# Biofuels for all? Understanding the Global Impacts of Multinational Mandates

by

Thomas W. Hertel*, Wallace E. Tyner and Dileep K. Birur

Center for Global Trade Analysis
Department of Agricultural Economics
Purdue University, West Lafayette, IN 47907, USA.

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*Corresponding author: T.W. Hertel. Email: hertel@purdue.edu

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## Abstract

The recent rise in world oil prices, coupled with heightened interest in the abatement of greenhouse gas emissions, has led to a sharp increase in domestic biofuels production around the world. Previous authors have devoted considerable attention to the impacts of these policies on a country-by-country basis. However, there are also strong interactions among these programs, as they compete in world markets for feedstocks and ultimately for a limited supply of global land. In this paper, we evaluate the interplay between two of the largest biofuels programs, namely the renewable fuel mandates in the US and the EU. We examine how the presence of each of these programs influences the other, and also how their combined impact influences global markets and land use around the world.

We begin with an analysis of the origins of the recent bio-fuel boom, using the historical period from 2001-2006 for purposes of model validation. This was a period of rapidly rising oil prices, increased subsidies in the EU, and, in the US, there was a ban on the major competitor to ethanol for gasoline additives. Our analysis of this historical period permits us to evaluate the relative contribution of each of these factors to the global biofuel boom. We also use this historical simulation to establish a 2006 benchmark biofuel economy from which we conduct our analysis of future mandates.

Our prospective analysis of the impacts of the biofuels boom on commodity markets focuses on the 2006-2015 time period, during which existing investments and new mandates in the US and EU are expected to substantially increase the share of agricultural products (e.g., corn in the US, oilseeds in the EU, and sugar in Brazil) utilized by the biofuels sector. In the US, this share could more than double from 2006 levels, while the share of oilseeds going to biodiesel in the EU could triple.

Having established the baseline 2006-2015 scenario, we proceed to explore the interactions between the US and EU policies. This involves decomposing the contributions of each set of regional policies to the global changes in output and land use. The most dramatic interaction between the two sets of policies is for oilseed production in the US, where the sign of the output change is reversed in the presence of EU mandates (rising rather than falling). In other sectors, the interaction is more modest. However, when it comes to the impacts of these combined mandates on third economies, the two policies combine to have a much greater impact than just the US or just the EU policies alone.

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## 1. Introduction

The recent rise in world oil prices, coupled with heightened interest in the abatement of greenhouse gas emissions and concerns about energy security, has led to a sharp increase in biofuels production and related policy measures. Indeed, analysis of biofuels has become a growth industry in its own right! Biofuel mandates in the US and the EU have commanded the most interest. Studies on the impacts of growth in the US biofuel industry generally have concluded that large programs such as those included in the "Energy Independence and Security Act of 2007" would lead to food price increases, use of a large fraction of US corn for ethanol, and bring about a consequent decline of corn use for domestic feed and industrial uses and exports (Tokgoz, S. *et al*, 2007; Tyner and Taheripour, 2007). While studies of the EU have concluded that the EU biofuel directive's 2010 target will not likely be reached. However, in attempting to do so, there will be an enormous increase in demand for biofuel feedstocks and a substantially larger agricultural trade deficit (Banse *et al*. 2007; Tokgoz *et al*. 2007). Other studies (McCarl *et al*. 2005; Fargione *et al*. 2008; Searchinger *et al*. 2008) have examined the Greenhouse Gas Emissions (GHG) impacts of biofuels programs, and there is currently a hot debate on that topic.

Most of these studies have examined the impacts of biofuels policies for one region; e.g., US or EU. However, there are also strong interactions among these programs, as biofuels compete in world markets for feedstocks and ultimately for a limited supply of global

land. This is particularly important in the case of the US and EU, since both regions are big players in international agricultural trade. The biofuel mandates in these two regions are anticipated to have a large impact on imports as well as exports, so it is important to consider how the two sets of policies are likely to interact through global markets. To what extent will the EU mandates raise the cost of attaining US renewable energy goals, and vice versa? Finally, what impact will these combined policies have on third countries – particularly in the developing world? How will land-use change, export revenues, and food costs be affected in the rest of the world? In this paper we explore these issues for both EU and US policies with an emphasis on production and land-use changes.

After a brief review of biofuel policies in the US and EU, we discuss our methodology for analyzing their interaction in global markets. This involves a specially designed global trade model which places at its center the emerging biofuels sectors, carefully developing their links to the energy and agriculture economies. Since biofuel feedstocks compete for land with other agriculture and forestry uses, we also pay special attention to global land use. Indeed, the indirect land use impacts of biofuel policies are at the heart of the current debate over their potential contributions to Greenhouse Gas (GHG) mitigation (Fargione *et al*. 2008, Searchinger *et al*. 2008).

Having laid out the basic modeling framework, we begin by validating it over the historical period: 2001-2006. This was a period of extremely rapid growth in biofuels production in both the EU and the US, and it offers an interesting "proving ground" for the model. We also use this historical simulation to estimate the critical elasticity of substitution between biofuels and petroleum products. Following this *ex post* analysis, we move on to an *ex ante* analysis of future biofuel mandates in these two regions. Our focus is particularly on

the interplay between the two sets of policies, their impacts on one another, and their impacts on third countries. The paper concludes with a summary of the major findings as well as a discussion of the limitations of our current work and directions for future research in this area.

## 2. Policy Background

*US Programs:* Interest in biofuels initially came about in the late 1970s as OPEC reduced crude oil supply on the world market and fuel prices increased substantially. Both the US and Brazil launched ethanol programs during this period with ethanol subsidies. Until 2006, Brazil was the global leader in ethanol production – in large part due to the relatively greater efficiency of sugar cane-based ethanol conversion. However, as a result of government policies and higher oil prices, ethanol production in the US has recently surged, and it now exceeds that in Brazil. Subsidization of ethanol in the US began with the Energy Policy Act of 1978. At the time, the main arguments that were used to justify the subsidy were enhanced farm income and, to a lesser extent, energy security. In 1990, the Clean Air Act was passed, which required vendors of gasoline to have a minimum oxygen percentage in their product. Adding oxygen enables the fuel to burn cleaner, so a cleaner environment became another important justification for ethanol subsidies. By requiring the oil industry to meet an oxygen percentage standard instead of a direct clean air standard, the policy favored additives like ethanol that contain a high percentage of oxygen by weight. However, methyl tertiary butyl ether (MTBE), a competitor for oxygenation, was generally cheaper than ethanol, so it continued to be the favored way of meeting the oxygen requirements throughout the 1990s.

The growth in MTBE use was short-lived, as it began to crop up in water supplies in

several regions in the country. Since MTBE is highly toxic, it was gradually banned on a state-by-state basis. That left ethanol as the major source of added oxygen, and this contributed to ethanol selling at a significant premium, relative to gasoline. Indeed, ethanol prices peaked at $3.58/gallon in June, 2006, shortly after the MTBE ban was complete. Much, but not all, of this huge price increase was due to this change in rules and legal liability. Since that time, the price of ethanol has been falling, as the demand for ethanol as an additive has become satiated, and ethanol is increasingly being priced for its energy content – which is only about 70% of that provided by an equivalent volume of gasoline.

During the 20 years between 1983 and 2003 the US ethanol subsidy varied between 40 and 60 cents per gallon. Today it is 51 cents per gallon on a volumetric basis and equivalent to 75 cents per gallon of gasoline on an energy basis. This subsidy, together with oil in the $10 to $30 range, was sufficient to permit steady growth in ethanol production from about 430 million gallons (1625 mil. l.) in 1984 to about 3.4 billion gallons (12.85 bil.l.) in 2004. In other words, production grew by about 149 million gallons (563 mil. l.) per year over this period. In 2004, the crude oil price began its steep climb to over $100/bbl. today. This rapid increase in the crude price, together with an exogenously fixed ethanol subsidy, led to a tremendous boom in the construction of ethanol plants. Ethanol production in 2007 was about 7 billion gallons, likely surpassing 13 billion gallons in 2008. It has been the combination of high oil prices, a shift in the demand for ethanol as a fuel additive, and a subsidy that was keyed to $20 oil that has led to this boom in US ethanol production.

*EU Policies:* The European Union Biofuels Directive requires that member states should realize 10% share of biofuels on the liquid fuels market by 2020 (European Commission (2007). To compare and contrast the EU biofuel directive with the US mandate,

we follow a conservative estimate for EU-27 made by the European Commission (2007), which is about 6.25% share of biofuels in the liquids for transport in 2015. This goal is projected to be largely filled by biodiesel. Germany is the largest producer (798 million gallons constituting about 54% of EU-27's total biodiesel production in 2006) followed by France (15%), Italy (9%), United Kingdom (4%), Austria (2.5%), Poland (2.4%), Czech Republic (2.2%), Spain (2%), and others (9%) (European Biodiesel Board, 2007). The spectacular growth in the German market is the result of very favorable legislation granting a total tax exemption for biofuels. This exemption has been particularly important in the EU, where fuel taxes are extremely high. However, it has recently been rescinded in Germany due to its high budgetary cost, as well as the suspicion that it might be having adverse impacts on land use in the rest of the world. The EU is currently re-evaluating its ambitious biofuels mandates, and a key factor in the deliberations is the global impact – particularly the impact on land use in the tropics. The remainder of this paper seeks to investigate this link between the energy economy, increased biofuel production, agricultural trade and global land use.

## 3. Methodology

*Global Model:* Given our goal of evaluating the individual and combined impacts of EU and US biofuel policies on one another, as well as the rest of the world, we need a model which is global in scope, and which links global production, consumption and trade. In light of the forgoing discussion of key drivers of the biofuels boom, we also need a tight link between the energy economy in general, and petroleum prices in particular, and the demand for biofuels. In order to make the link to land use, it is critical to have a clearly fleshed out channel from biofuels to agricultural production to the derived demand for land. And we

must take into account the global competition for agricultural products. All of this has led us to develop a special purpose version of the Global Trade Analysis Project (GTAP) model (Hertel, 1997) of the global economy. Specifically, we begin with the GTAP-E model (Burniaux and Truong, 2002), as revised by McDougall and Golub (2008), which has been widely used for analysis of energy and climate change policies. We augment this model by adding the possibility for substitutability between biofuels and petroleum products (see Birur, Hertel and Tyner, 2007 for details).

In order to accurately depict the global competition for land between food and fuel, we augment the model with a land use module, nick-named GTAP-AEZ – where the AEZ stands for Agro-Ecological Zones (Hertel *et al*., 2008). This disaggregates land use into 18 AEZs which share common climate, precipitation and moisture conditions, and thereby capture the potential for real competition between alternative land uses. Land use competition is modeled using the Constant Elasticity of Transformation (CET) revenue function, which postulates that land owners maximize total returns by allocating their land endowment to different uses, subject to the inherent limitations on land use change. This gives rise to well-defined land supply functions to each land-using sector (e.g., Hertel and Tsigas, 1988, 1997), whereby the acreage supply elasticity varies as a function of the constant elasticity of transformation and the relative importance of a given activity. In the particular application at hand, as a biofuel feedstock absorbs more land in a given AEZ, the acreage supply elasticity falls, eventually reaching zero when (and if) the entire endowment of land in a given AEZ is devoted to (e.g.) corn.

