The Role of Modeling Assumptions and Policy Instruments in Evaluating the Global Implications of U.S. Biofuel Policies[1]

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Abstract

A primary objective of current U.S. biofuel law – the “Energy Independence and Security Act of 2007” (EISA) – is to reduce dependence on imported oil, but the law also requires biofuels to meet carbon emission reduction thresholds relative to petroleum fuels. EISA created a renewable fuel standard with annual targets for U.S. biofuel use that climb gradually from 9 billion gallons per year in 2008 to 36 billion gallons (or about 136 billion liters) of biofuels per year by 2022. The most controversial aspects of U.S. biofuel policy have centered on the global social and environmental implications of land use. In particular, there is an ongoing debate about whether “indirect land use change” (ILUC) would cause biofuels to become a net source, rather than sink, of carbon emissions. Estimates of ILUC induced by biofuel production can only be inferred through modeling. This paper evaluates how model structure, underlying assumptions, and the representation of policy instruments influence the results of U.S. biofuel policy simulations. The analysis shows that differences in these factors can lead to divergent model estimates of land use and economic effects. Model estimates of the net conversion of forests and grasslands induced by U.S. biofuel policy range from 0.09 ha/1000 gallons described in this paper to 0.73 ha/1000 gallons from early studies in the ILUC change debate. We note that several important factors governing LUC change remain to be examined. Challenges that must be addressed to improve global land use change modeling are highlighted.

I. INTRODUCTION

U.S. biofuel policy has multiple goals that include a reduced reliance on imported crude oil and a reduction in the greenhouse gas (GHG) emission intensity of transportation fuels. The Energy Independence and Security Act of 2007 (EISA) establishes a new renewable fuel standard (often referred to as Renewable Fuel Standard-2, or RFS2) with categories and eligibility requirements to meet mandated GHG performance thresholds. The thresholds represent a percentage reduction in GHG emissions compared to baseline petroleum fuel based on lifecycle GHG emission - defined as "the aggregate quantity of greenhouse gas emissions (including direct emissions *and significant indirect emissions such as significant emissions from land use changes)*". The RFS2 sets annual targets for U.S. biofuels that climb gradually from 9 billion gallons per year in 2008 to 36 billion gallons[3] per year by 2022. The RFS2 includes specific production and emission reduction targets for new categories defined as "biomass-based diesel," "cellulosic" and "advanced" fuels (the latter being the sum of biomass-based diesel, cellulosic, or other biomass-based fuels that offer at least a 50% reduction in emissions compared to the baseline fuel displaced). The law also places a cap on "conventional" ethanol at 15 billion gallons per year, which in the U.S. is produced primarily from corn. New conventional ethanol production is required to GHG emissions by at least 20 percent compared to gasoline.

Corn-based ethanol production in the U.S. increased from 1.8 billion gallons in 2001 to 10.8 billion gallons in 2009. In 2010, installed corn ethanol capacity is estimated to reach 13.5 billion gallons per year and another 1.3 billion gallons capacity is reported as "under construction." Meanwhile, the development of advanced biofuels and cellulosic ethanol has been slower than that implied by EISA and the cellulosic target for 2010 was lowered by the U.S. Environmental Protection Agency (USEPA) from 100 million gallons to 6.5 million gallons (USEPA, 2010). The costs and benefits of using ethanol to replace imported fossil fuels have received attention, but most of the recent scientific debate has focused on the issue of "indirect land use change" (ILUC). In the U.S., this discussion has taken place in the context of expanding corn ethanol production. The precedents that are set for calculating the ILUC effects of conventional biofuels have crucial implications for any other biofuels, including dedicated cellulosic crops, if they are perceived to occupy potentially productive lands.

Since ILUC cannot be observed directly from data, it must be estimated through modeling. ILUC modeling is complicated by the multi-sectoral, spatial and temporal dimensions of land use change. Modeling efforts have incorporated different combinations of assumptions to address these complications, leading to different estimates of the ILUC effects of biofuels. For example, early analysis by Searchinger et al (2008) suggested that U.S. corn ethanol production could be a net GHG emission source when compared to fossil fuels. In March 2010, the USEPA ruled that U.S. corn ethanol met the emission threshold for conventional biofuel (i.e. 20 percent emission reduction compared to gasoline), but this outcome was influenced by the assumption of higher efficiency of ethanol conversion using natural gas, rather than coal, as fuel. The EPA rule also found that sugarcane-based ethanol produced in Brazil met the performance targets of an advanced biofuel (i.e. the 50 percent emission reduction threshold). Meanwhile, modeling by Lapola et al (2010) suggested that indirect land use change can overcome carbon savings from biofuels in Brazil. Thus, the debate on the ILUC effects of global biofuel production is far from closed and there is a continuing need to improve understanding of the modeling issues and results.

Simulations of U.S. biofuel policy generally assume that the shock to corn demand leads to dramatic shifts in land use from other crops to corn and to a reduction in U.S. grain exports. These factors in turn are assumed to induce new land clearing in other nations (ILUC) which would not have otherwise occurred. Evaluation of these assumptions is helped by the availability of empirical data for 2001-2009, a period when U.S. corn ethanol production increased at an annual average rate of 25 percent per year. An examination of these data suggests that many of the basic assumptions used in model simulations merit review.

Figure 1 provides a summary of the supply and use of corn in the U.S. from 1990-2009 (USDA, 2010). It shows that while corn use for ethanol production quintupled between 2001 and 2009, exports also increased

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[3] 1 U.S. gallon = 3.7854 liters

steadily through 2007 along with a growing global economy. The decline in exports during 2008 and 2009 was associated with reductions in global corn demand due to a worldwide recession. Other domestic uses of corn (Feed & Residual Use; Other Food, Seed & Industrial Use) shrank slightly or increased at a slow rate, and the growth in corn production exceeded the annual trend between 2002 and 2004, and again in 2007. The difference between production and total distributions suggests that despite some fluctuations, the net stock drawdown from 2001-2009 was minimal.

Figure 2 illustrates that the significant increase in U.S. corn production from 2001 to 2009 does not support the notion of dramatic changes in cropland use from the increased corn ethanol production. The harvested area under four major crop groups remained under 100 million hectares during the period. Harvested corn area changed significantly only in 2007, and coincided with record-level corn exports. The harvested area of oilseeds which is usually assumed to be displaced by corn, was maintained or grew with the exception of 2007. These land use data emphasize the importance of yield change and inter-crop land realignments (rather than cropland expansion) in producing larger volumes of corn in recent years.

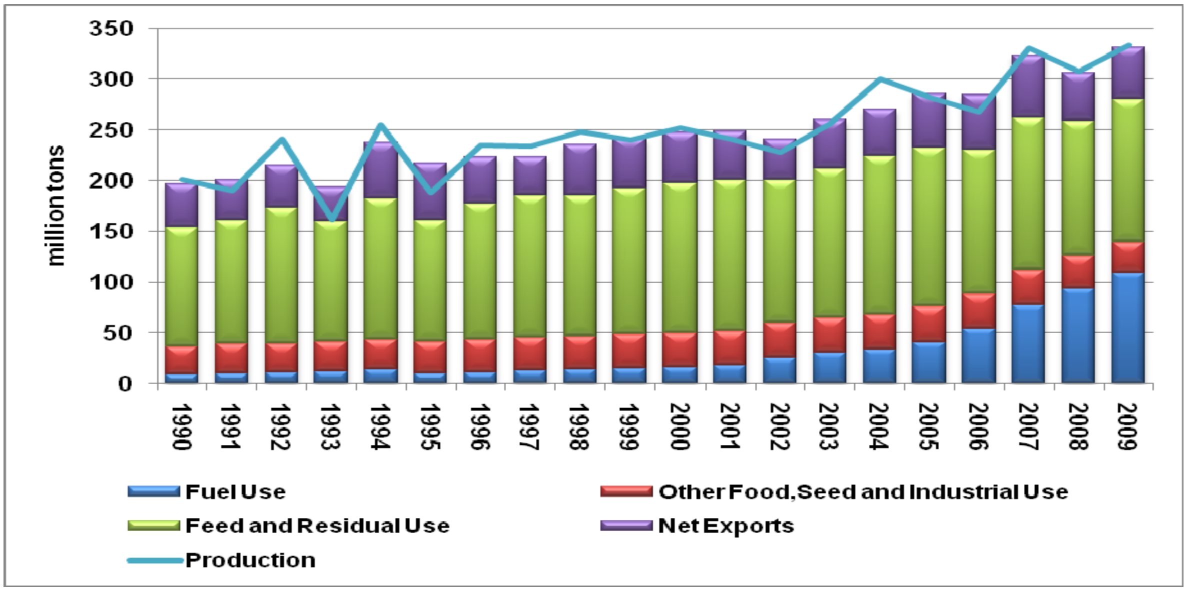

Figure 1. Supply and Distribution of Corn in the United States (1990-2009)

