under the REG model.

Stationary Dietary Preferences

Finally, 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 cereal products in the MICs and LICs at levels similar to US and EU. This means that people in developing countries are assumed to have the same elasticities towards meat and cereals as in developed nations, but at their lower consumption levels. As a result, their meat consumption increases much less rapidly with income than before. To compare, note that per capita meat consumption goes up by 8% in MICs and by 34% in LICs from 2007 to 2022 when preferences change endogenously as in the previous runs. When preferences are kept fixed, meat consumption is almost constant. Food prices *decrease* over time by about 9% in the same period, compared to a 15% increase in the BASE model (see Table 4). Since land rents fall, more biofuels are produced – for instance in the US, five billion gallons more than in the BASE case, reaching 11 billion gallons in 2022. Food prices are higher under regulation by only 7% compared to no regulation, when preferences are assumed stationary. To meet their biofuel targets, US and EU import less biofuels from MIC countries. MIC nations convert less land to farming.[48]

[48] To see what would happen to food prices if no second gen mandate was specified in the US, we run a scenario, 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. We find that second gen fuels are too costly and will not be produced without a mandate. With the mandate, 21 billion gallons are produced. Without mandates on second generation biofuels, food prices in 2022 go up by 40% from the base year 2007: in that case land-using first gen fuels supply most of the biofuel. One may expect more food to be produced when second gen fuels which are less land-intensive, are mandated. However, land rents decline, and US food exports double under second gen fuels, albeit from a low base. In summary, the mandate on second gen biofuels helps reduce imports, but does not release land for more food production in US since second generation biofuels are domestically produced.

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 findings have important implications for analysis of biofuel mandates, which tend to predict large price increases (Rosegrant *et al.* 2008; New York Times, 2008). We find that modeling land supply leads to price impacts of energy mandates that are generally lower than in most studies. Secondly, demand side effects that include expected changes in dietary preferences account for half of these price effects, another half coming from clean energy policies. Third, even mandates adopted by the big developing countries China and India, do not produce huge price effects, although more land is converted into farming.

Our results suggest that dietary changes towards increased meat and dairy consumption may have a big role in the projected growth of food prices. For example, if diets were kept constant, food prices would actually fall over time (9%) without energy regulation, and with biofuel mandates, they will rise by only 7% in year 2022.

The upshot of these results is that a lot of the effect of energy policies that divert corn from food to fuel can be neutralized by land conversion. The effect on prices may be muted, but indirect carbon emissions will be significant, leading to no net reduction in greenhouse gas emissions, one of the primary goals of biofuel policy. In fact, aggregate emissions are almost invariant with respect to assumptions about the crude oil market. If crude oil supplies are assumed to be scarce, more biofuels are used, leading to low direct emissions but high indirect emissions from land conversion. If crude oil is assumed abundant, less biofuel is used, causing high direct emissions and low indirect emissions. Thus biofuel mandates may not reduce aggregate emissions, unless new technologies such as genetically modified crops are widely used.

Mandates also cause spatial leakage, i.e., global oil prices fall due to reduced demand in the US and EU, leading to increased crude oil consumption by other nations that do not have energy mandates. Global emissions actually *increase*. Welfare declines in the developing countries.[49]

These results arise from a modeling strategy that allows for endogenous land allocation and the dynamic effects of exogenous income growth on preferences for meat and dairy products. Our results suggest that if supply-side effects are not taken into account, economic models may overestimate the role of energy mandates in determining food prices. In our model, food price increases result in more land conversion. Models that have found large impacts of biofuel policies often do not take into account this supply response to price. Moreover, it is important to understand that demand side effects play as much of a role in raising food prices as energy mandates.

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 choosing 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. An international climate treaty 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.

[49] 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.

Even if food price increases occur, whether from demand effects of energy policies, they may lead to increased efficiency in agriculture, such as irrigation, better seeds and other inputs. Our model assumes certain rates of technological change, but they are not linked to prices. This may further strengthen the supply response outlined in the paper. Another major issue not addressed directly in the paper is how food price increases may affect the poor. The price increases, even if modest may have major impacts in terms of increasing poverty and malnutrition in the low and medium income economies, which is home to large numbers of the very poor. This issue needs to be addressed further in future research, with data on the price-induced behavior of consumers at various income levels.