In keeping with the data base on global land use (see below), we adopt a *nested* CET function in which the land allocation decision is broken into two steps, by imposing

homothetic separability on the revenue function. At the first stage, the land-owner decides on *land cover*, i.e. whether a given parcel of land will be in crops, forestry or pasture. The second stage involves the allocation of crop land across different uses. At each stage, the econometrically-based elasticity of transformation differs, as will be seen below. Of course, more complex patterns of nesting are also possible, as evidenced in the work of Eickhout *et al*. (2008). However, we do not have sufficient econometric information to calibrate a more elaborate pattern of nesting.

We conclude our discussion of the model by noting one of its most important limitations: the absence of by-products associated with biofuel production. For example, when ethanol is produced from corn, Dried Distillers' Grains with Solubles (DDGS) are generated as a by-product, which can be used as a feed ingredient. Sales of DDGS as a livestock feed generate roughly 16% of total ethanol revenues in the US and may be viewed as displacing corn and other feedstuffs. So by ignoring these by-products, we overstate the impact of mandates on corn and livestock markets. A similar situation arises with biodiesel production from oilseeds. *Data Base:* Equally important as the model structure is the data base underpinning this analytical framework. In order to address the global impacts of the emerging biofuels industry, we capitalize on several recent data base advances. First of all, we build on the work of Taheripour *et al*. (2008) which disaggregates three biofuels sectors within the 2001, version 6 GTAP data base. Specifically, these authors break out three new sectors: corn-based ethanol, sugarcane-based ethanol, and biodiesel. They do so by bringing to bear state-of-the-art analyses of the cost structure of these industries, including domestic and imported feedstocks. With the exception of corn-based ethanol, all liquid biofuels are assumed to substitute in final fuel consumption for petroleum products. For corn-based

ethanol, we incorporate separately the additive demand for biofuels, as this is less price-responsive. It is treated as an intermediate demand by the petroleum refining industry, the level of which varies directly with total petroleum use. As we will see below, differentiating the price-sensitive and fixed proportions demands for ethanol is critical for our *ex post* analysis of recent history of the biofuel boom in the US, as well as for our *ex ante* analysis of future policies.

The global land use data base has four key pieces. The data on land cover are from Ramankutty *et al*. (2008). These distinguish global land cover by type, including built-up land as well as non-commercial land. For purposes of this study, we only use the forest, pastureland and cropland cover types. Other land uses are assumed to be invariant to biofuels policies. The data base on harvested land cover and yields is from Monfreda *et al*. (2008a, 2008b). This has its origins in the AgroMaps data base project of FAO, IFPRI and SAGE, which assembled county-level data for all countries of the world and mapped these to 0.5 degree grid cells. These two data bases are aggregated to the 18 AEZ level prior to their incorporation into the GTAP data base. The third land use data base is documented in Sohngen *et al*. (2008), and maps forestry activity to the forest land cover in the 18 AEZs. Assembling all of these pieces, Lee *et al*. (2008) produce a GTAP-compatible global land use data base at the AEZ level. This involves disaggregating land rents in the GTAP data base on the basis of prices and yields. This final product is the one used in the present study. Much more discussion of global land use data and associated modeling issues is offered in the volume edited by Hertel, Rose and Tol (2008).

*Parameters:* With the model and data base in place, it remains to discuss the parameters used in this study. A central parameter in our analysis is the elasticity of

substitution between biofuels and petroleum products. With very limited time series data, reliable estimates of this parameter are not available in the literature. Furthermore, these elasticities are likely to vary greatly by country. For example, the potential for biofuel-petroleum substitution in automobiles depends on the current intensity of biofuels, as well as the stock of flex-fuel vehicles in the national fleet. Accordingly, we utilize our historical data to offer *general equilibrium* estimates of these parameters over the 2001-2006 period.

From the perspective of supply response and land use, the key parameters in the model are those which govern the responsiveness of land use to changes in relative returns. The (absolute value of the) transformation elasticities in the CET function represents the upper bound supply elasticity of the factor (in response to a change in factor returns). The actual supply response is dependent on the relative importance of a given sector in the overall market for land. As noted previously, the more dominant a given use in total land revenue, the smaller its own-price elasticity of acreage supply. For land cover, we draw on Lubowski, Plantinga, and Stavins (2005), who report land use elasticities consistent with a 5 year land cover transformation parameter of -0.11 and a 10 year value of -0.22 (Ahmed, Hertel and Lubowski, 2008). In this paper, we set this value to -0.20. A transformation parameter of -0.5 for the crop frontier is obtained by taking the maximum acreage response elasticity from the FAPRI model documentation (FAPRI, 2004) for corn acreage response across the different regions of the United States.

The issue of an endogenous yield response to biofuels policy changes has been quite controversial. One article that has drawn attention to the land use impacts of biofuel policies is that of Searchinger *et al*. (2008) who assume that there is no change in baseline yields as a consequence of biofuels policies. This has proven quite controversial – particularly in light of

their finding that US biofuels programs are likely to result in very substantial indirect land use impacts in the rest of the world. Some biofuels advocates have argued the other extreme – namely that increased yields can accommodate *all* of the incremental feedstock demands. Fortunately, this is an area where a great deal of economic research has been undertaken – particularly for corn. Keeney and Hertel (2008) explore this issue in detail, and here we adopt their central case assumption of a long run yield response to price of 0.4. We follow those authors in calibrating to this parameter by adjusting the elasticity of substitution in crop production to hit this targeted yield response.

As Searchinger *et al*. (2008) have identified, the bilateral pattern of trade is also important in determining the global impacts of biofuels polices. Countries with a close trading relationship with the US, for example, are more likely to be affected by such policies. Those earlier authors focused solely on US exports of corn, and assumed that reductions in exports would be offset by increases in domestic production in the destination countries. However, in reality, the global trading system is much more complex. First of all, the US is both an exporter and an importer of corn. Secondly, these bilateral patterns of trade are price sensitive, and therefore endogenous to any biofuels policies. As US exports to the Middle East become more expensive, for example, competitors will seek to erode the US market share. This means that the land use impact may well crop up in third markets with which the US may not even trade directly. This price responsiveness of bilateral trade is governed by the "Armington" elasticity of substitution among imports. We draw on recent econometric estimates of Hertel, Hummels, Ivanic and Keeney (2007), who utilize variation in bilateral trade costs in order to estimate the elasticity of substitution amongst products supplied by different exporters. Those

authors estimate this elasticity for corn (coarse grains) to be 2.6 with a standard error of 1.1, and 4.9 (0.8) for oilseeds (Hertel *et al*. 2007, Table 1).

The final set of parameters which deserve our attention relate to the price elasticity of demand for petroleum products. Following the stochastic simulation approach of Valenzuela *et al*. (2007), Beckman *et al*. (2008) seek to validate the GTAP-E model with respect to the petroleum product market. They find that demand is far too elastic in GTAP-E. This is confirmed by Espey (1998) who conducted a meta-analysis based on over 300 estimates from the literature. Her study suggests that the median price elasticity of demand for petroleum is -0.23 with a range of 0 to -1.36, and averaging -0.26. Also, Beckman et al. (2008) note that the elasticity of substitution amongst energy sources was too elastic in GTAP-E -- a result key to our analysis. With these issues in mind, Beckman *et al*. (2008) offer a revised set of GTAP-E parameters, which is what we use for this study.

The model is implemented using GEMPACK (Harrison and Pearson, 1994), and we make special use of the decomposition feature developed by Harrison, Horridge and Pearson (2000) which exploits numerical integration techniques in order to exactly separate the impacts of different policy shocks on endogenous variables of interest.

## 4. Historical Analysis

As noted previously, we begin by validating the model against recent history. Since this is a global general equilibrium model, there are many different variables upon which we could focus our attention. However, we believe the most important of these is the *share of total liquid fuels provided by biofuels*. Indeed many of the biofuel mandates are expressed in terms of such a share, so being able to track this over the 2001-2006 period is quite important.

Table 1 reports changes in total liquid fuel consumption in the US and the EU. It can be seen that the US share tripled from 2001 to 2006, rising from about 0.6% to more than 1.8%. Most of this was in the form of domestically produced, corn-based ethanol, but a seventh of the total came in the form of imports of sugarcane-based ethanol; finally, a very small amount came from biodiesel. In the EU, the share of biofuels in total liquid fuel consumption rose more than six-fold over this same period, from 0.2% to 1.3%, with the majority being delivered as biodiesel.

*Partial Equilibrium Analysis:* As noted above, the major drivers of this growth in biofuels have been: petroleum prices, biofuel subsidies, and the ban on competing fuel additives in the US. While our empirical analysis of the biofuel boom is conducted in global, general equilibrium, it is instructive to begin with a simple, partial equilibrium model for biofuels which highlights the role of each of these three drivers of change. Appendix A develops such a model, which shows that (in the absence of trade) the equilibrium percentage change in biofuel output, *qo**, can be expressed as follows:

$$qo^* = \varepsilon_s[(1-\alpha)\,ai - \varepsilon_D\,(p+s)]/[\varepsilon_s - \varepsilon_D] \qquad (1)$$

Here the key drivers of ethanol output change are: *ai*, the percentage change in the input-output ratio prescribing additive use in gasoline (this will rise when alternative additives are banned), *p*, the percentage change in the price of composite liquid fuels, and *s*, the percentage change in the power of the *ad valorem*-equivalent subsidy on ethanol production. The parameters in this equation are as follows: $-\alpha\sigma = \varepsilon_D$ is the composite price elasticity of demand for ethanol, which is the product of the share of ethanol going to the price-sensitive side of the market and the elasticity of substitution in use between ethanol, biodiesel, and petroleum; $\nu_c\theta_c^{-1} = \varepsilon_s$ is the price elasticity of supply for biofuel (e.g., ethanol) which is

determined by the product of the own-price elasticity of supply of feedstock (e.g., corn) and the inverse of the share of costs of corn in ethanol production.

From (1), we can obtain some useful insights into the impact of these drivers on the growth in biofuels output. First of all, the contribution of changes in the additive requirements of gasoline to total ethanol output depend on the change in the input-output ratio, *ai*, as well as the initial share of total sales going to this market segment. The price sensitive portion of the market depends on what happens to the price of energy in general, *p*, and the power of the subsidy, *s*. When the change in the latter is expressed as the change in the power of the *ad valorem* subsidy equivalent (as is the case here), these two effects are additive. Their combined significance depends on the share of the total market for ethanol that is price sensitive ($\alpha$) and the ease of substitution between ethanol and other fuels ($\sigma$). Furthermore, we see from (1) that feedstock supply response is also important. If the total availability of feedstock (corn) is fixed ($\nu_c = 0$), then *qo*=0*. Furthermore, as $\nu_c$ rises and the share of corn in overall ethanol costs falls ($\theta_c \to 0$), $\nu_c \theta_c^{-1} = \varepsilon_s$ rises, thereby boosting supply.

From a validation point of view, note that, given estimates of the other parameters and shocks in equation 1, we could choose $\sigma$ to replicate the historically observed value of *qo*, or some derivative thereof, e.g., the renewable fuel share. By evaluating the plausibility of these estimates of $\sigma$, we obtain some further validation of the model.

Equation (1) is critical when it comes to decomposing the contribution of the three main drivers of US ethanol production over the 2001-2006 period: the ban or competing gasoline additives, the rise in the price of petroleum, and the change in the power of the subsidy on biofuels. In the EU, we restrict ourselves to the latter two effects, and in Brazil, we will focus solely on the impact of higher petroleum prices.