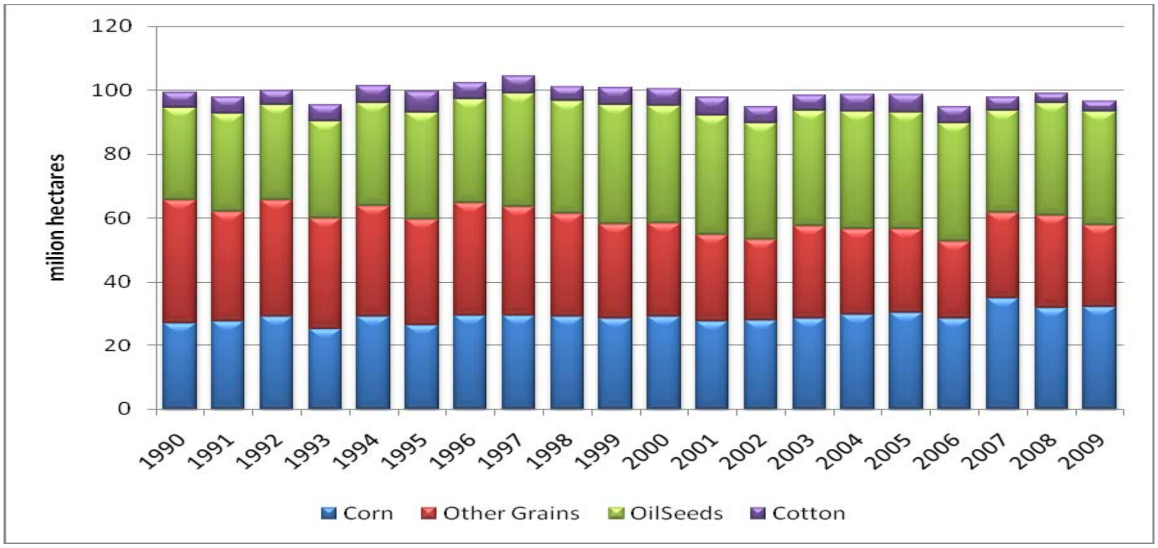

Figure 2. Harvested Area of Major Crops in the United States (1990-2009)

This paper evaluates the influence of model structure, underlying assumptions, and the representation of policy instruments in simulations that estimate the global effects of U.S. biofuel policies. The paper illustrates how these factors can lead to significantly different results and highlights the need to improve input data and modeling approaches to address global land use change. The rest of the paper is organized as follows. The next section discusses a number of issues, including model structure, policy instrument specifications and uncertainty. In the third section, we present an overview of the model employed in this study, as well as a description of the scenarios simulated with the model. The following section discusses our simulation results, and the paper ends with a concluding section.

II. ISSUES IN BIOFUEL POLICY MODELING: MODEL STRUCTURE, POLICY INSTRUMENTS AND UNCERTAINTY

Estimation of the global effects of biofuel policy requires modeling of socio-economic activities in four major areas: 1) Agricultural production and use; 2) Energy production and use; 3) Domestic and global economy-wide interactions; and 4) Land use change. Specifications in each of the above areas determine the overall structure of a given model. Partial and general equilibrium models have been used to simulate U.S. biofuel policy. Partial equilibrium (PE) models concentrate on one or a few sectors of the economy and can model these sectors in detail. General equilibrium (GE) models attempt to incorporate all sectors of an economy, but scale and tractability issues result in less detail than in PE models.

The Forest and Agricultural Sector Optimization Model (FASOM), Food and Agricultural Policy Research Institute (FAPRI), and Global Trade Analysis Project (GTAP) are the prominent models currently employed in the evaluation of the effects of U.S. biofuel policy. FAPRI is a global multi-market collection of non-spatial, econometric crop and livestock sub-models. FASOM is a model of the U.S. forest and agricultural sectors. These two PE models do not incorporate energy production and use and other sectors of the economy, although there is an ethanol sub-module. GTAP is a GE model incorporating endogenous interactions among energy, agriculture and other sectors of the economy. The basic differences between PE and GE models may lead to substantially different estimates of the global implications of biofuel policies. A shortcoming that is common to existing simulations of the ILUC estimates of U.S. biofuel policy is in the modeling of land use change. In addition, issues associated with how well biofuel policy is specified in the simulations are crucial to the model results. Finally, given serious data limitations on global land use and the scope of the processes involved in determining ILUC, current estimates incorporate considerable uncertainty.

a. Land use change modeling

Land is an economic asset that is essentially fixed in total availability and location. Thus, while land use decisions are investment decisions, land's fixed quantities and locations distinguish it from other capital assets, with crucial implications for modeling. Although it is an economic commodity, land also has intrinsic values to society, provides life-support for the planet and habitat for all terrestrial species. As such, land use is subject to a host of drivers, including cultural, biophysical, political and demographic forces, as well as market variables. Unlike other capital assets, non-market drivers dominate long-term land use change processes. Modeling that seeks to describe the effects of a policy on land use change must address land heterogeneity, non-market and market drivers of land use, the context of ongoing reallocation of land uses, and the effects of governance, tenure, technology change, and a host of local policies. In order to estimate the ILUC effects of biofuel policy, models must define the mechanisms by which changes in one nation or region are transmitted to the rest of the world. In addition, since the ultimate objective is to estimate the emissions associated with potential land use change, the latter must be understood at the local level. The heterogeneity and management of land over space and time, crucial to the pattern of emissions and stocks of carbon on the land, are expressly local.

Economic modeling of land use change is largely based on the concept of profit maximization where land is a factor of production like labor, energy, materials and capital. Partial equilibrium models incorporate land either in reduced form functions based on land price elasticities or through price-based optimization of land allocation. Heistermann et al (2006) include the FASOM model in the latter category. The POLYSYS model (Ugarte and Ray, 2000) allocates U.S. land to crops at the sub-national level using linear programming or supply elasticities based on expected returns. Other models allocate land in proportion to expected profits from different uses. In GE models the constant elasticity of substitution (CES) and constant elasticity of transformation (CET) functions are used to model the demand and supply of land, respectively. These functions imply that the relative ratio of land and other factors of production (in the case of the CES) or ratio of land supply to different uses (in the case of the CET) respond to their relative prices (rents) according to a given elasticity. Some implementations attempt to account for land heterogeneity and change dynamics. Recent GTAP models disaggregate land into agro-ecological zones and model land use decisions using a recursive dynamic framework where access cost is a nonlinear function of unconverted area and rate of conversion (Hertel et al, 2010; Hertel et al, 2010a; Golub et al 2008). Ronneberger et al (2008) include land owner risk aversion using the variance of expected profit, with total costs specified as a quadratic function of crop allocations. Heistermann et al (2006) indicate that the GTAPE-L model incorporates a land transition matrix that tracks the history of land movement across sectors.