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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 and the region index when necessary. The model is a discrete-time, non-linear dynamic programming problem and was solved using GAMS software. It runs for the period 2007-2207. Because of the leveling off of population and elasticity parameters, the solution does not change much after year 2100. To reduce computational time, the model is programmed in time steps of 5 years. The reference year for model calibration is thus 2007.

Demand

Demand for cereals and meat are assumed to be independent as in other studies (Rosegrant *et al*. (2001), Hertel *et al*. (2010)). Cereals include all grains, starches, sugar and sweeteners and oil crops.[50] Meat includes all meat products and dairy such as milk and butter. Demand functions are given by equation (1). Demand for food products (cereal, meat) and fuel is in billion tons and in billion Vehicle Miles Traveled (VMT), respectively. The constant demand parameter A_i is product and region-specific. It is computed using the regional per capita income, population, demand for each product and the price of the product in the base year (2007).[51]

All the data needed to calculate the constant demand parameters is shown in Table A1. Initial per capita income is taken from the World Bank database (World Bank 2010) and population from United Nations Population Division (2010). Per capita demand for cereals and meat are taken from FAOSTAT. Per capita demand for MICs and HICs is computed by aggregating across countries, weighted by the share of country population in the region. Initial per capita demand for transportation fuel is obtained by aggregating diesel and gasoline consumption for each region. For the US, EU, MICs and LICs, this data is readily available from WRI (2010). However, for Other HICs, they are aggregated from individual country data. Since cereals and meat are internationally traded, their world prices are reported in Table A1. These data are weighted averages for the base year. But transportation fuels are consumed and produced domestically so their price is region-specific.

[50] These categories are taken from the FAO (see FAOSTAT). Grains account for about half of all crop land followed by oil crops (20%) and starches (5%).
[51] For example, for cereal demand in the US in year 2007, US per capita income is $46,405, population 301 million, per capita demand for cereals is 0.27 tons and the initial price and income demand elasticities are -0.1 and 0.01, respectively. The price for cereals is $250/ton. From equation (1), the constant parameter A_i is calculated as 0.005. Other demand parameters are computed similarly.

Table A1. Demand parameters in base year (2007)

		US	EU	Others HICs	MICs	LICs
Per capita income	($)	46,405	30,741	36,240	5,708	1,060
Population	(millions)	301	496	303	4,755	765
Per capita demand	Cereals (tons/cap/yr)	0.27	0.14	0.22	0.20	0.20
	Meat (tons/cap/yr)	0.40	0.21	0.20	0.07	0.030
	Fuel (VMT/cap/yr)	10,730	3,429	3,219	644	214
Prices	Cereals ($/ton)	250	250	250	250	250
	Meat ($/ton)	2,260	2,260	2,260	2,260	2,260
	Fuel ($/VMT)	0.09	1.12	1.11	1.11	1.11
Income elasticity	Cereals	+0.01	+0.02	+0.03	+0.60	+0.65
	Meat	+0.89	+0.80	+0.85	+0.90	+1.10
	Fuel	+0.90	+0.90	+0.90	+0.99	+1.30
Price elasticity	Cereals	-0.10	-0.12	-0.13	-0.37	-0.40
	Meat	-0.68	-0.65	-0.65	-0.80	-0.80
	Fuel	-0.60	-0.65	-0.65	-0.50	-0.50
Constant	Cereals	0.421	0.379	0.329	0.004	0.008
	Meat	0.005	0.007	0.044	0.00008	0.00005
	Fuel	0.531	0.202	0.155	0.125	0.038

Notes: 1) Units: per capita income is in 2007 dollars; population in millions; per capita demand for cereals and meat in tons/cap/year; per capita demand for fuel in VMT/cap/year. 2) World cereal and meat prices are weighted average prices computed from World Bank (2011) data; US and EU fuel prices are from Davis *et al.* (2011); Other HICs, MICs and HICs fuel prices are world weighted averages from Chakravorty *et al.* (2011).

Price and income elasticities for cereals, meat and fuel products are given by Hertel *et al.* (2008). Regional demand elasticities for the EU, Other HICs, MICs and LICs are aggregated up from individual country demands. To illustrate our procedure, suppose we need to compute the cereal demand for a region with two countries. We use the per capita demand for cereals, the world cereal price, population and price and income elasticities for each country to compute the country demand curve for cereals, which is aggregated up to get the regional demand. Thus, the regional demand elasticity for cereals is the weighted average elasticity where the weight is the share of country consumption in regional consumption. These elasticities are reported in Table A1.

