Impact of Biofuel Production on World Agricultural Markets: A Computable General Equilibrium Analysis[*]

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GTAP Working Paper No. 53
2008

[*] *The earlier version of the paper was presented at the Tenth Annual Conference on Global Economic Analysis, Purdue University, West Lafayette, IN, USA, June 7-9, 2007.*

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Abstract

This paper introduces biofuels sectors as energy inputs into the GTAP data base and to the production and consumption structures of the GTAP-Energy model developed by Burniaux and Truong (2002), and further modified by McDougall and Golub (2008). We also incorporate Agro-ecological Zones (AEZs) for each of the land using sectors in line with Lee *et al*. (2005). The GTAP-E model with biofuels and AEZs offers a useful framework for analyzing the growing importance of biofuels for global changes in crop production, utilization, commodity prices, factor use, trade, land use change etc. We begin by validating the model over the 2001-2006 period. We focus on six main drivers of the biofuel boom: the hike in crude oil prices, replacement of MTBE by ethanol as a gasoline additive in the US, and subsidies for ethanol and biodiesel in the US and EU. Using this historical simulation, we calibrate the key elasticities of energy substitution between biofuels and petroleum products in each region. With these parameter settings in place, the model does a reasonably good job of predicting the share of feedstock in biofuels and related sectors in accordance with the historical evidence between 2001 and 2006 in the three major biofuel producing regions: US, EU, and Brazil. The results from the historical simulation reveal an increased production of feedstock with the replacement of acreage under other agricultural crops. As expected, the trade balance in oil sector improves for all the oil exporting regions, but it deteriorates at the aggregate for the agricultural sectors.

JEL Classification: C68, Q18, Q42, R14

Keywords: Biofuels, Renewable Energy, Computable General Equilibrium (CGE), Agricultural Markets, Agro Ecological Zones (AEZs), Land use change.

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1. Introduction

Energy is an important factor of production in the global economy, and 90% of the commercially produced energy is from fossil fuels such as crude oil, coal, and gas, which are non-renewable in nature. Much of the energy supply in the world comes from geo-politically volatile economies. In order to enhance energy security, many countries, including the US, have been emphasizing production and use of renewable energy sources such as biofuels, which is emerging as a growth industry in the current economic environment. This paper develops a framework which can shed light on the drivers of the current biofuel boom as well as its impacts on agricultural markets.

Biofuels have become a high priority issue in Brazil, the US, the European Union as well as many other countries around the world, due to concerns of oil dependence and interest in reducing CO_2 emissions. All these regions have had significant subsidies or mandates for renewable energy production from agricultural sources. The impacts of these subsidies and mandates reach far beyond the borders of these economies. The purpose of this paper is to assess the global and sectoral implications of biofuel programs on agricultural markets and land use across the world. The very nature of biofuels production as a global economic activity affecting the pattern of energy demand and resource use motivates us to employ a global computable general equilibrium (CGE) economywide approach for this study. Since biofuel programs in various countries are mainly driven by external shocks and domestic policies, CGE serves as an ideal framework to study potential repercussions.

1.1 An Overview of Biofuel Markets

Ethanol, a predominant biofuel, is produced today from sugarcane and cereal grains mainly corn. Biodiesel is produced from oilseeds or palm oil. Table 1 lists the major ethanol and biodiesel producing countries in the world. In 2006, the United States became the largest producer and consumer of ethanol in the world, producing about 37% (4.86 billion gallons) of the world ethanol production (13.1 billion gallons). Brazil is the second largest producer with 36 % (4.76 billion gallons) of world ethanol production. As seen from Figure 1, the world ethanol production has grown rapidly at a compound growth rate of 10 percent per annum since 1975, and at 23 percent per annum from 2001 through 2006. This recent acceleration may be attributed to push towards ethanol in the United States. Similarly, world biodiesel production has grown at a rate of 35 percent per annum since 1991; the majority of the boom comes from the biofuel initiative in the European Union countries. As seen from Table 1, Germany is the leading producer of biodiesel (41% of world market share) with the production of 799 million gallons during 2006, followed by the US (20%), France (11%), Italy (7%), and other countries.