The need to capture local landscape impacts has motivated applications of more detailed LUC modeling frameworks. Heisterman et al. (2006) highlighted the coupled GTAP-LEI/IMAGE model which links the rich global economy-wide interactions in the GTAP framework with the rule-based 0.5^o spatial grid resolution land cover sub-model of the IMAGE model. Cropland allocation is based on factors such as proximity to other agricultural cells, potential productivity, distance to water bodies and population density. Similarly, Lapola et al (2010) used a partial equilibrium agricultural model and a spatially explicit land allocation model, LandSHIFT, to examine the potential direct and indirect land use change effects of Brazil's biofuel production targets. LandSHIFT, like IMAGE, has a 0.5^o spatial grid resolution and uses multicriteria-suitability analysis, considering factors such as yield, slope, neighborhood to population and cropland, road network and soil fertility, to determine land allocation.

The above examples reflect considerable effort to improve the representation of land assets and land use decisions, but the models are still unable to fully address the ILUC implications of biofuel policy. Modeling of U.S. biofuel policy to date has yet to incorporate the dynamics of land use changes over space and time that are essential to generate accurate estimates of LUC emissions. Disaggregation of land into agro-ecological zones in some modeling efforts does not represent explicit spatial interactions, but are attempts to reflect productivity differences across land types. The implementation in GTAP-LEI/IMAGE and LandSHIFT begins to address some of the spatial issues. However, understanding and modeling of location-specific factors is only an initial step that needs to be integrated within a causal framework to separate the implications of biofuels from the multitude of other market and non-market factors that drive land use change.

b. Policy Instruments

The traditional classification of policy instruments recognizes that between the two extremes of “voluntary” and “command/control” is a continuum of other approaches for policy intervention in an economy. This continuum includes instruments such as taxes, tax exemptions, tariffs, subsidies, quotas, performance and technology standards, and regulated markets, among others. U.S. (and global) biofuel policies reflect a complex mix of policy instruments and have shifted over time (see reviews by Yaccoubi, 2008; Rajagopal and Zilberman, 2007; Koplow, 2006). Biofuel policies interact with other policies, and tend to involve several sectors of the economy (including energy, agriculture and trade) and multiple jurisdictions,

Each policy instrument may have a different level of effectiveness, efficiency, cost, welfare effects, environmental impacts and other implications. Some policies, such as taxes and tradable permits, are theoretically equivalent, but the economic and environmental implications differ substantially in practice due to transaction costs and other factors. In addition, the performance of policy instruments in partial equilibrium does not translate to the general equilibrium framework due to differences in their induced effects. Goulder and Parry (2008) highlighted several issues in the choice and effects of policy instruments. Among these are the significant tradeoffs in policy fairness, political feasibility and cost-effectiveness. In addition, potential interactions among different policies or among different jurisdictions are a matter of concern, although it is often necessary to design hybrid instruments that combine features of individual instruments. De Gorter and Just (2010) evaluate the social costs and benefits of biofuel policies within a partial equilibrium framework and suggest that mandates are superior to consumption subsidies, especially when fuel taxes are suboptimal. They conclude that subsidies in combination with mandates could lead to perverse incentives and that the welfare effects of biofuel policies could be significant. In addition, they note that "the ranking of a mandate and a tax credit becomes more complicated if general equilibrium effects are incorporated in the analysis." These issues point to the need for care in policy design (and policy simulation).

The fulcrum of current U.S. biofuel policy, the RFS2 under EISA, is substantially different from previous tax exemption and subsidy-based policies. It is a hybrid technology mandate and performance standard. The motor fuel blending requirements represent a technology mandate, while the emission thresholds set for each fuel type are performance standards. The oxygenate requirements in U.S. gasoline and recent rules that eliminate MTBE as an oxygenate can also be similarly interpreted as a hybrid technology and performance standard. These policies work in conjunction with other subsidy- and tax-based policies at federal and state levels, but the latter price-based incentives have not changed significantly in recent years. Despite this, most recent simulations of the effects of RFS2 have relied on price-based specifications (Hertel et al, 2010; Hertel et al, 2010a). Searchinger et al (2008) imposed a $10 increase on the price of crude oil in order to motivate the production of ethanol within the FAPRI model (Fabiosa et al, 2010). The simulations underlying the recent USEPA ruling decoupled the ethanol module of FAPRI and specified ethanol demand exogenously. Although the real world implementation of the policy is a blending, rather than a demand mandate, the USEPA approach is more consistent with the RFS2 since no new taxes or subsidies are imposed.

Major issues arise from inaccurate specification of biofuel policy in model simulations. Since ILUC is not yet well-understood, the affects of small changes in many interacting variables in model specifications have not been adequately assessed and documented. For example, a change in the oil price could have major ILUC effects that are unrelated to biofuel production. It is therefore essential to properly isolate the effects of the intended policy from other factors that could influence model simulation results. Otherwise, the ILUC estimates are likely to be under- or over-estimated due to the influence of these other variables, rather than biofuel policies. In essence, if the model specifications do not match the policy being analyzed, the resulting impacts cannot be assumed to be a product of the policy.

c. Other Modeling Uncertainties

Modeling the large number of processes underlying land use change invariably requires consideration of a large number of parameters. The parameters included in models simulating biofuel policy are selected from a wide-ranging set of potential data sources, including econometric estimation, “best guesses” or consensus and calibration. The data to support these parameters represent a major source of uncertainty in estimates of the land use implications of biofuel policy. Another source of modeling uncertainty is the aggregation involved in keeping such potentially large models tractable. Aggregation is often necessary in both partial and general equilibrium models, but more so in the latter because of the scope of economic activities represented. However, in some cases aggregation may affect simulation results significantly and needs to be accounted for in such cases. The economic and policy environments, as well as the quantity, quality and resolution (temporal and spatial scales) of data needed to specify models at the global level varies by locality, nation and region and represents another major source of uncertainty. Much of the data required for modeling the land use change implications of biofuel policy, such as high-resolution datasets that document historic land use changes and the corresponding changes in carbon stocks and GHG fluxes over time, simply do not exist.

In the face of data gaps and uncertainties, simulation results need to be accompanied by rigorous uncertainty evaluation. In the context of biofuel policy, sensitivity analysis needs to be conducted with respect to parameters such as land-related and ethanol-petroleum elasticities. In addition, model parameters should reflect the time frame of the simulations i.e. whether they represent appropriately defined short-, medium- or long-run outlooks. The largest sources of uncertainty when modeling the effects of biofuel policy are the land use data and land-related model specifications. These are issues that will require a concerted to address (Kline et al 2009; Kline et al 2009a).

III. BIOFUEL POLICY SIMULATION USING A MODIFIED GTAP MODEL

This study employs a modified GTAP model to perform simulations of the global implications of U.S. biofuel policy. GTAP is a dual database and modeling framework developed by the Center for Global Trade Analysis. The GTAP database as of version 6 includes 87 world regions and 57 producing sectors/commodities.[4] It combines "bilateral trade, transport and production data characterizing economic linkages among regions, together with individual country input-output databases which account for intersectoral linkages within regions" (CGTA, 2008). The standard model built on top of the GTAP database is implemented using a percentage change approach in which all equations of the model are solved as a sequence of linear approximations of the actual non-linear model. The freely available version of the GTAP model has only five regions and eight sectors, but is easily expanded by combining data generated from a licensed GTAP database package.