*General Equilibrium Analysis:* We are now ready to simulate the general equilibrium model over the 2001-2006 period. The most obvious approach to this would be to shock all the exogenous variables in the model by the observed values over this period, and then compare the endogenous variables to their observed values by way of model validation. Unfortunately the vast majority of exogenous variables are either unobserved (technological change) or unavailable on a global, time series basis for the period in question (bilateral trade policies, domestic taxes and subsidies). We are therefore forced to adopt a more modest approach to our historical simulation. Instead of shocking *all* the exogenous variables in the economy, we shock only those drivers that were key to shaping the EU and US biofuel economy over this period – namely the price of petroleum, biofuel policies in the US and the EU, and the ethanol additive requirements in the US (recall equation 1). In this way, *we seek to impose the 2006 biofuel economy on the observed 2001 global economy*. In doing so, we greatly reduce the information requirements for this historical analysis, thereby sharpening our focus on the issue at hand – namely the impact of changing the way liquid fuel is delivered to the global economy.

Let us begin with a discussion of the estimated elasticity of substitution between biofuels and petroleum products ($\sigma$). The default value for this parameter is 2.0 (Birur, Hertel, and Tyner, 2007). In the cases of Brazil, USA and EU, we have sufficient information to alter this default value. Specifically, we estimate using the non-linear form of equation (1) in which we seek to hit the observed renewable fuel share target reported in Table 1 (recall the discussion above). The resulting estimates of $\sigma$ are: Brazil = 1.35, EU = 1.65 and USA = 3.95. The relatively low elasticity in Brazil reflects the fact that ethanol already commands a large share of that market, and large percentage changes become more difficult as ethanol becomes

more dominant. The estimated elasticity of substitution in the US is high, relative to Europe, particularly in light of the fact that the EU renewable fuel share grew by a much larger percentage over this period. However, the latter growth is well-explained by the significant subsidies implicit in the fuel tax exemptions in France and Germany. In addition, in the base period (2001), the share of US ethanol going to the price inelastic, additive market was quite high (about 75%). This requires the elasticity of substitution in the price-sensitive part of the market to be higher. Finally, the economic "power" of the US ethanol subsidy has been diminishing as the prices of gasoline and ethanol rise. (See the lower panel of Table 1 in which *ad valorem* equivalent of the US subsidy falls by 10.9%.) For all these reasons, a relatively large elasticity of substitution is required to explain the growth in the renewable fuel share in the US.

Given these estimates of the elasticity of substitution between biofuels and other energy products, we can also decompose the impact of the main drivers of renewable fuel output growth in the EU and US markets. Table 2 provides the general equilibrium analogue to the decomposition of equilibrium output growth given in equation (1). In the top panel we have a decomposition of US output growth, due to the exogenously dictated change in renewable fuel share over the 2001-2006 period. Of the total change in ethanol growth (176.7%) driven by this compositional change in liquid fuels, 63.9% of the total figure is attributed to the MTBE ban, 148% is attributed to the rise in petroleum prices, -34.9% is due to the diminishing relative importance of the $.51/gallon blenders' subsidy, and a negligible amount in US output growth is attributed to the growth in EU subsidies.

The predicted changes in US agricultural and forestry output, due to the changing fuel economy, over this same period are reported in the subsequent rows of Table 4. Coarse grains

output is estimated to have been about 7% higher in 2006, solely due to the increase in renewable fuel use. The majority of this (5.6% output growth) was driven by higher oil prices, with the next largest portion (2.4%) being driven by the MTBE ban. With the exception of oilseeds, these changes in the global fuel economy led to declines in the output of other agricultural and forestry activities, as land was diverted to corn production. However, oilseed production shows a positive gain due to changes in the global fuel economy: albeit weakly through a small rise in US biodiesel production, but more strongly due to the boom in EU biodiesel production.

The lower panel of Table 2 reports comparable results for the EU, beginning with biodiesel output – the primary renewable fuel in the EU. Here, the percentage increase is much larger – more than 400%! This is driven by the combination of fuel tax exemptions (247.1%). The *ad valorem* equivalent of the power of the EU subsidy on biodiesel rose by 81.2% over this period. This is followed by the contribution of higher oil prices rise (184.5%). These are also the main drivers behind the associated changes in EU agricultural and forestry output reported in the bottom panel of Table 2. The predicted rise in oilseeds output in the EU in the wake of this change in the fuel economy is 17.5% -- driven almost equally by higher oil prices and increased EU subsidies.

Table 3 reports the disposition of key biofuel feedstocks in 2001 and 2006 in Brazil, EU and the US. (Bear in mind that these shares abstract from other developments in the global economy, including changes in EU and US farm programs, China's growing demand for Brazilian soybeans, etc.). As seen from Table 3, the model predicts that the share of US coarse grains (corn) going to ethanol production over this period increased from 5 % in 2001 to about 13% in 2006. This matches the historical experience in the US quite closely. This

eight percentage point increase in the share of coarse grain for ethanol has come from reduction in other sectors, including such as feed industry (-4 percentage points), exports (-2 percentage points) and other industries (-2 percentage points). Similarly, in the case of EU, the share of oilseeds going to biodiesel sector has increased from 5% to 23% during the 2001-06 period, which again comes from a large reduction in use of oilseeds in food products and other sectors. The EU also produces a small amount of grain based bio-ethanol and the model predicts a small increase in the share of coarse grains going to ethanol sector.

The final panel in Table 3 reports the results for Brazil, where there is a modest increase in the share of sugarcane going into the production of ethanol over the 2001-2006 period. The model also predicts a sharp rise in ethanol exports which has indeed been observed.

Finally, the first panel in Table 4 reports the predicted changes in land use over this historical period. The model predicts strong increases in US coarse grains and EU oilseed production, as well as a sharp rise in sugarcane production in Brazil. Obviously the fuel price rise, the MTBE ban, and the US and EU subsidy adjustments are not the only things going on over the 2001-2006 period. However, it is instructive to compare the actual changes in these key feedstock land areas over this period. In reality, US corn area was up by 3.5% (vs. 5.1% in our simulation), EU oilseed area rose by more than 11% (vs. 15% in Table 4), and Brazilian sugarcane area rose by about 20% (vs. 15% in our historical simulation). Overall, we estimate that, if no other changes had occurred over the 2001-2006 period, the change in composition of the fuel economy would have boosted crop land cover in US, EU and Brazil by roughly 0.3%, 0.7% and 1.1%, respectively.

## 5. *Ex Ante* Analysis of EU and US Biofuel Programs

We now turn to a forward-looking analysis of EU and US biofuel programs. As noted above, the US Energy Policy and Security Act of 2007 calls for 15 billion gallons of ethanol use by 2015. In the EU, the target is 5.75% of renewable fuel use in 2010 and 10% by 2020. However, there are significant doubts as to whether these goals are attainable. For this analysis, we adopt the conservative mandate of 6.25% by 2015 in the EU. The starting point for our prospective simulations is the updated, 2006 fuel economy which results from the foregoing historical analysis. Thus, we analyze the impact of a continued intensification of the use of biofuels in the economy – this time treating the mandates as exogenous shocks.[1]

*Impact on Output*: Table 5 reports the percentage changes in output for biofuels and the land-using sectors in the USA, EU and Brazil. The first column in each block corresponds to the combined impact of EU and US policies on a given sector's output (USEU-2015). The second column in each block reports the component of this attributable to the US policies (US-2015), and the third reports the component of the total due to the EU policies (EU-2015) using the decomposition technique of Harrison, Horridge and Pearson (2000). This decomposition approach is a more sophisticated approach to the idea of first simulating the global impacts of a US program, then simulating the impact of an EU biofuels program, and finally, simulating the impact of the two combined. The problem with that (rather intuitive) approach is that the impacts of the individual programs will not sum to the total, due to interactions. By adopting this numerical integration approach to decomposition, the combined impacts of the two programs are fully attributed to each one individually.

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[1] Technically, we endogenize the subsidy on biofuel use and exogenize the renewable fuel share, then shock the latter. For simplicity, all components of the renewable fuels bundle are assumed to grow in the same proportion.

In the case of the US impacts (columns labeled Outputs in US), most of the impacts on the land-using sectors are due to US policies. Coarse grains output rises by more than 16%, while output of other crops and livestock falls when only US policies are considered. However, oilseeds are a major exception. Here, the production impact is reversed when EU mandates are introduced. In order to meet the 6.25% renewable fuel share target, the EU requires a massive amount of oilseeds. Even though production in the EU rises by 52%, additional imports of oilseeds and vegetable oils are required, and this serves to stimulate production worldwide, including in the US. Thus, while US oilseeds output falls by 5.6% in the presence of US-only programs, due to the dominance of ethanol in the US biofuel mix, when the EU policies are added to the mix, US oilseed production actually rises.

In the case of the EU production impacts (Outputs in EU: the second group of columns in Table 5), the impact of US policies is quite modest, with the main interaction again through the oilseeds market. However, when it comes to third markets – in particular Brazil (Outputs in Brazil), the US and EU both have important impacts. US policies drive sugarcane production, through the ethanol sector, while the EU policies drive oilseeds production in Brazil. Other crops, livestock, and forestry give up land to these sectors.

*Impact on Bilateral Trade:* In order to better understand the impacts of US and EU policies on Brazil, and other third markets, we turn to Table 6, which reports the change in bilateral trade volumes for coarse grains, oilseeds and other food products as a result of the combined mandates. As can be seen from the first row of entries, US exports of coarse grains are reduced by nearly $1billion at constant prices. Of course, this prediction is made, holding all other changes in the world economy constant. In practice, rising demand in the rest of the world could counteract the impact of biofuel mandates on US exports.

On the other hand, EU exports of coarse grains, oilseeds and other food products are sharply reduced across the board. Other regions increase their exports to both the US and the EU, with the largest volume changes arising in the case of oilseed exports to the EU. Here, the leader is Brazil, followed by the US, other countries in the Americas and Eastern Europe, re-exports from Hong Kong, India, and Africa. In short, the EU draws on additional oilseeds from around the globe, thereby stimulating the demand for additional crop land in these regions as well.

*Impact on Land Use and Land Cover*: Table 7 reports changes in crop harvested area as a result of the biofuel mandates in the US and EU for all regions in the model. Coarse grains acreage in the US is up by about 10%, while sugar, other grains, and other crops are all down. Figure 1 shows the percentage change in land area under coarse grains, by AEZ and region, following the US and EU biofuel mandates for 2015. The percentage increase in acreage varies by AEZ, for instance in the US, the largest percentage changes in corn acreage (up to 19%) are in the less-productive AEZs which contribute little to national coarse grains output. Thus the productivity-weighted rise in coarse grains acreage is 10% (Table 7). This increase in corn acreage in the US comes from contribution of land from other land-using sectors such as other grains (Table 7) as well as pasture land and commercial forest land — to which we will turn momentarily.

From Table 7, we see that US oilseeds acreage is up slightly due to the influence of EU policies on the global oilseeds market. However, this marginal increase is dwarfed by the increased acreage devoted to oilseeds in other regions, where the percentage increases range from 11 – 16% in Latin America, and 14% in Southeast Asia and Africa, to 40% in the EU (see also Figure 2). If the EU really intends to implement its 2015 renewable fuels target,

there will surely be a global boom in oilseeds. Coarse grains acreage in most other regions is also up, but by much smaller percentages. Clearly the US-led ethanol boom is not as significant a factor as the EU oilseeds boom. Sugarcane area rises in Brazil, but declines elsewhere, and other grains and crops are somewhat of a mixed bag, with acreage rising in some regions to make up for diminished production in the US and EU and declines elsewhere.