In Brazil, ethanol is produced mainly from sugarcane beginning during the 1970s in order to reduce dependence on foreign oil. However, the ethanol industry had a setback in the 1990s due to cheap crude oil (Regaldo and Fan, 2007). When oil prices began to soar again in the recent years, ethanol became a more attractive alternative to gasoline, aided by the launch of flex-fuel vehicles (FFVs) in 2003. Brazil has a comparative advantage in producing ethanol, mainly due to its availability of land and its favorable climate for sugarcane cultivation. As Martines-Filho, Burniquist, and Vian (2006) report, the total cost of ethanol production in Brazil was about $1.10 per gallon and that of US was between $2.01 to $3.96 per gallon, during 2005. With its tremendous export potential, Brazil currently exports more than 50% of its sugar production and about 15% of ethanol production.

Though international trade in biofuels is still in an early stage, US imports from Brazil grew dramatically since 2004. Brazil invested heavily in ethanol production during the energy crisis of 1970s and now has one of the world's most advanced production and distribution systems. One impediment to trade in biofuels is the US tariff of about 50%. As Valdes (2007) reports, Brazil is aiming to replace 10% of gasoline consumed worldwide by 2012, which requires it to export 20% of its current production. It is interesting to see the potential for trade in biofuels amongst the major producing countries. The US has proposed 36 billion gallons of alternative fuel by 2022 which would replace about 15% of gasoline consumption in the country. The EU is also targeting a 10% share of biofuels in the transport fuel market by 2020.

For production of ethanol, US, China, France, Germany, Russia, and Canada mainly use corn as their main feedstock, whereas, Brazil and India use sugarcane, which is more energy efficient. In the US, about 90% of the ethanol is produced from corn (about 22% of total corn production in 2007) and in China, about 80% of the ethanol is corn-based, with the remainder produced from cassava and wheat (Konishi and Koizumi, 2007). For biodiesel production, all the remaining countries in Table 1 use rapeseed as their main feedstock, except for the US which uses soybeans.

The remainder of the paper is organized as follows: section-2 gives a review of literature on CGE analyses of biofuels and a brief history of the GTAP-E model. Section-3 deals with the study approach comprising modifications in the GTAP-E model and modeling land use change, followed by section-4 which informs about the database employed for this study. Section-5 illustrates the historical analysis involving the major biofuel drivers, calibration of the key parameters, and validation of the model. Resulting impact of biofuel drivers on output, prices, trade, and land-use change, are discussed in section-6, followed by conclusions in section-7.

2. Review of CGE Modeling for Biofuels

Though there is a plethora of literature on biofuel economics, most of them employ cost-accounting procedures and/or partial equilibrium frameworks. More recently, researchers have began to use a CGE framework, however, with several caveats such as lack of incorporating policy issues, absence of linkages to other energy markets, and land use changes etc. Our study makes an attempt to address all these issues. However, the studies on CGE modeling of biofuels are few, largely due to infancy of the industry and limitations on availability of data.

Sims (2003) described the benefits of displacement of oil through biofuels, on a country’s balance of trade and domestic economic activity and recommended general equilibrium modeling in order to understand the full benefits of biofuel production. A study by McDonald, Robinson, and Thierfelder (2006) is one of the earlier ones to utilize the GTAP data base for analyzing the effects of substituting a biomass (switchgrass) for crude oil in petroleum production in the US, using a CGE framework. As switchgrass is not recorded in the data base, the authors assume that the primary input coefficients were same as those for the US cereal crops and the intermediate input coefficients were 70% of those for cereals in the US They also assumed that the output is purchased as an intermediate input by the petroleum industry. The results from a direct substitution of switchgrass for crude oil revealed an increase in world price for cereals, but decline in world price of other crops, livestock, and crude oil. However, the world has yet to witness commercial production of switchgrass based biofuel, and the timing is uncertain. Furthermore, the study does not take into account the prevailing ethanol and biodiesel industries in many of the regions.

Banse *et al*. (2007) extended the GTAP-E model (Burniaux and Truong, 2002) to analyze the impact of the EU biofuel directive on agricultural markets. They introduced biofuels in implicit form in the production structure as a substitution between vegetable oil, crude oil, petroleum products, and ethanol composite. The ethanol composite comprised substitution between the feedstocks such as sugar-beet-cane, wheat, grain, and forestry sectors. In order to account for land conversion and land abandonment, they included a land supply curve by specifying a relationship between the land supply and rental rates. They adjusted the GTAP data base to account for the input demand for the biofuel feedstocks in the petroleum industry. Their EU biofuel mandatory scenario analysis revealed that the target of the EU biofuel directive will not be reached by 2010 and the increase in demand for biofuel feedstocks will result in a larger agricultural trade deficit.