The modified GTAP 6 database by Taheripour et al. (2007) has a 2001 base year and incorporates three types of biofuels: ethanol-1 (coarse grain based), ethanol-2 (sugarcane-beet based), and biodiesel (vegetable oil based). We additionally incorporate the ethanol by-product, Distillers Grains with Solubles (DGS), which is a substitute for corn and soymeal in livestock feed. The SAGE[5] land-use database and GTAP 6 emission data were also added to the database. SAGE disaggregates global land into Agro-Ecological Zones (AEZ) in seven broad land-cover categories, with the crop category further divided into 175 crops. Our model, designated GTAP-ORNL, was built on top of the GTAP-E-6.2[6] model version, which relaxes some assumptions of the standard GTAP model by allowing for energy substitution in production. The structure of production activities in the GTAP-ORNL model is shown in Figure 3 and the elasticity of substitution/transformation parameters are largely based on Hertel et al (2010), where the specifications are the same. The model includes 18 world regions and 28 sectors/commodities. The above data sources and underlying model are the same components on which the GTAP-BIO (Hertel et al, 2010) was built, and the structure of the two models are similar except for differences in land and biofuel specifications that are described below.

a. Biofuel Specification

The GTAP database employed for this study allocates 75 percent of biofuel sales to the petroleum sector. This reflects the essence of ethanol blending so that purchases of petroleum products in the model represent a petroleum-biofuel mix. The remaining 25 percent of biofuel sales is allocated mostly to households, while small proportions are purchased by industries.

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[4] The database is available by subscription only. Version 7 of the database was released in late 2008 and has 113 regions and 57 commodities. The simulations discussed in these paper are based on version 6 of the database

[5] The Center for Sustainability and the Global Environment (SAGE) is a Research Center of the Nelson Institute for Environmental Studies at the University of Wisconsin-Madison. http://www.sage.wisc.edu/about.html

[6] The GTAP-E version of the model used by ORNL is labeled GTAP-E 6-pre2 (McDougall and Golub, 2007) and seems to be the most recent version of the GTAP model available on the GTAP website. This model is based on an 8 sector by 8 regions database.

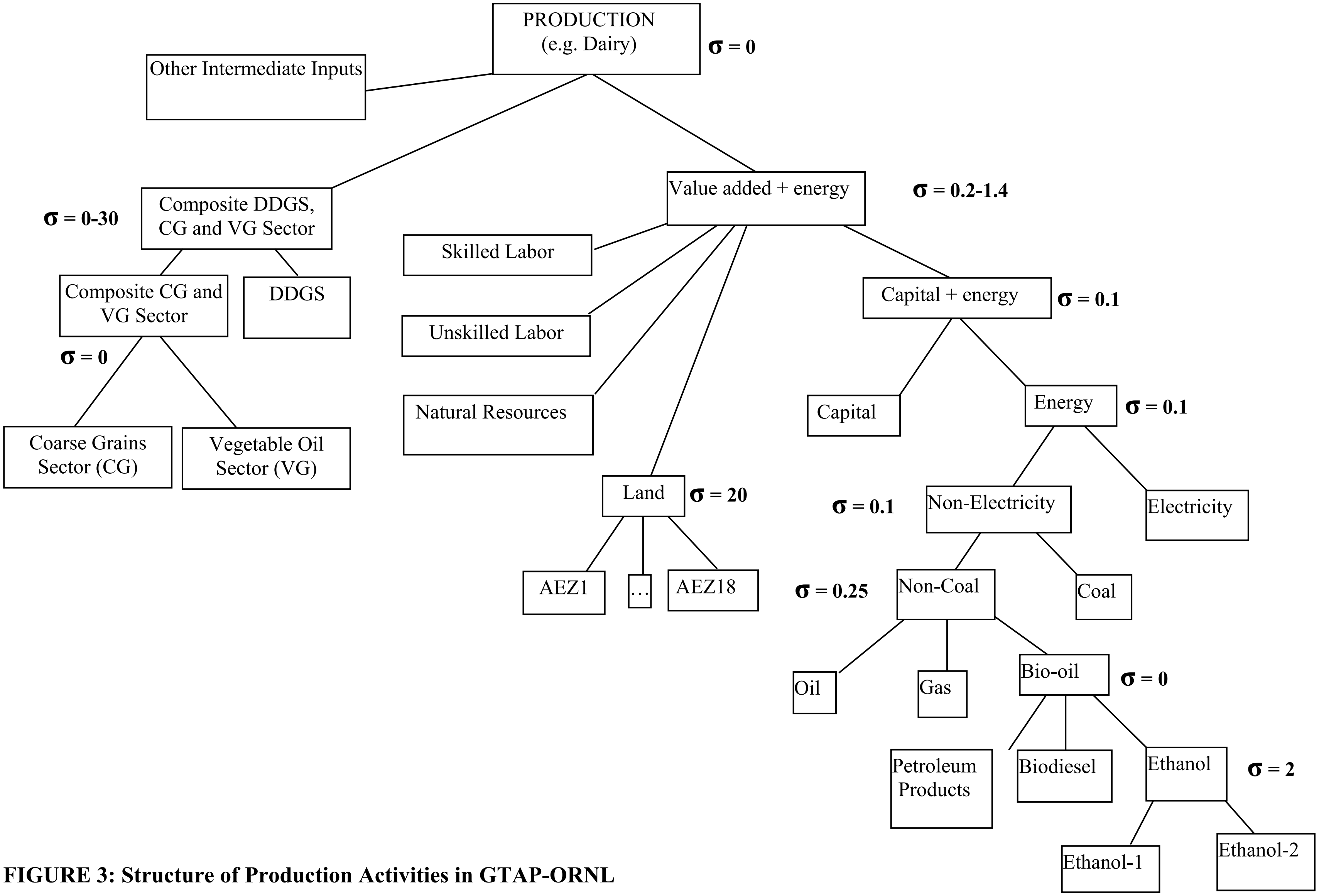

FIGURE 3: Structure of Production Activities in GTAP-ORNL

Given the use of a CES function to model the mixing of ethanol and petroleum products on the production and household side of the model, the marginal demand function for ethanol can be written as:

$$\frac{Q_e}{Q} = A_e \left(\frac{P}{P_e} \right)^{\sigma} \tag{1}$$

where

Q_e, P_e = Ethanol use and price, respectively

Q, P = Total liquid fuel use and price, respectively

A_e = CES Share parameter

σ = Elasticity of substitution between biofuels and petroleum products

In the percentage format of the GTAP modeling framework equation (1) can be equivalently written as:

$$q_e = q + a_e - \sigma(p_e - p) \tag{2}$$

where a_e, q_e, q, p_e and p represent the percentage change counterparts to A_e, Q_e, Q, P_e and P, respectively. These two equations may also contain technical progress or calibration parameters.

The CES share parameter, A_e, is a structural or technology parameter which determines the initial quantity share of ethanol in total liquid fuel before price effects are taken into consideration. It is also equal to the quantity share during model simulations if:

> 1) $\sigma = 0$ - this is the fixed coefficient Leontief production function in which ethanol and petroleum products are blended in fixed proportions or
> 2) $\sigma > 0$, the price ratio in equation (1) is equal to 1, as is usual in CGE calibrations, and the price ratio does not change.

Thus, the main role of σ is to determine how rapidly the quantity ratio changes from the initial calibration of equation (1) or (2) in response to price changes. The share parameter is usually assumed to be constant in simulations with the CES function. In that case, the percentage change in the share parameter, a_e, is zero. It is that form that was used in Hertel et al (2010) to calibrate ethanol use change from 2001-2006, so that the increase in ethanol use was attributed to three of the four potential factors in equation (2) the since A_e is held constant. As such, the elasticity of substitution for the U.S. in 2006 was calibrated at 3.95, a rather large value not representative of the U.S. biofuel market, given the very limited availability of biofuel infrastructure and vehicles.