Demand for food products and blending fuel depend upon the growth in per capita income and population. Per capita income data is taken from Nordhaus and Boyer (2000); world population figures are from the UN Population Division (2010). Table A2 shows the level of per capita income and population by region in 2007 and 2050. Since our model is calibrated in time steps of five years, annual growth rates of population and per capita income are constant within each five year period.

Table A2. Population and per capita income in 2007 and 2050

	Population (millions)		**Per capita income** ($)	
	2007	2050	2007	2050
US	301	337	46,405	63,765
EU	496	554	30,741	42,241
Other HICs	303	339	36,240	49,798
MICs	4,755	6,661	5,708	16,451
LICs	765	1,791	1,061	3,743
World	6,620	9,682	--	--

Income is reported in 2007 dollars.

The AIDADS system (An Implicit Direct Additive Demand System) is the most flexible demand function that takes into account the change in dietary preferences with a rise in the level of income. However, there are no studies that provide the demand parameters for cereal and meat products by region.[52] We thus make some adjustments in the calibration of demand given by (1). First, the change in food preferences is driven by the rise in per capita income. As a result, we consider the per capita income and not the global income (per capita income times population) as in other studies (e.g., Rosegrant *et al*,.2008). Second, we introduce flexibility in food consumption by letting income elasticities vary exogenously with the level of income. These country-level elasticities are taken from Hertel *et al.* (2008). For each country, we match the per capita income from the World Bank (2010) database to the elasticity for cereals and meat. Table A3 shows the resulting income-based elasticities (see numbers in bold). Per capita income in the LICs in year 2050 is assumed to converge to the per capita income for MICs in year 2007. As a result, LIC income elasticities in year 2050 are similar to MIC income elasticities in 2007.

Energy Demand and Supply

Primary energy is provided by three resources - gasoline, first gen and second gen biofuels indexed by $\{g, bf, bs\}$. World is endowed with an initial stock of oil $\bar{X}$. Data on stocks is taken from the World Energy Council (WEC 2010) and reported in Table A4. Oil is also an input in sectors other than transportation, such as in chemicals and heating. Studies (IEA 2011) suggest that around 60% of oil

[52] Cranfield *et al.* (2002) estimate consumer demand patterns for different groups of products (food, beverages and tobacco, gross rent and fuel, household furnishings and operations and other expenditure) using the AIDADS demand system. Unfortunately his classification is not useful for our analysis of preferences over cereals and meat.

consumption occurs in transportation. We thus consider 60% of total oil reserves as the initial stock available for transport.[53]

Table A3. Changes in income elasticities for food products conditional on per capita income

Region	Year	Per capita income ($)	Cereals	Meat
US	2007	46,405	+ 0.01	+ 0.89
	2050	63,765	+ 0.01	+ 0.89
EU	2007	30,741	+ 0.02	+ 0.80
	2050	42,241	+ 0.02	+ 0.80
Other HICs	2007	36,240	+ 0.03	+ 0.85
	2050	49,798	+ 0.03	+ 0.85
MICs	**2007**	**5,708**	**+ 0.60**	**+ 1.01**
	2050	16,451	+ 0.55	+ 0.90
LICs	2007	1,061	+ 0.65	+ 1.30
	2050	**4,000**	**+ 0.59**	**+ 1.03**

Table A4. Extraction cost parameters for oil

Available stock (trillion gallons)	**Extraction cost parameters** ($/gallon)		
	ϕ_1	ϕ_2	ϕ_3
153	0.47	100	5

Let $x(t)$ be the amount of oil used globally in period *t* and $X(t)$ the oil stock in period *t*. Then, the change in the stock is given by $X(t+1) - X(t) = -x(t)$. Differences in extraction costs are captured by making these costs depend on the cumulative quantity of oil extracted. Unit extraction costs are given by (5) in which 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 or diesel for transportation use. We consider a representative fuel in each region - gasoline for the US and diesel in the EU. However, in the paper we use the term gasoline for all petroleum products. One gallon of oil produces 0.47 gallons of gasoline or 0.25 gallons of diesel.[54]

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

[54] In the paper, we discuss the sensitivity of our results to change in oil reserve estimates. Conversion rates between oil and products may vary based on crude oil quality and refinery characteristics, but we abstract from regional differences in crude oil and product quality.