From an environmental point of view, the big issue is not which crops are grown, but how much cropland is demanded overall, and how much (and where) grazing and forestlands are converted to cropland. Table 8 reports the percentage changes in different land cover area as a result of the EU and US mandates. Furthermore, as with the output changes in Table 5, we decompose this total into the portion due to each region's biofuels programs. From the first group of columns, we see that crop cover is up in nearly all regions. Here we also see quite a bit of interaction between the two sets of programs. For example, in the US, about one-third of the rise in crop cover is due to the EU programs. In the EU, the US programs account for closer to one quarter of the rise in crop cover. In other regions, the EU programs play the largest role in increasing crop cover. For example, in Brazil, the EU programs account for nearly 11% of the 14.2% rise in crop cover.

Where does this crop land come from? In our framework it is restricted to come from pastureland and commercial forest lands, since we do not take into account idle lands, nor do we consider the possibility of accessing currently inaccessible forests. The largest percentage reductions tend to be in pasturelands (Table 8, final set of columns). For example, in Brazil, we estimate that pasturelands could decline by nearly 10% as a result of this global push for biofuels, of which 8% decline is from EU mandates alone. The largest percentage declines in commercial forestry cover are in the EU and Canada, followed by Africa. In most other

regions, the percentage decline in forest cover is much smaller. (Figures 3 and 4 provide maps of the global changes in pastureland and forest cover, by AEZ.)

*Systematic Sensitivity Analysis of the Results:*

Given the uncertainty associated with the key parameters in this model, it is critical to undertake a systematic sensitivity analysis in which the model is resolved for different draws from the underlying parameter distributions. Monte Carlo analysis is the standard approach to this problem. However, it is impractical for large scale models. Therefore, we adopt the Gaussian Quadrature approach which DeVuyst and Preckel (1997) show to be much more efficient for large-scale models. Here, we follow the implementations by Arndt (1996) and Pearson and Arndt (2000). These authors employ this technique in the GTAP framework using the Stroud Quadrature, which requires the model to be solved only 2N times where N is the number of varying parameters/variables. We use symmetric triangular distributions to approximate the underlying distribution of the key parameters, as this permits us to completely characterize the parameter distribution by simply specifying the mean and lower end points of each distribution.

Information about the assumed parameter distributions is reported in Table 9. We follow Keeney and Hertel (2008) in allowing the elasticity of crop yields with respect to price to vary from 0.00 to 0.80, with a mean of 0.40. The lower bounds on the absolute value of the acreage response parameters (elasticities of land transformation) are assumed to be 20% of the mean for both the land cover elasticity and the harvested crop land elasticity. Finally, we also sample from the distribution of Armington trade elasticities, based on the estimated standard deviations from the source study for those estimates (Hertel et al., 2007). In total we vary

eight parameters (see Table 9), and the model is solved 16 times, retaining each solution and the associated weight in order to calculate the mean and standard deviation of the model variables. Based on these statistics, we are able to compute mean changes for all variables, as well as the associated confidence intervals.

Given the focus on land cover in the debate over biofuels, we have chosen to focus here on the land cover (95%) confidence intervals. These are reported in the final two columns of each section in Table 8, and correspond to the combined, EU-US-2015 experiment. So, for example, the confidence interval on US crop cover range from +0.4% to +1.20% changes in the wake of the combined mandates.[2] The crop cover confidence interval is even larger in the case of Canada and Brazil, but the lower bound is still large and positive. However, in the cases of most Asian economies, the sign of the impact on crop cover is uncertain. For example, in India, the confidence interval on crop cover change ranges from -0.05% to +0.23%. Pasture cover is quite similar in the pattern of countries in which the sign of the land cover change is uncertain with respect to the parameter distributions in Table 9. However, forest cover uncertainty is more pervasive. Indeed, the only regions where we can say for certain that forest cover will decline in the context of the combined biofuel mandates are: USA, Canada, EU, Brazil, Latin American Energy Exporters, Africa and Oceania.

## 6. Conclusions

Recently there has been a boom in research into the impact of biofuel programs on both domestic and global resource use, as well as prices of energy and food products. Previous

[2] These are confidence intervals around the mean land cover estimates which differ – but only very slightly – from the point estimates reported in the first column of Table 8. To save space, we have only reported the point estimates. Typically these differ in the first or second decimal place.

authors have devoted considerable attention to the impacts of these policies on a country-by-country basis. However, there are also strong interactions between these programs, as they compete in world markets for feedstocks and ultimately for a limited supply of global land. In this paper, we have evaluated the interplay between two of the largest biofuels programs, namely the renewable fuel mandates in the US and the EU.

We began with an analysis of the origins of the recent bio-fuel boom, using the historical period from 2001-2006 for purposes of model validation. This was a period of rapidly rising oil prices, increased subsidies in the EU, and, in the US, there was a ban on the major competitor to ethanol for gasoline additives. Our analysis of this historical period permits us to evaluate the relative contribution of each of these factors to the global biofuel boom. We find that, in the US, the rising oil price was the most important contributor to the biofuel boom in that country, followed by the MTBE additive ban. In the EU, subsidies – in the form of fuel tax exemptions -- were the most important factor in driving biofuel growth, followed by the rising oil price.

Our prospective analysis of the impacts of the biofuels boom on commodity markets focused on the 2006-2015 time period, during which existing investments and new mandates in the US and EU are expected to substantially increase the share of agricultural products (e.g., corn in the US, oilseeds in the EU, and sugar in Brazil) utilized by the biofuels sector. In the US, this share could more than double from 2006 levels, while the share of oilseeds going to biodiesel in the EU could triple. In analyzing the biofuel policies in these regions, we decompose the contribution of each set of regional policies to the global changes in output and land use. The most dramatic interaction between the two sets of policies is for oilseed production in the US, where the sign of the output change is reversed in the presence of EU

mandates (rising rather than falling). The other area where they have important interactions is in the aggregate demand for crop land. About one-third of the growth in US crop cover is attributed to the EU mandates. When it comes to the assessing the impacts of these mandates on third economies, the combined policies have a much greater impact than just the US or just the EU policies alone, with crop cover rising sharply in Latin America, Africa and Oceania as a result of the biofuel mandates. These increases in crop cover come at the expense of pasturelands (first and foremost) as well as commercial forests. It is these land use changes that have attracted great attention in the literature (e.g., Searchinger et al.) and a logical next step would be to combine this global analysis of land use with estimates of the associated greenhouse gas emissions.

## 7. References


Ahmed, A. S., T. W. Hertel, and R. Lubowski (2008, forthcoming) "Calibration of a Land Cover Supply Function Using Transition Probabilities". GTAP Research Memorandum No 12. Center for Global Trade Analysis, Purdue University, West Lafayette, IN, USA.

Alexander, C. and C. Hurt (2007) "Biofuels and Their Impact on Food Prices." Bioenergy, Purdue Extension, ID-346-W. Purdue University, West Lafayette, IN, USA. http://www.ces.purdue.edu/extmedia/ID/ID-346-W.pdf

Arndt, C. (1996) "An Introduction to Systematic Sensitivity Analysis via Gaussian Quadrature." GTAP Technical Paper No. 2. Center for Global Trade Analysis, Purdue University, West Lafayette, IN, USA.

Banse M., H van Meijl, A. Tabeau, and G. Woltjer (2007) "Impact of EU Biofuel Policies on World Agricultural and Food Markets." Paper presented at the Tenth Annual Conference on Global Economic Analysis, Purdue University, West Lafayette, IN. 7-9 June, 2007.

Beckman, J. B. *et al.* (2008, forthcoming) "Validation of the GTAP-E Model", Center for Global Trade Analysis, Purdue University.

Birur, D.K., T.W. Hertel and W.E. Tyner (2007). "*Impact of Biofuel Production on World Agricultural Markets: A Computable General Equilibrium Analysis*." GTAP Working Paper, presented earlier at the 10th Annual Conference on Global Economic Analysis, Purdue University, West Lafayette, IN, USA.

Burniaux, J. and T. Truong (2002) "GTAP-E: An Energy-Environmental Version of the GTAP Model", GTAP Technical Paper No. 16, Center for Global Trade Analysis. Purdue University, West Lafayette, IN.

DeVuyst, E.A. and P.V. Preckel (1997) "Sensitivity Analysis Revisited: A Quadrature-Based Approach." *Journal of Policy Modeling* 19(2):175-85.

Dimaranan, B.V., Edt. (2006). *Global Trade, Assistance, and Production: The GTAP 6 Data Base*, Center for Global Trade Analysis, Purdue University, West Lafayette, IN, USA.

Eickhout, B. H., van Meijl, A. Tabeau, and E. Stehfest (2008) "*The Impact of Environmental and Climate Constraints on Global Food Supply*" GTAP Working Paper No. 47, Center for Global Trade Analysis, Purdue University, West Lafayette, IN, USA.

Espey, M. (1998). "Gasoline Demand Revisited: An International Meta-Analysis of Elasticities." *Energy Economics*, 20: 273-295.

European Biodiesel Board (2007) Data accessed at http://www.ebb-eu.org/stats.php

European Commission (2007) "Impact Assessment of the Renewable Energy Roadmap – March 2007," Directorate-General for Agriculture and Rural Development, European Commission, AGRI G-2/WM D (2007) Accessed at: http://ec.europa.eu/agriculture -/analysis/markets/biofuel/impact042007/text_en.pdf

FAPRI (2004) "Documentation the FAPRI Modeling System." FAPRI-UMC Report #12-04, Food and Agricultural Policy Research Institute, Iowa State University, University of Missouri-Columbia, Ames, IA, USA. December 2004.

FAPRI (2007) "U.S. and World Agricultural Outlook," FAPRI-UMC Report #01-07, Food and Agricultural Policy Research Institute, Iowa State University, University of Missouri-Columbia, Ames, Iowa, USA, January 2007.

Fargione J. *et al.* (2008) "Land Clearing and the Biofuel Carbon Debt." *Science* 319 (5867): 1235-1238.

Harrison, W. J., and K. R. Pearson (1994) "Computing Solutions for Large General Equilibrium Models using GEMPACK," Impact Project Preliminary Working Paper No. IP-64.

Harrison, W. J., Horridge, J. M., and Pearson, K. R. (2000). "Decomposing Simulation Results with Respect to Exogenous Shocks". *Computational Economics.* 15(3): 227-249. doi: http://dx.doi.org/10.1023/A:1008739609685

Hertel, T. W. (1997) "Global *Trade Analysis, Modeling and Applications*." Cambridge University Press, Cambridge.

Hertel, T. W. and M. E. Tsigas (1988) "Tax Policy and U.S. Agriculture: A General Equilibrium Analysis," *American Journal of Agricultural Economics*, 70(2):289-302.

Hertel, T.W. and M.E. Tsigas (1997) "Structure of GTAP." In: Hertel, T.W. (1997) "Global *Trade Analysis, Modeling and Applications*." Cambridge University Press, Cambridge.

Hertel, T.W., D. Hummels, M. Ivanic, and R. Keeney. (2007). "How Confident Can We Be of CGE Analysis of Free Trade Agreements?" *Economic Modeling*, 24: 611-635.

Hertel, T.W., S. Rose and R. Tol (eds.) (2008) *Economic Analysis of Land Use in Global Climate Policy*, forthcoming from Routledge.

Hertel, T. W., H. Lee, S. Rose and B. Sohngen, (2008). "Modeling Land-use Related Greenhouse Gas Sources and Sinks and their Mitigation Potential", Chapter 6 in *Economic Analysis of Land Use in Global Climate Change Policy*. Edited by T. Hertel, S. Rose and R. Tol. Routledge: forthcoming.