Elimination of MTBE from U.S. gasoline (driven by rules leading to the loss of liability protection against water contamination by MTBE) and the RFS ethanol blending requirements (a hybrid technology and performance mandate) are precisely changes in the technology parameter, A_e. In essence, given the forecasted consumption of liquid fuels at the beginning of a given year, the USEPA specifies the required A_e parameter that would meet the RFS requirement. Since the share parameters of the components of liquid fuels must sum to one, this also specifies the share parameter for petroleum products. The ultimate consumption of ethanol during the course of the year is then determined by a combination of the specified proportion, prices, total liquid fuel consumption and the elasticity of substitution. Once the implied change in a_e is accounted for as in equation (2), the estimated/calibrated elasticity of substitution between petroleum products and ethanol in the U.S. economy would be shown to be low. For the current study the elasticity of substitution between petroleum products and ethanol is 0.1 in the United States and the rest of the world, except Brazil. In the case of Brazil, a value of 0.1 was also used on the production side of the economy to represent blending requirements, while retaining the value of 1.35 used for Brazilian households in Hertel et al (2010). The latter is appropriate since Brazil's mature flexible-fuel vehicle stock and ethanol supply infrastructure enables a large proportion of consumers to exercise flexible price-based fuel choice at the pump.

b. Land use change Modeling

Figure 4 illustrates the modeling of land in GTAP-ORNL. The formulation incorporates a land supply sub-model and a land use sub-model. On the supply side, total land cover for a given AEZ is allocated to three aggregate cover types: 1) forests, 2) composite shrub/grass/agricultural land, and 3) other land cover (made up of built-up/other uses). The composite shrub/grass/agricultural land is distributed to shrub/grass and agricultural lands. The land supply sub-model is calibrated using physical data, while the land use sub-model is calibrated using economic data.

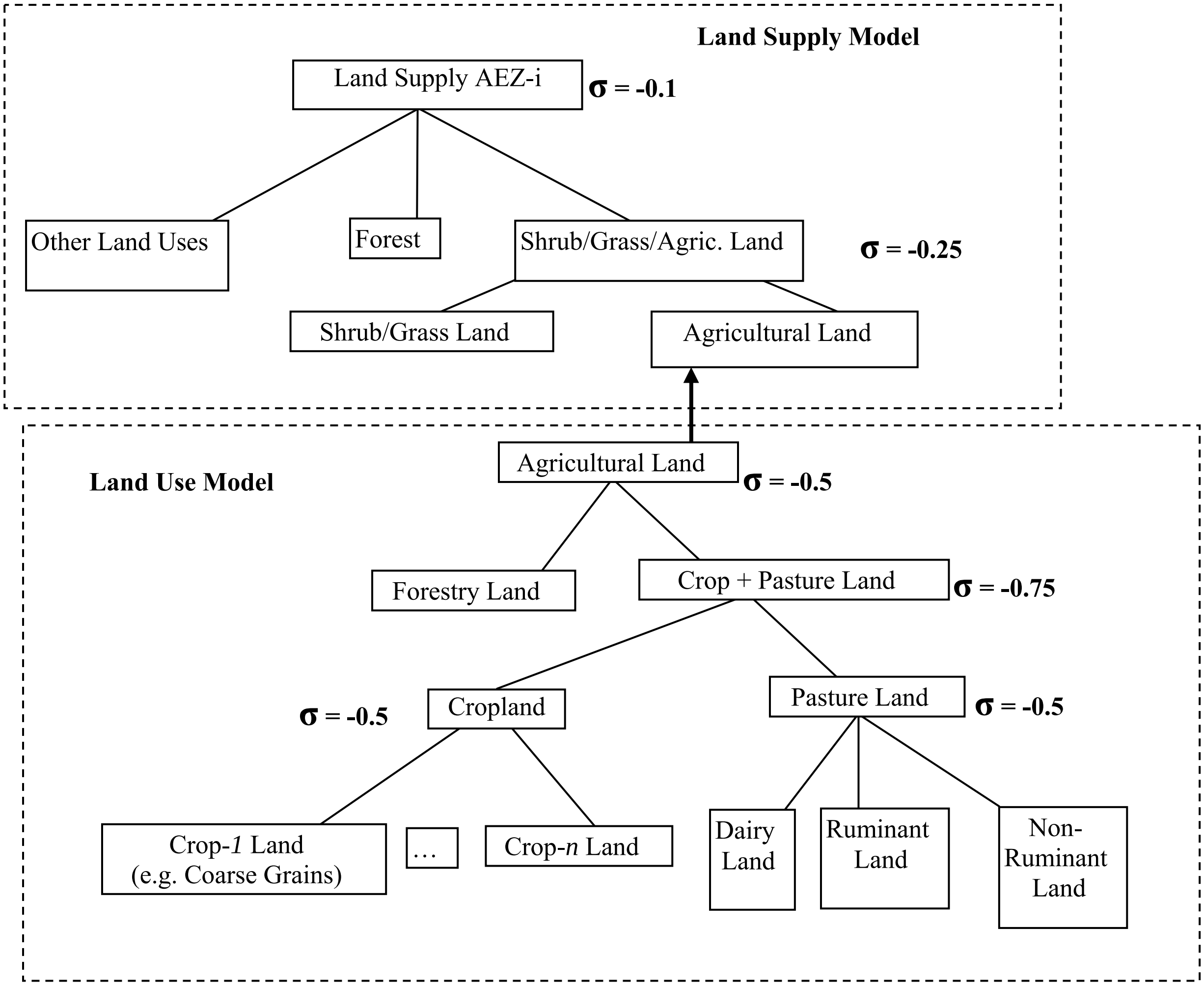

FIGURE 4: Land Supply and Demand Sub-Models in GTAP-ORNL

The two sub-models are linked by equating the percentage change in agricultural land quantity and price[7] on the supply and land use side of the model. This formulation adequately partitions the two sub-models so that only rents from the land use side enter the economic accounts in the model. The two-level nesting of the land supply sub-model implies a process of new land conversion from forest/other land to shrub/grass/agricultural land, and the disaggregation of the latter into shrub/grass and agricultural lands on the second level. Exchanging percentage changes across the two sub-models implies that the conversion factor between the physical and economic measure of agricultural land is constant. Yield adjustments that may occur as new land

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[7] The boxes in Figure 4 indicate parts of the land supply and use model that are calibrated in physical and economic terms.

is brought into production are made on the land use side of the model, but its effects are transmitted to the supply model through percentage changes in quantities and prices. The transformation elasticities in the land supply sub-model generate upward sloping supply curves for agricultural land, and determine the distribution of converted land among the various land cover classes.

c. Simulation Scenarios

We design five broad cases to examine the domestic and global implications of policy-motivated changes in ethanol production and use in the U.S. as shown in Table 1. The simulations in this study are static, and the base year is 2001. The simulated ethanol increase is the actual change in U.S. consumption in 2006 relative to 2001. The first simulation, Case A, examines a blending mandate implemented as changes in the share parameters of the CES function involving petroleum products and biofuels. The second set of simulations, Case B, is an output mandate, with the tax rates on ethanol and petroleum products adjusting endogenously to offset each other in order to keep the overall tax to income ratio of households constant. The latter is a price-based approach to simulating ethanol policy and we examine two variations: (B1) Ethanol and petroleum product tax rates on household consumption adjust; and (B2) Ethanol and petroleum product tax rates on output and imports adjust.

Table 1. Simulation Scenarios for U.S. Corn Ethanol Policy Evaluation

	Case A Blending Mandate	**Case B Output Mandate**		**Case C Yield-Adjusted Blending/Output Mandate**		**Case D Yield-Adjusted Blending Mandate & Parameter Changes**			**Case E Yield-Adjusted Output Mandate & Parameter Changes**		
	A	B1	B2	C1	C2	D1	D2	D3	E1	E2	E3
Share Parameters	X	-	-	X	-	X	X	X	-	-	-
Ethanol Output	-	X	X	-	X	-	-	-	X	X	X
Petroleum & Ethanol Consumption Tax	-	E	-	-	E	-	-	-	E	E	E
Petroleum & Ethanol Output Tax	-	-	E	-	-	-	-	-	-	-	-
Change in Overall Household Tax to Income Ratio	-	X	X	-	X	-	-	-	X	X	X
Household Ethanol/Petroleum Elasticity of Substitution	-	-	-	-	-	X	-	X	X	-	X
Land Supply Transformation Elasticities	-	-	-	-	-	-	X	X	-	X	X

Note: E & X indicate variables/parameters that were changed under each simulation. E stands for endogenous to indicate variables that were exogenous in the base model, but endogenous in the simulations, while X indicates exogenous variables whose values were changed or variables that were endogenous in the base model but made exogenous for the simulation.