Transportation energy is supplied by gasoline and biofuels in a convex linear combination given by (3), where λ is a constant, μ_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 parameter λ is region-specific. It is computed from equation (4) using regional demands for fuel (q_e), gasoline (q_g), and biofuels (q_{bf}), the observed share of gasoline (μ_g), and the elasticity of substitution (ρ). Table A5 presents the data used in calibration for the base year (2007).

Table A5. Energy supply parameters by region

	US	EU	Others HICs	MICs	LICs
Blending fuel use q_e (bln miles)	3,230	1,701	975	3,063	164
Gasoline use q_g (bln gal)	134	62	26	130	8
Gasoline use q_g (MJ)	16,080	8,494	3,120	15,600	936
Biofuel use q_{bf} (bln gal)	7	3	2	5	0.5
Biofuel use q_{bf} (MJ)	560	360	80	400	40
Share of gasoline in fuel θ_g	0.90	0.96	0.97	0.96	0.98
Elasticity of substitution ρ	2	1.65	2	1.85	1.85
Constant λ	1.057	1.196	1.090	1.065	0.774

Notes: gal=gallons, MJ = megajoules. *Sources:* 1) Transportation fuel consumption (WRI 2010); 2) Biofuel consumption (EIA 2010, 2011) is the sum of ethanol and biodiesel use. 3) Share of gasoline and biofuels in transportation is computed from observed data. The elasticity of substitution is taken from Hertel *et al.* (2010).

Aggregate consumption of transportation fuel (per capita demand time population) is in megajoules (MJ) which is then converted into Vehicle Miles Traveled (VMT).[55] One MJ of transportation energy equals 0.177 VMT for a gasoline-powered car and 0.155 miles for a diesel car (Chen *et al.* 2012).[56] Country-level gasoline consumption data is available from the Energy Information Administration (2011). They can be aggregated for to get regional consumption. To calculate biofuel consumption, we only consider first-generation biofuels since the actual consumption of second generation biofuels is negligible. Gasoline and biofuel consumption are given in volume units. Their energy content is reported in Table A6.

[55] Transportation fuel is domestically refined and not traded, but crude oil is a traded commodity.
[56] For simplicity we assume that only conventional passenger cars are used. To meet the US target, the share of biofuels in total transportation fuel should exceed 15%; as a result, some conventional cars should be replaced by more efficient Flex Fuel Vehicles (FFVs): for these, one MJ of transportation energy equals 0.216 VMT for a gasoline-powered car and 0.189 for diesel. By not considering the choice of vehicles in our model (as in Bento *et al.*, 2009 and Chen *et al.*, 2012) we may be overestimating the demand for fuel, hence our estimate of the impact on food prices may be biased upward.

Table A6. Energy content of fuels

	Gasoline	Ethanol	Cellulosic Ethanol	Diesel	Biodiesel	BTL Diesel
Energy content (MJ/gal)	120	80	80	137	120	135

Source: Chen *et al.* (2012)

Land Quality

The USDA database divides world land area into nine categories based on climate and soil properties and suitability for agricultural production (Eswaran *et al.* 2003) labeled I to IX (see Figure 3), 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) into three classes. Category I and II are grouped as land class 1, III and IV as class 2, and V and VI as class 3. We thus have three land classes indexed by $i = \{1,2,3\}$. 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 the lowest quality. Initial acreage available for each land class can be divided into cultivated land ($\overline{L}_i$) and available land (L_i^s). Then, we have $L_i^s(t+1) - L_i^s(t) = -l_i^s(t)$. At time θ, the land available for agricultural production is given by $\overline{L_i} + \sum_{t=0}^{\theta} l_i^s(t)$. The land allocation constraint is given by $\overline{L_i} + \sum_{t=0}^{\theta} l_i^s(t) - \sum_j L_i^j \geq 0$, 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.[57]

Forests under plantations or under legislative protection are not included in the model. The parameters for land conversion costs (see equation 2) are reported in Table A7. They are assumed to be the same across land classes but varying by region.[58]

Table A7. Cost Parameters for Land Conversion

	ϕ_1	ϕ_2
USA	234	235
MICs	38	42
LICs	83	126

Source: Gouel and Hertel 2006

Cultivated land may be allocated either to food crops or to first or second gen biofuels. For each use, we need to obtain yield data by land class. Each land class covers a group of countries and FAOSTAT gives

[57] Since our model is coded in time steps of five years and harvests are annual, we multiply the production function $k_i^j L_i^j$ by the number of time periods (5 years).