A disaggregated CGE approach was adopted by Gohin and Moschini (2007) to analyze the potential impacts of full implementation of the European biofuel policy in EU-15 economy where the farm sector is finely represented in terms of product coverage and behavioral specification. Their policy simulation of an exogenous increase in demand for ethanol and biodiesel revealed significant positive effects on the arable crop sectors with increase in price and production. In addition, the demand for ethanol is fully met by domestic production due to significant import tariffs, while the demand for biodiesel is met by imported vegetable oils. They also argued that the downstream livestock sectors are not negatively affected as the production cost of compound feed increases only slightly and in the case of dairy sector, milk production is constrained by milk quotas. Finally, they concluded that there would be a positive impact on farm income and the creation of additional farm jobs.

Rajagopal and Zilberman (2007) provide an extensive review of the literature on environmental, economic, and policy studies on biofuels. While highlighting the gaps, they emphasize the need to focus on potential biofuel producing developing countries and impact of producing biofuels on the poor. Also they caution that while measuring welfare impacts, the models should account for the utility derived by the consumers from the cleaner environment due to biofuels. Several studies in the recent past have focused on modeling production of biomass or cellulosic ethanol in a long run, recursive-dynamic CGE framework (Reilly and Paltsev, 2007; Dixon, Osborne, and Rimmer, 2007). In this study we do not consider biofuel from cellulosic materials since it has not been produced commercially; rather, we focus on liquid biofuels produced from food or feed crops.

2.1 History of GTAP-E

In order to analyze the implications of biofuel production in a CGE framework, we utilize a modified version of the GTAP-Energy model. The GTAP-E model was first developed by Truong (1999) where the substitution between capital and fuels was allowed by modifying the standard GTAP model (Hertel, 1997). For representing energy substitution, a simple top-down[1] approach was used with allowing for capital and energy to be either substitutes or complements. The GTAP-E model introduces energy substitution in production by allowing energy and capital to be either substitutes or complements. In order to allow for different elasticities of substitution across value added and energy, and non-energy inputs, a nested CES function has been employed in the model. First, the energy inputs are separated from the non-energy intermediate inputs in the production structure, and then the energy inputs are aggregated with capital in a composite, allowing for capital-energy substitution with other factors. One of the main assumptions of the standard GTAP production structure is separability of primary factors from intermediate inputs, implying that the optimal mix of primary factors is invariant to

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[1] A top-down approach starts with a detailed description of the macro economy, and the demand for energy inputs in various sectors' outputs are derived through highly aggregated production or cost functions (Wilson and Swisher, 1993).

price of intermediates. Thus, the elasticity of substitution between any primary factor and intermediates is the same. This assumption is relaxed in the GTAP-E model such that, in the value added branch, labor-energy substitution is different from capital-energy substitution. The non-energy intermediate inputs exclude all the energy inputs, but include fossil-fuel based feedstocks.

Since energy usage affects the environment through emission of CO_2 and other green house gases (GHGs), Burniaux and Truong (2002) further improved the GTAP-E model to encompass carbon emission from the combustion of fossil fuels along with the mechanisms to trade these emissions internationally. In their model, reduction in CO_2 emission can be achieved either through energy substitution or by output reduction. They used an aggregated database of eight sectors and eight regions keeping in view the emission policy analyses as per the 1997 Kyoto Protocol Annex I (OECD countries except for Korea and Mexico) countries that pledged to reduce their emissions of GHGs to 5.2 percent below 1990 levels. Though the US decided to withdraw from the Protocol, the remaining Annex I countries except for Australia, reiterated their commitment. Thus, the GTAP-Energy model emerged with the main purpose of climate change policy analysis, such as GHG mitigation. However, over time a large number of problems emerged through continued use of this model, and these have been recently addressed by McDougall and Golub (2007). Most importantly, they made substantial improvements in the programming of the GTAP-E model which greatly facilitate its modification by others. Therefore, we build on the McDougall/Golub version of GTAP-E in this paper.

3. Study Approach

This technical paper introduces biofuel linkages into the improved version of GTAP-E model in order to capture the implications of biofuels mandates for global agricultural markets. Since the primary focus of this study is to analyze the impact of biofuel production on agricultural markets and land use change, we ignore the CO_2 emissions module for this analysis. We consider both ethanol and biodiesel, the two prominent biofuels produced across the world today. Ethanol is produced from feedstocks such as cereal grains, sugarcane, and sugar beet, and biodiesel is produced mainly from vegetable oil seeds.