The third set of simulations, Case C, examines yield-adjusted blending (C1) and output (C2) mandates. Yield changes are crucial to measuring the ILUC effects of U.S. ethanol because of its direct dependence on corn. The GTAP model incorporates endogenous intensive yield response to price changes, but this is only one aspect of yield adjustments and is incapable of capturing the extent of yield change observed over time. Corn is part of the coarse grains sector in the GTAP database and the yield adjustment is applied to that sector based on empirical data for 2001 and 2006. The yield contribution to year to year changes in corn production is calculated using a total differential of the relationship between corn production, yield and harvested land.[8] Based on this method the yield contribution to the increase in corn production for 2006 relative to 2001 is estimated at 74 percent. Assuming that corn production is distributed proportionally, the change in corn uses can be allocated to land and yield changes in the same proportions. Applying this approach, the land contribution represented 26 percent of the 177 percent increase in ethanol output from 2001-2006, or about 46 percent of the total increment in ethanol. This portion of the ethanol use can then be simulated in a 2001 base year model as an approximation of the yield-adjusted ethanol production in 2006.

The last two sets of simulations, Cases D and E, examine the implications of parameter changes on the effects of the yield-adjusted blending and output mandate cases. Three cases involving changes in the household ethanol/petroleum product elasticity of substitution and land supply transformation elasticities are examined. In these cases, the magnitudes of elasticities are increased from the base model (0.1 and 0.25) for land supply and 0.1 for ethanol/petroleum substitution to a value of 2 (for land), and 2 (for ethanol/petroleum substitution in the rest of the world), 3.95 (for ethanol/petroleum substitution in the U.S.), while the ethanol/petroleum substitution in Brazil remained at 1.35.

IV. SIMULATION RESULTS

a. Case A: Blending Mandate

Table 2 shows the results of simulating the increase in ethanol use in the U.S. between 2001 and 2006 as a blending mandate. Corn ethanol production in the U.S. increased by 171 percent with similar increases in sugarcane ethanol production and ethanol imports. Production of corn ethanol increased in Canada (19 percent) and sugarcane ethanol in Brazil (2.4 percent), and there were small increases in other world regions. Coarse grain output in the U.S. increased by 4.7 percent, exports declined by 1.9 percent, which represents a decrease in export share of total production of about 6 percent. Coarse grains production in other world regions increased by between 0.08 and 0.5 percent. Land use for coarse grains increased in the U.S. by 3.12 percent, and the difference from the change in coarse grain output represents the intensive yield change of about 1.54 percent.

Table 2 shows that the increase in U.S. land use for coarse grain leads to decreases in land under other crops, forestry and pasture, as well as new land conversion. The largest cropland decrease is for oilseeds and other grains, both losing 0.8 percent of their land area. Land use by the three pasture categories decreased by less than 0.4 percent, while forestry declined by only 0.04 percent. The net increase in agricultural land in the U.S. is only about 0.2 percent, which is accompanied by a 0.43 percent decline in shrub/grass land, 0.045 percent decline in other land, and 0.08 percent decline in forest land. Net increases in agricultural land in Brazil and Canada are less than 0.04 percent, and even smaller in the rest of the world regions.

Three measures for gauging the economic impacts of the simulated ethanol policy are included in Table 2. U.S. oil imports declined by 3.8 percent and by 1.3 percent in Canada, but increased by between 0.2 and 0.9 percent in the other world regions. The change in real GDP and equivalent variation (EV) are presented as measures of economic welfare change. In the U.S. the simulated policy implied a $110 million decrease in real GDP, while the EV amounted to a welfare increase worth $764 million. The EV is a more direct measure of household welfare effects and is the amount of expenditure the regional household is willing to receive as equivalence to the impacts of the policy. Thus, the broader U.S. economy-wide GDP effects of the policy are negative, while household welfare impacts are positive. However, both are small when compared to the U.S.

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[8] The decomposition is applied to the relationship between Q (corn production), L (land) and Y (yield): Q = Y*L. Using a percentage change decomposition similar to that used in the GTAP model solution algorithm, the percentage change in Q, q is equal to the sum of percentage changes in L, l and percentage change in Y, y as $q = l + y$.

value-added and household expenditure of about $7 trillion in the 2001 GTAP database. The welfare measures are also mixed in the rest of the world. Canada shows both a decrease in real GDP of about $4.3 million and EV of -$90 million, while Brazil and EU-27 have positive GDP and EV effects. The result for Canada is related to reductions in oil exports to the U.S. given the decrease in the latter's import seen in Table 2. In the rest of the world, the net GDP effect is positive, while the EV is negative.

Table 2. Results of U.S. Ethanol Use Change from 2001-2006 Simulated as a Blending Mandate (Case A)

	United States	Canada	Brazil	EU-27	Rest of World
Ethanol production and import change (%)					
Corn ethanol output	171.07	18.83	0.01	0.20	0.09
Corn ethanol import	179.98	-0.51	0.00	0.19	-0.16
Sugarcane ethanol output	173.40	0.39	2.36	0.26	0.16
Sugarcane ethanol import	182.47	0.14	0.51	0.06	0.11
Coarse grains output, export and land use change (%)					
Coarse grains output	4.69	0.49	0.25	0.08	0.14
Coarse grains export	-1.90	-0.06	0.86	0.34	0.91
Coarse grains export share	-6.30	-0.54	0.61	0.27	0.52
Coarse grains ethanol	171.07	18.83	0.01	0.20	0.25
Coarse grains land	3.12	0.27	0.14	0.03	0.10
Land use change (%)					
Coarse grains	3.12	0.27	0.14	0.03	0.10
Other grains	-0.80	-0.02	-0.12	0.00	0.00
Forestry	-0.04	0.00	0.00	0.00	0.00
Oil seeds	-0.80	0.16	0.03	0.07	0.03
Other agriculture	-0.58	0.02	-0.06	0.00	0.00
Sugarcane	-0.32	-0.07	0.73	-0.02	-0.01
Dairy farms	-0.32	-0.08	-0.03	-0.02	0.00
Ruminant cattle	-0.38	0.02	-0.08	-0.01	-0.02
Non-Ruminants	-0.38	-0.08	-0.10	-0.02	-0.01
Land-cover change (%)					
Forest	-0.075	-0.002	-0.007	-0.004	-0.002
Agricultural land	0.187	0.030	0.038	0.009	0.007
Shrub/Grass land	-0.425	-0.085	-0.034	-0.022	-0.010
Other land	-0.045	-0.001	-0.009	-0.005	0.000
Oil import change (%)	-3.80	-1.25	0.90	0.25	0.22
Real GDP Change ($million)	-111	-4	2	516	188
Equivalent Variation ($million)	764	-90	79	1484	-191

This result suggests that more of the rest of world consumption is self-produced, but at a higher cost. This is reasonable given the simulated reduction in U.S. coarse grains exports and the shift of production to less efficient regions of the world.

b. Case B: Output Mandate with Adjusting Ethanol and Petroleum Tax Rates

Tables 3 and 4 show the results of Cases B1 and B2 which simulate U.S. biofuel policy as an output mandate combined with adjustments to tax rates on ethanol/petroleum products. The corn ethanol production results for the U.S. under these cases are similar to those under Case A. Unlike Case A, ethanol output change is equal to the exogenously fixed increase of 177 percent. The results of Case B are however markedly different from Case A with respect to global changes in ethanol production and imports. U.S. imports of corn and sugarcane ethanol are reduced in both cases to zero, while sugarcane ethanol production decreased under Case B1 by 22 percent and 95 percent under Case B2. Similarly, corn ethanol production decreased in Canada, but increased by minimal amounts in other world regions under Case B1. In Case B2, corn ethanol output decreased everywhere, except in Brazil. These sharply different ethanol production results between Case A and Case B suggest that the two policy types exert very different impacts on modeled regional and global economic activities. Under Case B the model is not allowed to adjust U.S. production to optimal levels, and as such other potential sources of ethanol (imports and domestic output) are small relative to Case A. Under Case A, all sources adjust to the increased blending mandate, which is why the rate of increase in production and imports of both corn and sugarcane ethanol are similar. However, the loss of ethanol imports under Case B also implies small or negative changes in coarse grain production outside the U.S. and the decline in export share of output is slightly more pronounced in Case B because of the greater reliance on domestic sources of corn ethanol in the U.S.. Land use and supply implications in the U.S. are similar for Cases A, B1 and B2. Decreases or smaller increases in ethanol production in the rest of the world under Case B reduce global land use implications relative to Case A.