Keeney, R. and T.W. Hertel (2005) "GTAP-AGR: A Framework for Assessing the Implications of Multilateral Changes in Agricultural Policies." GTAP Technical Paper No. 24, Center for Global Trade Analysis, Purdue University, West Lafayette, IN, USA.

Keeney, R. and T.W. Hertel (2008) "Indirect Land Use Impacts of US Biofuels Policies: The Importance of Acreage, Yield and Bilateral Trade Responses". GTAP Working Paper (forthcoming), Center for Global Trade Analysis, Purdue University, West Lafayette, IN, USA.

Lee, H.-L., T. W. Hertel, B. Sohngen and N. Ramankutty (2005) "*Towards and Integrated Land Use Data Base for Assessing the Potential for Greenhouse Gas Mitigation*." GTAP Technical Paper # 25, Center for Global Trade Analysis, Purdue University, West Lafayette, IN, USA.

Lee, H.-L., T. W. Hertel, S. Rose and M. Avetisyan (2008) "An *Integrated Global Land Use Data Base for CGE Analysis of Climate Change Policy Options*." GTAP Working Paper No. 42, Center for Global Trade Analysis, Purdue University, West Lafayette, IN, USA.

Lubowski, R. N., A.J. Plantinga and R.N. Stavins (2006) "Land-use Change and Carbon Sinks: Econometric Estimation of the Carbon Sequestration Supply Function," *Journal of Environmental Economics and Management*, 51:135-152.

Martines-Filho, J.; H.L. Burniquist, and C.E.F. Vian (2006) "Bioenergy and the Rise of Sugarcane-Based Ethanol in Brazil." *Choices*, 2nd Quarter, 21(2): 91-96.

McCarl, B. A. *et al*. (2005) "Potential for Biofuel-based Greenhouse Gas Emission Mitigation: Rationale and Potential" In: J. Outlaw and K. Collins (Eds.) "Agriculture as a Producer and Consumer of Energy", forthcoming.

McDougall, R.M. and A. Golub (2008) "GTAP-E: A Revised Energy-Environmental Version of the GTAP Model" forthcoming GTAP Technical Paper, Center for Global Trade Analysis. Purdue University, West Lafayette, IN.

Monfreda, C., N. Ramankutty, and J. A. Foley (2008a), "Farming the Planet: 2. Geographic Distribution of Crop Areas, Yields, Physiological Types, and Net Primary Production in the Year 2000," *Global Biogeochem. Cycles*, *22*, GB1022, doi:10.1029/2007GB002947.

Monfreda, C., N. Ramankutty, and T.W. Hertel (2008b), "Global Agricultural Land Use Data for Climate Change Analysis," Chapter 2 in T. Hertel, S. Rose and R. Tol (eds.) *Economic Analysis of Land Use in Global Climate Policy*, forthcoming from Routledge, also available as GTAP Working Paper # 40, Center for Global Trade Analysis, Purdue University, West Lafayette, IN, USA.

Muller, M.; T. Yelden., and H. Schoonover (2007) "Food versus Fuel in the United States: Can Both Win in the Era of Ethanol?" Institute for Agriculture and Trade Policy (IATP) Environment and Agriculture Program. Minneapolis, MN.

Pearson, K. and C. Arndt (2000) "Implementing Systematic Sensitivity Analysis Using GEMPACK." GTAP Technical Paper No. 3, Center for Global Trade Analysis, Purdue University. West Lafayette, IN, USA.

Rajagopal, D. and D. Zilberman (2007) "Review of Environmental, Economic, and Policy Aspects of Biofuels." World Bank Policy Research Working Paper 4341.

Ramankutty, N., A. Evan, C. Monfreda, and J. A. Foley (2008), "Farming the Planet: 1. Geographic Distribution of Global Agricultural Lands in the Year 2000." *Global Biogeochem. Cycles*, *22*, GB1003, doi:10.1029/2007GB002952.

Regaldo, A. and G. Fan (2007) "Ethanol Giants Struggle to Crack Brazil Market." *The Wall Street Journal*, September 10, 2007.

Lubowski, R. N., A. J. Plantinga, and R. N. Stavins (2005) "Land-Use Change and Carbon Sinks: Econometric Estimation of the Carbon Sequestration Supply Function," Regulatory Policy Program Working Paper RPP-2005-01. Cambridge, MA: Center for Business and Government, John F. Kennedy School of Government, Harvard University.

Schneider, U. A. and B. A. McCarl (2003) "Economic Potential of Biomass Based Fuels for Greenhouse Gas Emission Mitigation." *Environmental and Resource Economics*, 24(4): 291–312.

Searchinger, T. R. *et al.* (2008) "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases through Emissions from Land-Use Change." *Science* 319 (5867): 1238-1240.

Sohngen, B., C. Tennity, M. Hnytka and Karl Meeusen (2008), "Global Forestry Data for the Economic Modeling of Land Use", Chapter 3 in T. Hertel, S. Rose and R. Tol (eds.) *Economic Analysis of Land Use in Global Climate Policy*, forthcoming from Routledge, also available as GTAP Working Paper # 41, Center for Global Trade Analysis, Purdue University, West Lafayette, IN, USA.

Taheripour, F., D.K. Birur, T.W. Hertel, and W.E. Tyner (2007) '*Introducing Liquid Biofuels into the GTAP Database*' GTAP Research Memorandum No. 11. Center for Global Trade Analysis, Purdue University, West Lafayette, IN, USA.

Tokgoz, S. *et al*. (2007) "*Emerging Biofuels: Outlook of Effects on U.S. Grain, Oilseed, and Livestock Markets*." Staff report 07-SR 101, Center for Agricultural and rural Development, Iowa State University. http://www.card.iastate.edu/publications/synopsis.aspx?id=1050

Tyner, W.E. (2007a) "Biofuels, Energy Security, and Global Warming Policy Interactions." Paper presented at the National Agricultural Biotechnology Council Conference, South Dakota State University, Brookings, SD, May 22-24, 2007.

Tyner, W. E. (2007b) "The U.S. Ethanol and Biofuels Boom: Its Origins, Current Status, and Future Prospectus." Forthcoming in *BioScience*.

Tyner, W. E. (2007c) "What We Know and What We Need to Know on biofuels, Food, and Feed Tradeoffs," Presentation at the Farm Foundation Biofuels Conference, St. Louis, MO, April 2007. http://www.farmfoundation.org/projects/documents/biofuelspaper-tyner.pdf

Tyner W. E., and F. Taheripour (2007) "*Future Biofuels Policy Alternatives*." Paper presented at the Biofuels, Food, & Feed Tradeoffs Conference Organized by the Farm Foundation and USDA, St. Louis, Missouri, April 12-13.

Tyner, W. E. and J. Quear (2006) "Comparison of a Fixed and Variable Corn Ethanol Subsidy." Choices, 21(3): 199-202.Valdes, C. (2007) "Ethanol Demand Driving the Expansion of Brazil's Sugar Industry." Sugar and Sweeteners Outlook, Economic Research Service, United States Department of Agriculture, SSS-249, June 4, 2007. pp: 31-38.

Valenzuela E., T.W. Hertel, R. Keeney, and J.J. Reimer (2007) "Assessing Global CGE Model Validity using Agricultural Price Volatility." *American Journal of Agricultural Economics*, 89(2):383–397

Table 1. The Changing Structure of the Biofuel Economy

| | | US | | | EU-27 | | |
|---|---|---|---|---|---|---|---|
| *Fuel Consumption:* | *Units* | **2001** | **2006** | **2015** | **2001** | **2006** | **2015** |
| Liquid fuels for Transport: | | | | | | | |
| Petroleum | *Quad Btu* | 25.96 | 27.57 | 29.63 | 18.20 | 18.20 | 18.50 |
| Total Biofuels[1] | *Quad Btu* | 0.150 | 0.503 | 1.508 | 0.037 | 0.224 | 1.156 |
| Ethanol | *Quad Btu* | 0.149 | 0.471 | 1.341 | | 0.035 | 0.183 |
| Biodiesel | *Quad Btu* | 0.001 | 0.032 | 0.167 | 0.037 | 0.189 | 0.973 |
| Share of biofuels in liquids for transport (energy basis) | *%* | ***0.58*** | ***1.83*** | ***5.09*** | ***0.20*** | ***1.23*** | ***6.25*** |
| *Biofuel Policies:* | | | | | | | |
| Subsidy for Ethanol | *$/gallon* | 0.51 | 0.51 | | - | 1.00 | |
| Average Price of Ethanol[2] | *$/gallon* | 1.48 | 2.58 | | 1.48 | 1.96 | |
| *Ad valorem equivalent of subsidy* | | 1.34 | 1.20 | | 1.00 | 1.51 | |
| **% ch in subsidy (2001-2006)** | | | ***-10.9*** | | | ***51.0*** | |
| Subsidy for Biodiesel[3] | *$/gallon* | 1.00 | 1.00 | | - | 1.90 | |
| Average Price of Biodiesel[4] | *$/gallon* | 2.45 | 3.23 | | 2.33 | 2.34 | |
| *Ad valorem equivalent of subsidy* | | 1.41 | 1.31 | | 1.00 | 1.81 | |
| **% ch in subsidy (2001-2006)** | | | ***-7.0*** | | | ***81.2*** | |

Note: [1]Biofuels include both domestic production and imports of ethanol and biodiesel
[2]Ethanol prices for EU-27 corresponds to France
[3] Subsidies in the US and Tax Credits in the EU-27
[4] Biodiesel prices for EU-27 corresponds to Germany
Data Sources: Projected data is from Energy Information Administration, U.S. Department of Energy.

Table 2. Decomposition of the Drivers behind the Biofuels Boom: 2001-2006 *(Percent change in output by sector*)

| **US** | **Total Change** | *Decomposed by Driver* | | | |
|---|---|---|---|---|---|
| | | Additives | Oil Price | Subsidy-US | Subsidy-EU |
| Ethanol | 176.7 | 63.9 | 148.0 | -34.9 | -0.3 |
| Coarse Grains | 6.7 | 2.4 | 5.6 | -1.3 | 0.0 |
| Other Grains | -3.2 | -1.1 | -2.8 | 0.6 | 0.1 |
| Oilseeds | 0.7 | -0.7 | 0.2 | 0.3 | 0.8 |
| Sugarcane | -0.9 | -0.2 | -0.8 | 0.1 | 0.0 |
| Other Agri | -0.8 | -0.2 | -0.7 | 0.1 | 0.0 |
| Livestock | -1.2 | -0.1 | -1.1 | 0.1 | 0.0 |
| Forestry | -0.3 | -0.2 | -0.3 | 0.1 | 0.0 |
| **EU-27** | **Total Change** | *Decomposed by Driver* | | | |
| | | Additives | Oil Price | Subsidy-US | Subsidy-EU |
| Biodiesel | 431.4 | -0.7 | 184.5 | 0.4 | 247.1 |
| Coarse Grains | 0.8 | 0.1 | 0.6 | -0.1 | 0.2 |
| Other Grains | -1.1 | 0.1 | -0.1 | 0.0 | -1.1 |
| Oilseeds | 17.5 | 0.2 | 7.8 | -0.1 | 9.6 |
| Sugarcane | -0.5 | 0.0 | -0.2 | 0.0 | -0.2 |
| Other Agri | -0.3 | 0.0 | 0.0 | 0.0 | -0.3 |
| Livestock | -0.5 | 0.0 | -0.4 | 0.0 | -0.1 |
| Forestry | -1.5 | 0.0 | -1.0 | 0.0 | -0.5 |

Table 3. Disposition of Feedstock in the Changing Global Biofuel Economy (%)

| **US** | | | | **EU-27** | | | | **Brazil** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Base **2001** | Base **2006** | Mandates **2015** | | Base **2001** | Base **2006** | Mandates **2015** | | Base 2001 | Base 2006 | Mandates 2015 |
| *Disposition of Coarse grains (%)* | | | | *Disposition of Oilseeds (%)* | | | | *Disposition of Sugarcane (%)* | | | |
| Ethanol1 | 4.9 | 12.7 | 29.9 | Biodiesel | 5.3 | 23.3 | 69.2 | Ethanol2 | 43.5 | 51.6 | 56.2 |
| Feed | 47.4 | 43.6 | 36.4 | Food products | 51.8 | 42.1 | 17.7 | Sugar | 44.3 | 37.1 | 32.8 |
| Other | 20.1 | 18.6 | 15.7 | Other | 23.7 | 19.3 | 9.1 | Other | 12.1 | 11.3 | 10.9 |
| Exports | 27.6 | 25.1 | 18.0 | Exports | 19.3 | 15.3 | 4.0 | | | | |
| | | | | *Disposition of Coarse Grains (%)* | | | | *Disposition of Ethanol-2 (%)* | | | |
| | | | | Ethanol-1 | 0.5 | 1.9 | 9.5 | Dom use | 97.4 | 86.9 | 69.8 |
| | | | | Feed | 50.6 | 49.9 | 46.1 | Exports | 2.6 | 13.1 | 30.2 |

Note: Ethanol1refers to the corn based ethanol and ethanol2 is the sugarcane based ethanol.