[58] We examine the sensitivity of the results to a 50% reduction in the land conversion cost, i.e., we reduce the value of the parameters by a factor of 2.

crop yields for each country. USDA has data on the volume of land by land class in each region. We thus match USDA and FAOSTAT data by country to get the yield per unit land in each region and the corresponding volume of land available. To calculate yields for food crops, we use yield data for each crop, namely cereals, starches, sugar and sweeteners and oil crops weighted by their share of production for each land class and region. These values are presented in Table A8.

Table A8. Yields by Land Class and Region

	Land class	US	EU	Other HICs	MICs	LICs
Initial crop yields (tons/ha)	1	4.0	4.0	3.5	3.5	2.0
	2	2.5	2.0	2.2	1.7	1.0
	3	1.7	1.5	1.7	1.0	0.5
Annual growth in crop 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: Average annual growth rates are adapted from Rosegrant *et al.* (2001).

Biofuels are produced from specific crops in each region (see Table 3), e.g., sugar cane in MICs and rapeseed in EU. For each land class we determine the crop-specific biofuel yield by using a conversion coefficient (Rajagopal and Zilberman 2007). These yields are reported in Table A9. Information on second gen biofuels is scarce. Their yields are assumed to be uniform across land class. This assumption is reasonable because second-gen biofuels are less demanding in terms of land quality than first gen biofuels (Khanna 2008). Recall that 2,000 gallons per hectare are produced from ligno-cellulosic whereas 1,000 gallons per hectare are produced from Biomass-to-liquids (BTL).

Table A9. Yields for first generation biofuels

		US	EU	Other HICs	MICs	LICs
	Crop type	Corn	Rapeseed	Corn	Sugar-cane	Cassava
Energy yield per land class (gallons/ha)	1	820	500	717	1,800	400
	2	512	250	451	874	200
	3	350	18	349	514	100

Production costs are taken from the GTAP database 5 for the year 1997, the latest year available, aggregated suitably for the different regions (Other HICs, MICs and LICs). The GTAP database divides the total costs into intermediate inputs, skilled and unskilled labor, capital, land and taxes. Using equation (3), we can recover the cost parameters by using total production costs and volume. They are reported in Table A10.

Food crops can be used directly for food (i.e., cereals) or animal feed that is transformed into meat. We assume that one ton of primary crop produces 0.85 tons of the final food product (FAOSTAT), assumed uniform across regions.[59] The quantity of meat produced from one ton of crop 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.

Table A10. 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
Initial unit production cost ($/ton)	110	120	120	140	150

Carbon emissions

The model tracks direct as well as indirect carbon emissions. Emissions from gasoline are constant across regions, but emissions from first and second gen biofuels are region-specific and depend upon 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 in the model are shown in Table A11. Finally, indirect carbon emissions are released by conversion of new land, namely forests and grasslands into food or energy crops. This sequestered carbon is released back into the atmosphere. Let z_i^s be the amount of carbon sequestered per unit of land of class *i* brought into production. Then, aggregate indirect carbon emissions by region 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 while grasslands emit 75 tons (Searchinger *et al.* 2008).[60] For each land class and region, we weight the acreage converted by the share of new land 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 (=0.55*75+0.45*604) tons of

[59] Other models make similar assumptions (e.g., Rosegrant *et al.* 2001).

[60] 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 Searchinger *et al*. (2008) available at: http://www.sciencemag.org/content/suppl/2008/02/06/1151861.DC1/Searchinger.SOM.pdf.

CO_2 per hectare.[61] Land class 3 has 84% forest, so emissions are 519 tons CO_2/ha. The corresponding figures for LICs are 323 tons (land class 2) and 530 tons (class 3). In the LICs, for land class 2, 47% is under forests and 53% under pasture; for land class 3, 86% is under forest and 14% under pasture.

Table A11. Carbon emissions from gasoline and representative biofuels

	Carbon emissions (tons of CO_2/gallon)	**Emission reductions relative to gasoline**
Gasoline	0.0032	**--**
Corn ethanol	0.0020	35%
Cellulosic ethanol	0.0005	83%
Diesel	0.0031	--
Rapeseed biodiesel	0.0015	50%
BTL diesel	0.0005	83%
Sugarcane ethanol	0.0008	72%
Cassava ethanol	0.0008	72%

Source: Gasoline, corn ethanol and sugar-cane ethanol figures are taken from Ando *et al.* (2010) and Chen *et al.* (2012).

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