The non-land results under Cases B present the most glaring differences compared to Case A. Although U.S. oil imports declined in Case B1, the decline is only 1 percent compared to 3.7 percent under Case A. In Case B2, U.S. oil imports actually increased by about 0.3 percent. Also, unlike Case A, the real GDP change and EV for both Cases B1 and B2 are negative and one order of magnitude higher than under Case A at between -$4.3 to -$5.4 billion compared with a real GDP change of about $0.1 billion and EV of about -$0.8 billion under Case A. In the rest of the world, the impacts are almost uniformly negative, except for the EU-27 under Case B1, but the magnitudes are relatively small at less than $0.5 billion.

c. Cases C, D and E: Sensitivity Cases

Table 5 contains a summary of key results for the simulations outlined in Table 1. These results include initial land cover base, change in land cover, oil import change, real GDP change and EV. The yield-adjusted results, Cases C1 and C2, are placed side-by-side with counterpart simulations that did not adjust for yield, Case A and Case B1. Comparisons of these cases show that the yield-adjustment has a significant and nearly proportional impact on the magnitude of estimated ILUC change and economic effects.

The results of Cases D1-D3 can be compared to those for Case C1. In general, all three cases show that increasing the household ethanol/petroleum products elasticity of substitution and land supply elasticities, increase the LUC impacts but improve the economic effects. For example, the estimated land cover loss under Case D1 increased to 0.13 ha per 1000 gallons from 0.09 ha per 1000 gallons under Case C1. In Case D2 and D3 this increased to 0.19 ha per 1000 gallons. In contrast, the real GDP loss in the U.S. changed from $63 million in Case C1 to $22 million in Case D3, with similar improvements observed for the EV. These results are consistent with expectations because higher ethanol/petroleum substitution elasticities imply that lower price increases are needed to accommodate the ethanol policy, thus minimizing economic losses or increasing gains. On the other hand, as the land supply elasticity increases, land prices fall and the demand for land in the production process increases relative to other inputs, leading to both higher land conversion and lower economic costs. A comparison of Case C2 and Cases E1-E3 leads to similar conclusions. However, the progressive improvement seen in the real GDP and EV results in Cases D1 through D3 is not as pronounced in Cases E1 through E3. Case E2, which incorporates higher land supply elasticities, provides only a small improvement in the economic effects over Case C2 compared to Case E1. However, the combination of higher land supply and ethanol/petroleum substitution elasticities in Case E3 generates larger improvements compared to Case E1.

Table 3. Results of U.S. Ethanol Use Change Between 2001-2006 Simulated as an Output Mandate with Adjusting Household Ethanol and Petroleum Tax Rates (Case B1)

	United States	Canada	Brazil	EU-27	Rest of World
Ethanol production and import change (%)					
Corn ethanol output	177.00	-9.96	0.00	0.04	0.01
Corn ethanol import	-94.66	-0.76	0.00	0.04	-0.17
Sugarcane ethanol output	-22.36	0.04	-1.60	0.05	0.04
Sugarcane ethanol import	-100.00	0.10	-0.08	0.16	0.04
Coarse grains output, export and land use change (%)					
Coarse grains output	4.87	0.21	0.36	0.08	0.14
Coarse grains export	-1.93	0.02	1.09	0.37	0.91
Coarse grains export share	-6.48	-0.19	0.73	0.29	0.53
Coarse grains ethanol	177.00	-9.96	0.01	0.04	0.18
Coarse grains land	3.23	0.08	0.23	0.03	0.10
Land use change (%)					
Coarse grains	3.23	0.08	0.23	0.03	0.10
Other grains	-0.81	0.03	0.03	0.01	0.00
Forestry	-0.04	0.00	0.01	0.00	0.00
Oil seeds	-0.83	0.14	0.14	0.05	0.02
Other agriculture	-0.60	0.04	0.05	0.00	0.01
Sugarcane	-0.34	-0.06	-0.54	-0.02	-0.01
Dairy farms	-0.34	-0.07	-0.01	-0.02	-0.01
Ruminant cattle	-0.39	0.03	0.01	-0.01	-0.01
Non-Ruminants	-0.40	-0.08	0.02	-0.02	-0.01
Land-cover change (%)					
Forest	-0.079	-0.002	-0.002	-0.005	-0.002
Agricultural land	0.198	0.029	0.014	0.011	0.010
Shrub/Grass land	-0.449	-0.082	-0.015	-0.027	-0.014
Other land	-0.048	-0.001	-0.006	-0.007	-0.001
Oil import change (%)	-1.00	-0.31	0.22	0.07	0.06
Real GDP Change ($million)	-5372	-2	2	117	-2
Equivalent Variation ($million)	-4705	-46	-1	338	-332

Table 4. Results of U.S. Ethanol Use Change Between 2001-2006 as an Output Mandate with Adjusting Household Ethanol and Petroleum Tax Rates (Case B2)

	United States	Canada	Brazil	EU-27	Rest of World
Ethanol production and import change (%)					
Corn ethanol output	177.00	-10.38	0.02	-0.05	-0.05
Corn ethanol import	-100.00	72054.59	0.00	1.51	9629.85
Sugarcane ethanol output	-94.74	-0.12	-1.45	-0.04	-0.01
Sugarcane ethanol import	-100.00	0.03	-0.16	0.06	-0.02
Coarse grains output, export and land use change (%)					
Coarse grains output	4.86	0.19	0.36	0.08	0.14
Coarse grains export	-1.90	0.00	1.10	0.38	0.90
Coarse grains export share	-6.45	-0.19	0.73	0.30	0.52
Coarse grains ethanol	177.00	-10.38	0.03	-0.05	0.13
Coarse grains land	3.22	0.07	0.23	0.03	0.10
Land use change (%)					
Coarse grains	3.22	0.07	0.23	0.03	0.10
Other grains	-0.79	0.03	0.04	0.02	0.00
Forestry	-0.04	0.00	0.01	0.00	0.00
Oil seeds	-0.82	0.14	0.13	0.05	0.02
Other agriculture	-0.60	0.03	0.05	0.00	0.01
Sugarcane	-0.36	-0.06	-0.49	-0.02	-0.01
Dairy farms	-0.36	-0.07	-0.02	-0.02	-0.01
Ruminant cattle	-0.41	0.02	0.01	-0.01	-0.01
Non-Ruminants	-0.41	-0.09	0.02	-0.02	-0.01
Land-cover change (%)					
Forest	-0.080	-0.002	-0.002	-0.006	-0.002
Agricultural land	0.198	0.027	0.016	0.012	0.011
Shrub/Grass land	-0.450	-0.079	-0.018	-0.030	-0.015
Other land	-0.048	-0.001	-0.006	-0.008	-0.002
Oil import change (%)	0.28	0.35	0.04	-0.01	-0.01
Real GDP Change ($million)	-4651	-3	-3	-121	-157
Equivalent Variation ($million)	-4304	-16	-24	-335	-487