Table 4. Change in Land Use due to US-EU Biofuel Programs (%)

| | **2001-2006** | | | **2006-2015** | | |
|---|---|---|---|---|---|---|
| | US | EU-27 | Brazil | US | EU-27 | Brazil |
| *Land use change (%):* | | | | | | |
| Coarse Grains | 5.1 | -0.2 | -0.3 | 9.9 | -2.3 | -3.2 |
| Oilseeds | -0.4 | 15.3 | 0.7 | 1.5 | 40.1 | 16 |
| Sugarcane | -1.7 | -1.3 | 14.8 | -5.8 | -7.4 | 3.9 |
| Other Grains | -3.4 | -2.0 | -0.7 | -10.1 | -15.1 | -10.9 |
| Other Agri | -1.0 | -0.7 | -2.2 | -2.7 | -6.2 | -5.2 |
| *Land cover change (%)* | | | | | | |
| Crops | 0.3 | 0.7 | 1.1 | 0.8 | 1.9 | 2.0 |
| Forest | -0.7 | -2.1 | -2.6 | -3.1 | -8.3 | -5.1 |
| Pasture | -1.4 | -2.3 | -2.2 | -4.9 | -9.7 | -6.3 |

Table 5. Change in Output due to EU and US Biofuel Mandates: 2006-2015 (%)

| Sectors: | Outputs in US | | | Outputs in EU | | | Outputs in Brazil | | |
|---|---|---|---|---|---|---|---|---|---|
| | USEU -2015 | US-2015 | EU-2015 | USEU -2015 | US-2015 | EU-2015 | USEU -2015 | US-2015 | EU-2015 |
| Ethanol | 177.5 | 177.4 | 0.1 | 430.9 | 1.3 | 429.7 | 18.1 | 17.9 | 0.2 |
| Biodiesel | 176.9 | 176.8 | 0.1 | 428.8 | 1.2 | 427.6 | - | - | - |
| Coarse Grains | 16.6 | 16.4 | 0.2 | 2.5 | 0.8 | 1.7 | -0.3 | 1.1 | -1.4 |
| Oilseeds | 6.8 | -5.6 | 12.4 | 51.9 | 1.2 | 50.7 | 21.1 | 0.6 | 20.5 |
| Sugarcane | -1.8 | -1.9 | 0.1 | -3.7 | 0.0 | -3.7 | 8.4 | 9.3 | -0.9 |
| Other Grains | -7.6 | -8.7 | 1.2 | -12.2 | 0.1 | -12.3 | -8.7 | -2.0 | -6.8 |
| Other Agri | -1.6 | -1.7 | 0.2 | -4.5 | 0.0 | -4.5 | -3.8 | -1.5 | -2.4 |
| Livestock | -1.2 | -1.2 | 0.0 | -1.7 | 0.1 | -1.8 | -1.4 | -0.6 | -0.7 |
| Forestry | -1.2 | -1.4 | 0.1 | -5.4 | -0.3 | -5.1 | -2.7 | -1.0 | -1.8 |

Note: Ethanol in the US and EU is from grains and it is sugarcane-based in Brazil.

Table 6. Impact of US and EU Biofuel Mandates on Bilateral Trade (change in import volume): 2006-2015 ($ millions)

| | Exporters: | Coarse Grains | | | | Oilseeds | | | | Other Food Products | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | US | EU | RoW | Tot Exp | US | EU | RoW | Tot Exp | US | EU | RoW | Tot Exp |
| 1 | US | 0 | -5 | -987 | -992 | 0 | 1504 | -663 | 840 | 0 | 83 | 249 | 332 |
| 2 | Canada | 53 | 9 | 16 | 78 | 11 | 275 | 95 | 380 | 42 | 16 | 24 | 82 |
| 3 | EU-27 | -15 | 0 | -565 | -580 | -2 | 0 | -1450 | -1452 | -111 | 0 | -1882 | -1993 |
| 4 | Brazil | 0 | 32 | -9 | 23 | 0 | 1703 | -261 | 1441 | -48 | -189 | -212 | -449 |
| 5 | Japan | 0 | 0 | 0 | 0 | 0 | 4 | 2 | 6 | 7 | 5 | 43 | 55 |
| 6 | China-Hong Kong | 0 | 4 | 124 | 129 | 2 | 443 | 122 | 567 | -9 | 14 | -25 | -19 |
| 7 | India | 1 | 2 | 4 | 7 | 21 | 237 | 124 | 382 | -4 | 11 | -5 | 1 |
| 8 | Latin American Energy Exporters | 5 | 63 | 122 | 190 | 4 | 482 | 157 | 644 | -43 | 24 | -29 | -47 |
| 9 | Rest of Latin America & Caribbean | 23 | 21 | 23 | 67 | 1 | 282 | 44 | 326 | -68 | -9 | -94 | -170 |
| 10 | EE & FSU Energy Exp | 2 | 57 | 80 | 139 | 1 | 569 | 20 | 590 | 1 | 75 | 53 | 129 |
| 11 | Rest of Europe | 0 | 6 | 13 | 19 | 1 | 80 | 4 | 84 | -2 | 39 | -1 | 36 |
| 12 | Middle Eastern N Africa energy exporters | 2 | 5 | 18 | 25 | 1 | 97 | 10 | 109 | 0 | 15 | 10 | 25 |
| 13 | Sub Saharan Energy exporters | 3 | 10 | 11 | 24 | 3 | 165 | 42 | 209 | 0 | 62 | 14 | 77 |
| 14 | Rest of North Africa & SSA | 1 | 3 | 43 | 47 | 1 | 42 | 3 | 45 | -1 | 14 | -6 | 7 |
| 15 | South Asian Energy exporters | 0 | 0 | 2 | 3 | 1 | 22 | 14 | 37 | 9 | 70 | 121 | 200 |
| 16 | Rest of High Income Asia | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 2 | -40 | -9 | -195 | -244 |
| 17 | Rest of Southeast & South Asia | 0 | 1 | 7 | 8 | 1 | 14 | 37 | 52 | 6 | 48 | 40 | 94 |
| 18 | Oceania countries | 0 | 1 | 58 | 59 | 1 | 116 | -7 | 111 | 6 | 18 | 67 | 92 |
| | **Total** | **75** | **209** | **-1039** | **-755** | **47** | **6036** | **-1708** | **4375** | **-255** | **289** | **-1828** | **-1794** |

Note: Change in volume of exports of coarse grains, oilseeds, and other food products, from all the 18 regions to the US and EU, respectively, were evaluated at initial market prices (trade volume changes in $ millions).

Table 7. Change in Crop Harvested Area by Region, due to EU and US Biofuel Mandates: 2006-2015 (%)

| Region: | Crops | | | | |
|---|---|---|---|---|---|
| | Coarse Grains | Oilseeds | Sugarcane | Other Grains | Other Agri |
| U.S.A. | 9.9 | 1.5 | -5.8 | -10.1 | -2.7 |
| Canada | 3.5 | 17.0 | -3.3 | -2.6 | -1.6 |
| EU-27 | -2.3 | 40.1 | -7.4 | -15.1 | -6.2 |
| Brazil | -3.2 | 16.0 | 3.9 | -10.9 | -5.2 |
| Japan | 10.8 | 7.6 | -0.7 | 0.8 | -0.1 |
| China-Hong Kong | 1.3 | 8.2 | -0.6 | -0.5 | -0.5 |
| India | -0.7 | 0.9 | -0.8 | 0.5 | -0.2 |
| Latin American Energy Exporters | 1.9 | 11.3 | -2.3 | -0.2 | -0.8 |
| Rest of Latin America & Caribbean | 1.8 | 11.6 | -1.6 | -0.6 | -0.3 |
| EE & FSU Energy Exp | 0.5 | 18.2 | -0.6 | 0.4 | -0.5 |
| Rest of Europe | 2.4 | 10.6 | 0.0 | 1.8 | 0.4 |
| Middle Eastern North Africa energy exporters | 4.0 | 8.6 | -0.9 | 2.5 | -0.4 |
| Sub Saharan Energy exporters | -0.8 | 13.8 | 0.0 | 2.4 | 1.2 |
| Rest of North Africa & SSA | 1.5 | 14.3 | -0.4 | 1.1 | 1.1 |
| South Asian Energy exporters | -0.5 | 3.7 | -0.9 | -0.6 | -0.1 |
| Rest of High Income Asia | 3.7 | 6.1 | -0.1 | -0.2 | 0.0 |
| Rest of Southeast & South Asia | -0.2 | 2.9 | -0.8 | 0.0 | -0.1 |
| Oceania countries | 4.0 | 17.3 | -0.6 | -1.3 | 0.3 |