In order to distinguish the source of feedstock, and in line with the work of Taheripour *et al*. (2007), we name the biofuels as follows: ethanol-1 is coarse grain based, ethanol-2 is sugarcane-beet based, and biodiesel is vegetable oil based[2]. The substitution of biofuels is represented by intermediate demand substitution as well as household substitution, which required appropriate modifications in the production and consumption structures, respectively. For analyzing the land use changes, we use the GTAP land use data base developed by Lee *et al*. (2005) which disaggregates the land endowment into 18 Agro-ecological zones (AEZs), which characterize the biophysical growing conditions and land use for crops and forestry. These modifications are explained in detail as below.

3.1 Modifications to the GTAP-E Model

Given the emerging potential for trade in biofuels, we have treated biofuels as a tradable sector. The new GTAP-E model re-coded in a prudent style by McDougall and Golub (2008) does not require us to define distinct price and quantity variables for any addition of new sectors into the model – these are simply inherited from the set definitions, which have been expanded to include biofuels. Apart from the standard GTAP sets used in this model, listed below are some of the new sets used for convenience in representing private household demand, biofuel production structure, and land-use change.

New Sets	*Elements*
HHLD_COMM:	*TRAD_COMM* + *henergy* + *hbiooil*
CDE_COMM :	*henergy* + all non-energy commodities (*NEGY_COMM)*
BIOOIL_COMM :	oil_pcts, ethanol1, ethanol2, biodiesel
HEGY_COMM :	coal, oil, gas, electricity, *hbiooil*
AEZ_COMM:	the 18 Agro-Ecological Zones
CROP_COMM:	Coarse grains, oilseeds, sugarcane, other grains, other agri.
NCROP_COMM:	All other non-crop sectors
AGRLAND_COMM:	Land-using agri commodities (CROP + GRAZE)
LAND_COMM:	All land-using sectors (AGRLAND + FOREST)

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[2] We recognize that ethanol1 and ethanol2 should be perfect substitutes in use. This is not the case in our current formulation and needs to be addressed in future work.

New sets introduced by McDougall and Golub (2007) along with biofuel components:	
SUBPR_COMM:	*vaen, land, ken, eny, nely, ncoal, biooil*
FIRM_COMM:	*DEMD_COMM + SUBPR_COMM*
NCOAL_COMM :	oil, gas, *biooil*
NELY_COMM:	coal, *ncoal*
ENY_COMM :	electricity, *nely*
KEN_COMM :	capital, *eny*
VAEN_COMM :	*Land*, UnSkLab, SkLab, NatRes, *ken*
TOP_COMM :	*vaen* + all non-energy commodities (*NEGY_COMM*)

3.1.1 Modification of the Consumption Structure

The standard GTAP model (Hertel 1997) has separate structures for household 'private' consumption and 'government' consumption[3]. Private consumption assumes constant-difference of elasticities (CDE) functional form to accommodate nonhomothetic preferences and fully flexible functional form. Since biofuels are substitutable for petroleum products at the pump, we allow for substitution in the private household demand through CES nesting. Figure 2 represents the modified consumption structure of household demand for private goods.

3.1.1.1 Composite Demands:

At the top level, private household consumption demand is defined over *CDE_COMM* which is comprised of an aggregated composite energy good including biofuels (*henergy*) and all other non-energy tradeables. The following is the linearized form of the demand equation (in percentage change form) as stipulated in Hertel (1997).

$$qp(i,r) - pop(r) = \sum_{i \in CDE\_COMM} \sigma_P(i,k,r) * pp(k,r) + \sigma_Y(i,r) * [yp(r) - pop(r)] \qquad (1)$$

Where; i, k $\in$ *CDE_COMM;* $\sigma_P(i,k,r)$ and $\sigma_Y(i,r)$ are the uncompensated price and income elasticities of demand respectively; *pp(i,r)* and *qp(i,r)* are the private

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[3] For in-depth discussion, please refer to Hertel, T.W. and M.E. Tsigas "Structure of GTAP", Chapter-2 in Hertel (1997)

consumption price and quantities for commodity i in region r; the term [*yp(r) - pop(r)*] represents percent change in per capita income. In the energy nest, we specify a CES sub-structure allowing for substitution between petroleum-biofuel composite (*hbiooil)* and all other energy commodities. Furthermore, within the *hbiooil* composite good, we specify a CES sub-structure allowing for substitution between petroleum products and the three types of biofuels.