Table 5. Summary of Simulation Results for Land-Cover Change and Economic Effects and Sensitivity to Yield Adjustment, Household Ethanol/Petroleum Substitution Elasticities and Land Supply Elasticities

	U.S.	ROW	Total	U.S.	ROW	Total	U.S.	ROW	Total
Cases A & C1: Blending Mandate									
		Case A			**Case C1**				
Land Cover Impacts									
Base	529	8401	8929	529	8401	8929	-	-	-
Change (%)	-0.15	0.00	-0.01	-0.04	0.00	0.00	-	-	-
Change (mha)	-0.77	-0.25	-1.02	-0.20	-0.06	-0.26	-	-	-
Change (ha per 1000 gallons)	-0.25	-0.08	-0.33	-0.07	-0.02	-0.09	-	-	-
Non-Land Impacts									
Oil Imports (% Chg)	-3.80	0.22	0.00	-0.96	0.06	0.00	-	-	-
Real GDP ($million)	-111	188	77	-63	46	-16	-	-	-
Equivalent Variation ($million)	764	-191	572	201	-60	141	-	-	-
Cases B1 & C2: Output Mandate									
		Case B1			**Case C2**				
Land Cover Impacts									
Base	529	8401	8929	529	8401	8929	-	-	-
Change (%)	-0.15	0.00	-0.01	-0.04	0.00	0.00	-	-	-
Change (mha)	-0.82	-0.34	-1.16	-0.21	-0.08	-0.29	-	-	-
Change (ha per 1000 gallons	-0.27	-0.11	-0.38	-0.07	-0.03	-0.09	-	-	-
Non-Land Impacts									
Oil Imports (% Chg)	-1.00	0.06	0.00	-0.27	0.02	0.00	-	-	-
Real GDP ($million)	-5372	-2	-5374	-1293	3	-1289	-	-	-
Equivalent Variation ($million)	-4705	-332	-5037	-1105	-91	-1197	-	-	-
Case D: Blending Mandate									
		Case D1			**Case D2**			**Case D3**	
Land Cover Impacts									
Base	529	8401	8929	529	8401	8929	529	8401	8929
Change (%)	-0.06	0.00	0.00	-0.12	0.00	-0.01	-0.12	0.00	-0.01
Change (mha)	-0.33	-0.06	-0.39	-0.65	0.07	-0.58	-0.64	0.07	-0.57
Change (ha per 1000 gallons	-0.11	-0.02	-0.13	-0.21	0.02	-0.19	-0.21	0.02	-0.19
Non-Land Impacts									
Oil Imports (% Chg)	-0.96	0.06	0.00	-0.96	0.06	0.00	-0.96	0.06	0.00
Real GDP ($million)	-49	53	4	-26	53	26	-22	54	32
Equivalent Variation ($million)	210	-50	160	228	-45	183	230	-42	188
Case E: Output Mandate									
		Case E1			**Case E2**			**Case E3**	
Land Cover Impacts									
Base	529	8401	8929	529	8401	8929	529	8401	8929
Change (%)	-0.06	0.00	0.00	-0.13	0.00	-0.01	-0.13	0.00	-0.01
Change (mha)	-0.34	-0.08	-0.42	-0.67	0.03	-0.64	-0.67	0.04	-0.62
Change (ha per 1000 gallons	-0.11	-0.03	-0.14	-0.22	0.01	-0.21	-0.22	0.01	-0.20
Non-Land Impacts									
Oil Imports (% Chg)	-0.63	0.04	0.00	-0.27	0.02	0.00	-0.62	0.04	0.00
Real GDP ($million)	-735	26	-709	-1254	8	-1246	-706	28	-678
Equivalent Variation ($million)	-435	-74	-510	-1077	-77	-1154	-414	-65	-480

V. SUMMARY AND CONCLUSION

This study reviewed the empirical U.S. corn market and land use data from 2001-2009, a period when corn ethanol use increased at an annual average rate of 25 percent. This overview suggested that the most important adjustments in the U.S. corn market are in domestic uses and production, rather than exports. U.S. exports reached historic record levels during the period of rapid ethanol growth. The study underscores the role that model structure and policy specifications play in simulating the global implications of U.S. biofuel policy. Simulations with a modified version of the GTAP general equilibrium model were used to examine the impact of policy specifications, yield change, and parameter values on estimates of the LUC and economic impacts of biofuel policy.

The results suggest that the policy alternatives simulated in this study lead to similar LUC impacts, although those under the price-based output mandate specification impacts are slightly larger. Ethanol production and trade results, on the other hand, were more sensitive to policy specifications with price-based policies producing larger negative (or smaller positive) economic impacts than the blending specification.

Simulation results also showed that land and other input parameters are important determinants of biofuel policy impacts in the model. Yield change is shown to have significant influence on these results, although it represents only one possible adjustment in the U.S. corn market. The land-cover loss estimate of 0.09 ha per 1000 gallon of ethanol produced (under Case C1, the yield-adjusted blending mandate case) is smaller than most other published estimates. An estimate for 2006-2022 in Hertel et al (2010a), which was adjusted post-estimation to the 2007 yield level, is about 0.27 ha per 1000 gallons. Tyner et al (2010) reported a number of estimates based on different baseline cases, ranging from 0.15 ha per 1000 gallon to about 0.22 ha per 1000 gallons (depending on whether 2006 or 2001 was used as baseline). The Tyner et al. (2010) estimate fell to 0.12 ha per 1000 gallons when yield and demand variable changes were considered.

The ILUC estimate from the Searchinger et al (2008) study was about 0.73 ha per 1000 gallons. The CARD (2009) results estimate increases in cropland of 0.08 ha per 1000 gallons in the U.S. and 0.26 ha per 1000 gallons in the rest of the world at reference yield levels in a simulation of a 2.64 billion gallon increase in corn ethanol use. The high yield case for the same model, with about 27 percent higher yield than the reference case, generates a cropland increase of 0.014 ha per 1000 gallons in the U.S. and 0.21 ha per 1000 gallons in the rest of the world.[9] Thus, the CARD (2009) estimates are much smaller than the Searchinger et al (2008) estimate. The yield adjusted estimates in the current study are much smaller than the yield-adjusted estimates in CARD (2009), and this is also true for the comparison between the yield-adjusted cases in Tyner et al (2010) and CARD (2009) results. This suggests, as expected, that the PE models used by Searchinger et al (2008) and CARD (2009) tend to produce higher impact estimates due to the absence of full adjustment mechanisms that are included in GE models.

A consistent difference between the results in this study on the one hand and those in Tyner et al (2010), CARD (2009) and Hertel et al (2010a) on the other is the distribution of ILUC impacts between the U.S. and the rest of the world. In Tyner et al (2010) the U.S. share of total ILUC ranges from 28-34 percent under the various cases, while the CARD (2009) results imply 6-23 percent. In contrast, the simulations in this study imply that more than 75 percent of the ILUC occurs in the U.S., with even higher concentration in the U.S. under cases with high land supply elasticity. We believe that this is a function of different land availability constraints incorporated in the models and this is a topic for future research.

Although this study demonstrated the importance of a number of factors in simulating the global implications of U.S. biofuel policy, the simulations do not fully account for the multitude of processes that drive domestic and global LUC. One important factor is the demand for exports. In contrast to the export results in this and the other studies highlighted in this paper, U.S. exports of corn increased almost steadily as corn use for ethanol quintupled over the last decade. In addition, the empirical data over the last decade suggest that

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[9] Note that the countries listed in the CARD (2010) result referenced here are the United States, Argentina, Brazil, China, Australia, India and Thailand. Thus, these results may not represent the entire global estimate.

domestic adjustments in grain use are more elastic than usually assumed. Finally, the full specification of land transitions necessary to model causality and allocate changes among a plethora of factors driving LUC at local scales, is absent in existing models but fundamental to reach valid conclusions.

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