Table 8. Decomposition of Change Land Cover by EU and US Biofuel Mandates (with Sensitivity Analysis): 2006-2015 (% change)

| | Crop Cover | | | | | Forest Cover | | | | | Pasture Cover | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | USEU 2015 | US 2015 | EU 2015 | Confidence Interval (95%) | | USEU 2015 | US 2015 | EU 2015 | Confidence Interval (95%) | | USEU 2015 | US 2015 | EU 2015 | Confidence Interval (95%) | |
| | | | | Lower | Upper | | | | Lower | Upper | | | | Lower | Upper |
| US | 0.80 | 0.57 | 0.24 | 0.41 | 1.20 | -3.14 | -2.29 | -0.85 | -4.74 | -1.53 | -4.93 | -3.35 | -1.58 | -7.48 | -2.39 |
| Canada | 2.75 | 0.73 | 2.02 | 1.27 | 4.23 | -2.71 | -0.72 | -1.99 | -4.26 | -1.16 | -4.57 | -1.15 | -3.42 | -7.29 | -1.85 |
| EU-27 | 1.92 | 0.13 | 1.80 | 1.07 | 2.78 | -8.34 | -0.54 | -7.80 | -11.78 | -4.89 | -9.68 | -0.66 | -9.02 | -13.29 | -6.06 |
| Brazil | 1.98 | 0.54 | 1.45 | 1.03 | 2.93 | -5.13 | -1.51 | -3.62 | -7.59 | -2.68 | -6.30 | -1.60 | -4.70 | -9.44 | -3.16 |
| Japan | 0.35 | 0.12 | 0.22 | -0.03 | 0.72 | -0.79 | -0.27 | -0.51 | -1.77 | 0.20 | -1.38 | -0.52 | -0.85 | -2.55 | -0.20 |
| China-Hong Kong | 0.03 | 0.02 | 0.01 | -0.08 | 0.13 | 0.09 | -0.06 | 0.15 | -0.39 | 0.57 | -0.82 | -0.18 | -0.64 | -1.72 | 0.08 |
| India | 0.09 | 0.01 | 0.07 | -0.05 | 0.23 | -0.05 | -0.02 | -0.03 | -0.50 | 0.41 | -0.44 | -0.06 | -0.38 | -1.04 | 0.16 |
| Latin American EEx. | 0.70 | 0.25 | 0.45 | 0.21 | 1.18 | -1.43 | -0.56 | -0.86 | -2.47 | -0.38 | -1.90 | -0.63 | -1.27 | -3.33 | -0.47 |
| Rest of Latin Am. | 0.53 | 0.14 | 0.40 | 0.16 | 0.91 | -0.40 | -0.28 | -0.13 | -1.44 | 0.63 | -2.10 | -0.46 | -1.64 | -3.56 | -0.63 |
| EE & FSU EEx. | 0.54 | 0.10 | 0.44 | 0.08 | 0.99 | -0.50 | -0.14 | -0.37 | -1.85 | 0.84 | -2.87 | -0.48 | -2.39 | -4.90 | -0.84 |
| Rest of Europe | 1.14 | 0.23 | 0.91 | 0.38 | 1.90 | -1.01 | -0.32 | -0.69 | -2.28 | 0.25 | -2.69 | -0.44 | -2.26 | -4.43 | -0.96 |
| Middle Eastern N Africa EEx. | 0.44 | 0.12 | 0.33 | 0.07 | 0.82 | -1.13 | -0.31 | -0.82 | -2.30 | 0.03 | -1.70 | -0.45 | -1.25 | -3.06 | -0.33 |
| Sub Saharan EEx. | 1.36 | 0.32 | 1.04 | 0.35 | 2.36 | -0.81 | -0.19 | -0.62 | -1.51 | -0.10 | -2.05 | -0.45 | -1.60 | -3.38 | -0.73 |
| Rest of North Africa & SSA | 1.56 | 0.36 | 1.20 | 0.60 | 2.52 | -1.81 | -0.45 | -1.36 | -3.10 | -0.51 | -3.22 | -0.66 | -2.56 | -5.25 | -1.18 |
| South Asian EEx. | -0.06 | -0.01 | -0.05 | -0.19 | 0.08 | 0.29 | 0.06 | 0.24 | -0.24 | 0.83 | -0.58 | -0.13 | -0.45 | -1.17 | 0.01 |
| Rest of High Income Asia | 0.00 | 0.01 | 0.00 | -0.03 | 0.03 | 0.53 | 0.07 | 0.46 | -0.09 | 1.15 | -0.79 | -0.29 | -0.50 | -1.54 | -0.04 |
| Rest of Southeast & South Asia | 0.06 | 0.01 | 0.05 | -0.02 | 0.13 | -0.12 | -0.04 | -0.08 | -0.51 | 0.28 | -0.61 | -0.11 | -0.50 | -1.33 | 0.11 |
| Oceania countries | 0.93 | 0.22 | 0.70 | 0.27 | 1.58 | -0.96 | -0.28 | -0.68 | -1.64 | -0.28 | -1.25 | -0.28 | -0.98 | -2.22 | -0.28 |

Note: USEU2015 policy impact is decomposed into US2015 and EU2015 effects. The confidence intervals pertain to the USEU2015 combined impact.

Table 9. Systematic Sensitivity Analysis (SSA) of US and EU Biofuel Mandates – Amount of Variation of Key Parameters

| | Parameters | Lower bound | Mean | Upper bound | Standard Deviation | Amount of Variation: SD*(6^0.5) |
|---|---|---|---|---|---|---|
| 1 | Yield elasticity[1] (YDE_Target) | 0.00 | 0.40 | 0.80 | 0.163 | 0.400 |
| 2 | Elasticity of transformation of land supply (ETRAE-2)[2] | -0.10 | -0.50 | -0.90 | 0.163 | 0.400 |
| 3 | Elasticity. of transformation for crop land (ETRAE-1)[3] | -0.04 | -0.20 | -0.36 | 0.065 | 0.16 |
| 4 | Armington CES elasticity of substitution for domestic and imported (ESUBD)[4]: | | | | | |
| | a. Coarse Grains | 0.75 | 1.30 | 1.85 | 0.225 | 0.550 |
| | b. Other Grains | 2.43 | 4.52 | 6.61 | 0.853 | 2.089 |
| | c. Oilseeds | 2.05 | 2.45 | 2.85 | 0.163 | 0.400 |
| | d. Sugarcane | 1.70 | 2.70 | 3.70 | 0.408 | 1.000 |
| | e. Other Agri | 2.18 | 2.49 | 2.81 | 0.129 | 0.315 |

Sources: [1]Keeney and Hertel (2008); [2]Ahmed, Hertel and Lubowski (2008); [3]FAPRI (2004); [4]Hertel *et al.* (2007)

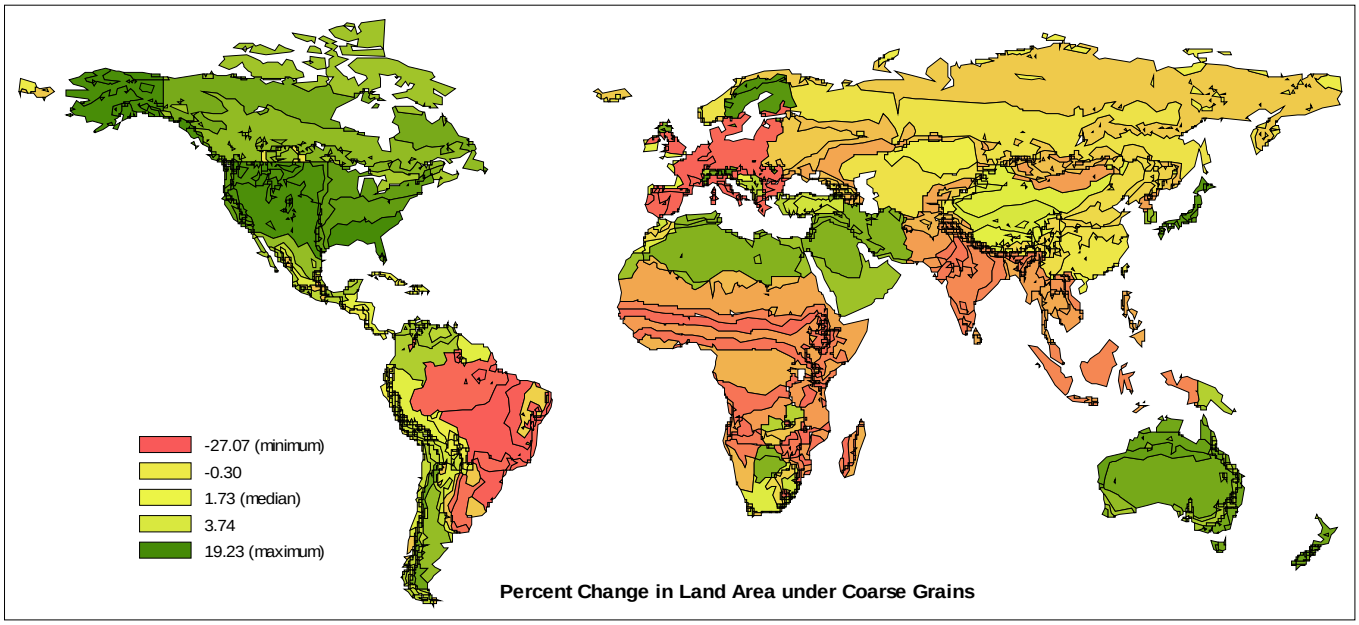


Figure 1. Change in Land Area under Coarse Grains across AEZs (2006-2015)

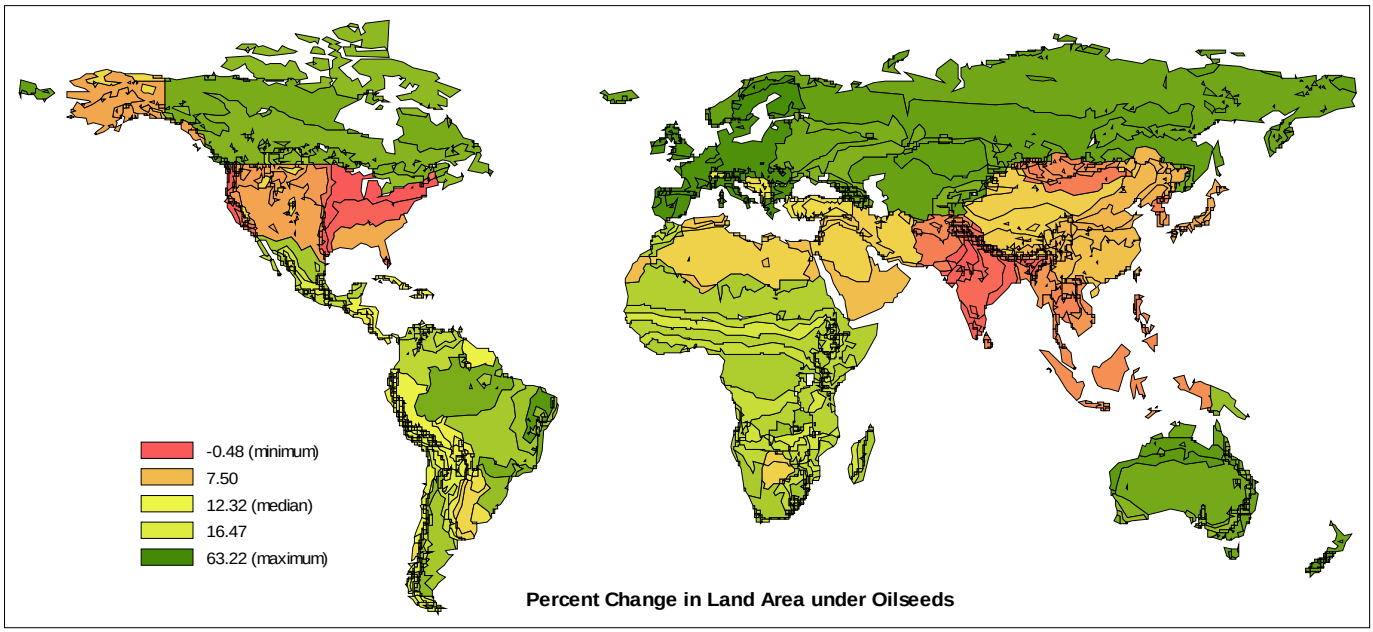


Figure 2. Change in Land Area under Oilseeds across AEZs (2006-2015)