3.1.1.2 Composite Tradeables:

The composite tradeables at the lowest level are determined as follows.

$$pp(''hbiooil'', r) = \sum_{i \in BIOOIL\_COMM} [\Psi_{CSHHBIOIL} * pp(k, r)] \tag{2}$$

$$qp(i, r) = qp(''hbiooil'', r) - \sigma_{ELHBIOIL}(r) * [pp(i, r) - pp(''hbiooil'', r)] \tag{3}$$

where i, j $\in$ *BIOOIL_COMM;* $\Psi_{CSHHBIOIL}$ is the share of good i in cost to j of household biofuel-petroleum (*hbiooil*) sub-product; $\sigma_{ELHBIOIL}$ is the elasticity of substitution in *hbiooil* sub-consumption which is calibrated using historical evidence, which will be discussed in the subsequent sections. Equation (2) determines the price of the composite *hbiooil* sub-product and (3) represents the demand for inputs into *hbiooil* sub-consumption nest.

At the energy composite sub-product level, the price of *henergy* and the demand for inputs of *henergy* sub-consumption are determined by equations (4) and (5):

$$pp(''henergy'', r) = \sum_{i \in HEGY\_COMM} [\Psi_{CSHEGY}(j, r) * pp(j, r)] \tag{4}$$

$$qp(i, r) = qp(''henergy'', r) - \sigma_{ELEGY}(r) * [pp(i, r) - pp(''henergy'', r)] \tag{5}$$

where i, j $\in$ *HEGY_COMM*; Ψ_{CSHEGY} is the share of good i in cost to j of household energy sub-product; σ_{ELEGY} is the elasticity of substitution among energy commodities and the petroleum-biofuel composite. Typically, the energy demands are found to be relatively price-inelastic. Cooper (2003) estimates the short-run and long-run elasticities of demand for crude oil in 23 countries and concluded that demand for crude oil is highly insensitive to changes in price. The estimated short-run elasticities range from 0.001 to -

0.109 and that of long-run elasticities range from 0.005 to -0.453. Following Beckman *et al*. (2008), we assume a uniform own price elasticity of 0.1 (σ_{ELEGY}) across all regions[4].

3.1.2 Modification of the Production Structure

One of the major improvements made by McDougall and Golub (2007) in the GTAP-E model (Burniaux and Truong, 2002) is the ease with which additional levels of nesting can be added within the production and consumption structures. We take advantage of this feature to incorporate biofuels as well as land-use information as shown in Figure 3. This production tree represents how the firm combines its individual inputs to produce its output *qo(i,s)*. Truong (1999) removed energy commodities from the intermediate input nest and introduced them into the value-added nest thereby allowing for substitution between capital and energy goods in a composite.

Two important variables in the production structure are *qf(i,j,r)* and *pf(i,j,r)* which indicate demand and firm's price for commodity *i* for use by *j* in *r*. At the bottom-most level of the CES technology tree (Figure 3) we incorporate substitution between petroleum production and the three types of biofuels, with an elasticity ($\sigma_{ELBIOOIL}$) of 0. That is, we treat biofuels and petroleum sectors as complementary inputs. This permits us to separately model the use of ethanol as an oxygenator (as opposed to an energy source - the role of ethanol as an energy substitute is handled through the consumption structure). As Yacobucci and Schnepf (2007) report, nearly half of all US gasoline contains some ethanol blended around 10% level or lower. In 2006, the United States consumed most of the ethanol as an additive in gasoline. We discuss more on the additive demand aspect of ethanol in Section 5.2.

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[4] In this study, we use revised GTAP-E parameters offered by Beckman *et al*. (2008). They seek to validate GTAP-E model using stochastic simulation approach of Valenzuela *et al*. (2007) and they found that the price elasticities of demand for petroleum products used originally by Burniaux and Truong (2002) are too elastic and hence they offer revised set of GTAP-E parameters as below.