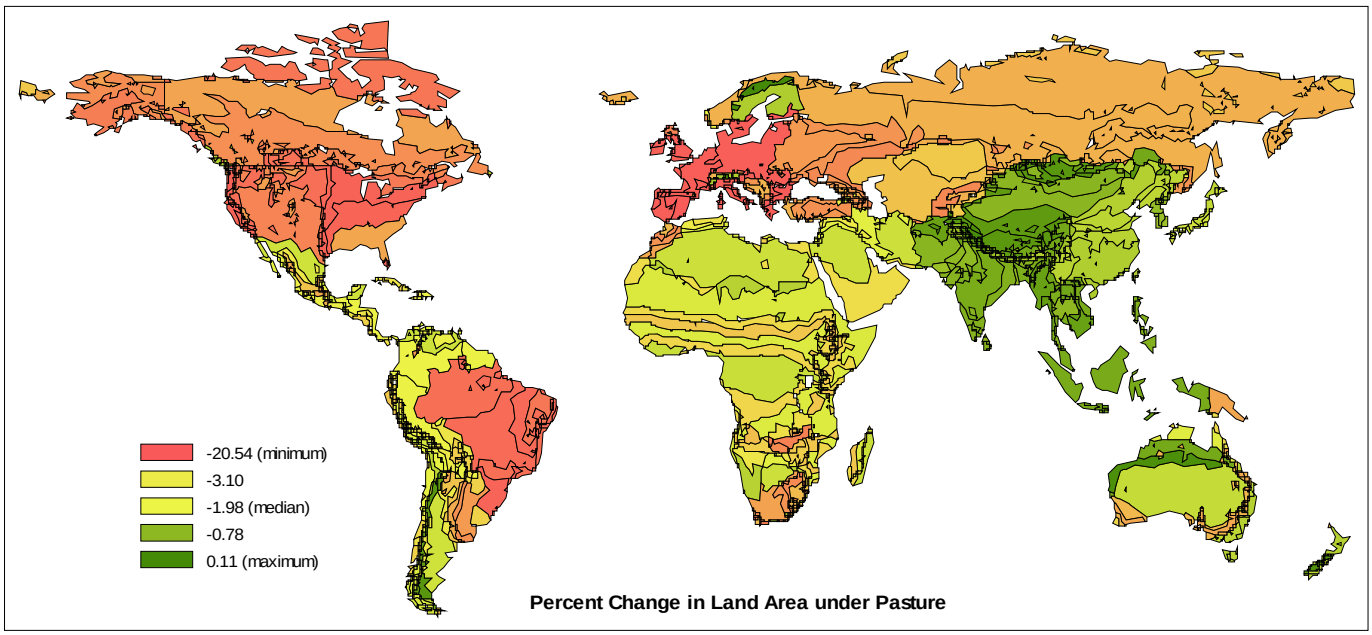


Figure 3. Change in Land Area under Pasture land across AEZs (2006-2015).

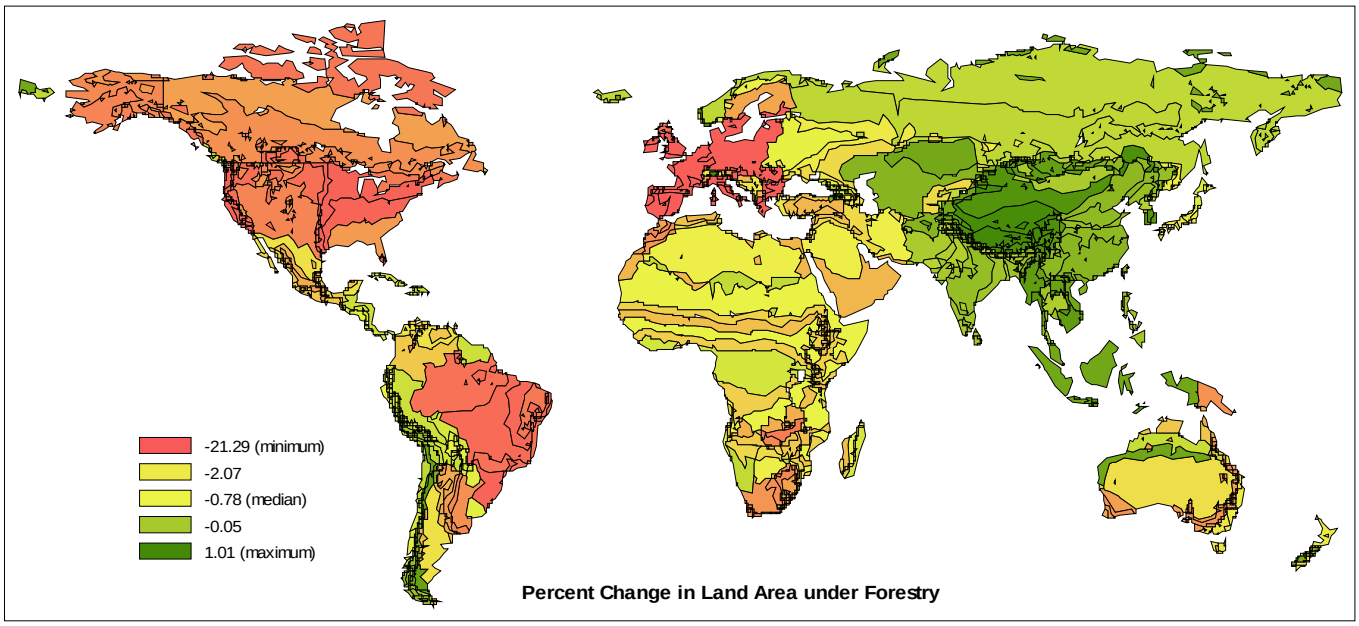


Figure 4. Change in Land Area under Forest across AEZs (2006-2015).

## Appendix A: A Partial Equilibrium Model of the Ethanol Market

Consider an ethanol industry selling into two domestic market segments: in the first market, ethanol is used as a gasoline additive ($QI$), in strict proportion to total gasoline production. As discussed in the paper, legal developments in the additive market were an important component of the US ethanol boom between 2001 and 2006. The second market is the market for ethanol as an energy substitute ($QE$). In contrast to the additive market, the demand in this market is price sensitive, with ethanol's market share depending on its price, relative to refined petroleum. For ease of exposition, and to be consistent with the general equilibrium model, we will think of the additive demand as a derived demand by the petroleum refinery sector, and the energy substitution as being undertaken by consumers.

Market clearing, in the absence of exports, may then be written as:

$$QO = QI + QE \tag{1}$$

or, in percentage change form, where lower case denotes the percentage change in the upper case variable:

$$qo = (1-\alpha)qi + \alpha qe \tag{2}$$

where $\alpha = \mathrm{QE} / \mathrm{QO}$, is the share of total ethanol output ($\mathrm{QO}$) going to the price sensitive side of the market.

Now we formally characterize the behavior of each source of demand for ethanol as follows:

$$qi = ai + qp \tag{3}$$

where $\mathrm{AI} = \mathrm{QI}/\mathrm{QP}$ is the ethanol input – output coefficient in the Leontief production function for petroleum products, and:

$$qe = ue - \sigma(pe - p) \tag{4}$$

where UE is the level of utility from household energy consumption and $\sigma$ is the constant elasticity of substitution ($\mathrm{CES}$) amongst energy products consumed by the household. The price ratio $\mathrm{PE}/\mathrm{P}$ refers to the price of ethanol relative to a composite price index of all energy products consumed by the household. The percentage change in this ratio is given by the difference in the two percentage changes: ($pe - p$). When pre-multiplied by σ, this determines the price-sensitive component of households' change in demand for ethanol. Substituting (3) and (4) into (2), we obtain *the market demand for ethanol*:

$$qo = (1-\alpha)(ai + qp) + \alpha[ue - \sigma(pe - p)] \tag{5}$$

On the supply side, we assume constant returns to scale in ethanol production, which, along with entry/exit, gives zero pure profits in the medium run:

$$po = \sum_j \theta_j pf_j \tag{6}$$

Where $po$ is the percentage change in the producer price for ethanol, $pf_j$ is the percentage change in price of input $\mathrm{j}$, used in biofuel production, and $\theta_j$ is the cost share of that input. Assuming that corn is the only input in less than perfectly elastic supply, and that it is used in fixed proportion to ethanol output (fixed $QF_c / QO$), we can complete the supply–side specifications with the following equations:

$$qf_c = qo \tag{7}$$

$$qf_c = \nu_c pf_c \tag{8}$$

where $\nu_c$ is the supply elasticity of corn to the ethanol sector. With $pf_j = 0 \ \forall j \neq c$, we can solve (6) for $pf_c = \theta_c^{-1} po$. Plugging this and (7) into (8) gives the *market supply of ethanol*:

$$qo = \nu_c \theta_c^{-1} po \tag{9}$$

We complete the model by allowing for ethanol subsidies. These are typically provided in the form of blenders' subsidies (U.S.) or tax abatements (EU). We write them here as the power of an *ad valorem* equivalent subsidy: $\mathrm{S} = \mathrm{PO} / \mathrm{PE}$, i.e. the ratio of producer to user prices for ethanol. Totally differentiating and converting to percentage change form, we have the final equation in the partial equilibrium model:

$$po = pe + s \tag{10}$$

Now, in solving this model, we will make the additional assumption that: (a) the aggregate level of petroleum output is fixed ($\mathrm{qp}=0$) (b) aggregate household utility from energy consumption is fixed ($ue = 0$), and (c) the composite price of energy is exogenously given (i.e., ethanol's share in the total is small, so that we can approximate *p* without referring to *pe*). All of these assumptions are relaxed in the empirical section of the model. Using (10) to eliminate *pe* from (6) and equating supply (9) and demand (6), we can solve for the equilibrium producer price of ethanol:

$$po^* = [(1-\alpha)ai + \alpha\sigma(p+s)] / [\nu_c \theta_c^{-1} \alpha\sigma] \tag{11}$$

Where $-\alpha\sigma = \varepsilon_d$ is the composite price elasticity of demand for ethanol, and $\nu_c \theta_c^{-1} = \varepsilon_s$ is the price elasticity of supply for ethanol. To determine the equilibrium output, multiply both sides by $\varepsilon_s$ to get the following (where we have used the definitions of supply and demand elasticities given above):

$$qo^* = \varepsilon_s[(1-\alpha)ai - \varepsilon_D(p+s)]/[\varepsilon_s - \varepsilon_D] \tag{12}$$

From (12), we can see a number of important things. First of all, the contribution of changes in the additive requirements of gasoline to total ethanol output depend on the change in the input-output ratio (*ai*) as well as the initial share of total sales going to this market segment. The price sensitive portion of the market depends on what happens to the price of energy in general (*p*) and the power of the *ad valorem* subsidy (*s*), which are additive in the solution of the model. Their significance depends on the share of the total market for ethanol that is price sensitive ($\alpha$) and the ease of substitution between ethanol and other fuels ($\sigma$).

We also see from (12) that supply response is important. If the total availability of feedstock (corn) is fixed ($\nu_c = 0$), then $qo^* = 0$. Furthermore, as the supply response of corn, $\nu_c$, rises and the share of corn in overall ethanol costs falls ($\theta_c \to 0$), $\nu_c \theta_c^{-1} = \varepsilon_s$ rises, thereby boosting supply and dampening the equilibrium price change.

Equation (12) is critical when it comes to decomposing the contribution of the three main drives of US ethanol production over the 2001-2006 period: the ban or competing gasoline additives, the rise in the price of petroleum, and the change in the power of the subsidy or ethanol. In the EU, we restrict ourselves to the latter two effects, and in Brazil, we will focus solely on the impact of higher petroleum prices.