Elasticities	Burniaux and Truong (2002)	Beckman *et al*. (2008)
ELEGY	1	0.1
ELKE	0.5	0.1
ELEN	1	0.1
ELNEL	0.5	0.5
ELCOAL	1	0.25

The price of *biooil* energy sub-production is determined by equation (6) and the demand for inputs into *biooil* energy sub-production is given by equation (7) below.

$$pf("biooil", j, r) = \sum_{k \in BIOOIL\_COMM} \{\Psi_{CSHBIOOIL}(k, j, r) * [pf(k, j, r) - af(k, j, r)]\} \tag{6}$$

$$\begin{aligned} qf(i, j, r) = -af(i, j, r) + qf("biooil", j, r) - \sigma_{ELBIOOIL}(j, r) \\ *[pf(i, j, r) - af(i, j, r) - pf("biooil", j, r)] \end{aligned} \tag{7}$$

where i, k $\in$ *BIOOIL_COMM* and j $\in$ *PROD_COMM* ; $\Psi_{CSHBIOOIL}$ is the share of *k* in cost to *j* of *biooil* energy sub-product.

Moving upward in the production structure, the price and demand of non-coal energy sub-production are determined as below.

$$pf("ncoal", j, r) = \sum_{k \in NCOAL\_COMM} \{\Psi_{CSHNCOAL}(k, j, r) * [pf(k, j, r) - af(k, j, r)]\} \tag{8}$$

$$\begin{aligned} qf(i, j, r) = -af(i, j, r) + qf("ncoal", j, r) - \sigma_{ELNCOAL}(j, r) \\ *[pf(i, j, r) - af(i, j, r) - pf("ncoal", j, r)] \end{aligned} \tag{9}$$

where *i, k* $\in$ *NCOAL_COMM* and *j* $\in$ *PROD_COMM;* $\Psi_{CSHNCOAL}$ is the share of *k* in cost to *j* of non-coal energy sub-product. The non-coal nest allows substitution between crude oil, natural gas, and *biooil* composite good, with an elasticity of substitution ($\sigma_{ELNCOAL}$) of 0.25.

The non-electricity sub-production nest allows for substitution between coal and non-coal energy composite with an elasticity of substitution (σ_{ELNEL}) of 0.1. The equations (10) and (11) refer to the price of non-electricity energy sub-product and demand for input into non-electricity energy sub-production.

$$pf("nely", j, r) = \sum_{k \in NELY\_COMM} \{\Psi_{CSHNELY}(k, j, r) * [pf(k, j, r) - af(k, j, r)]\} \tag{10}$$

$$\begin{aligned} qf(i, j, r) = -af(i, j, r) + qf("nely", j, r) - \sigma_{ELNEL}(j, r) \\ *[pf(i, j, r) - af(i, j, r) - pf("nely", j, r)] \end{aligned} \tag{11}$$

where *i, k* $\in$ *NELY_COMM* and *j* $\in$ *PROD_COMM;* $\Psi_{CSHNELY}$ is the share of *k* in cost to *j* of non-electricity energy sub-product.

Further up in the production tree, the price of composite energy good and demand for input into energy sub-production are given by equations (12) and (13), respectively.

$$pf("eny", j, r) = \sum_{k \in ENY\_COMM} \{\Psi_{CSHENY}(k, j, r) * [pf(k, j, r) - af(k, j, r)]\} \tag{12}$$

$$\begin{aligned} qf(i, j, r) = -af(i, j, r) + qf("eny", j, r) - \sigma_{ELEN}(j, r) \\ *[pf(i, j, r) - af(i, j, r) - pf("eny", j, r)] \end{aligned} \tag{13}$$

where *i, k* $\in$ *ENY_COMM* and *j* $\in$ *PROD_COMM* ; Ψ_{CSHENY} is the share of *k* in cost to *j* of energy sub-product. The elasticity of substitution between electricity and non-electric composite (σ_{ELEN}) used here is 0.1.

The important sub-nest is the capital-energy composite which determines the following variables:

$$pf("ken", j, r) = \sum_{k \in KEN\_COMM} \{\Psi_{CSHKEN}(k, j, r) * [pf(k, j, r) - af(k, j, r)]\} \tag{14}$$

$$\begin{aligned} qf(i, j, r) = -af(i, j, r) + qf("ken", j, r) - \sigma_{ELKE}(j, r) \\ *[pf(i, j, r) - af(i, j, r) - pf("ken", j, r)] \end{aligned} \tag{15}$$

where i, k $\in$ *KEN_COMM* and j $\in$ *PROD_COMM;* Ψ_{CSHKEN} is the share of *i* in cost to *j* of capital-energy sub-product, and the elasticity of substitution (σ_{ELKE}) employed here is 0.1. Equation (14) indicates the price of capital-energy sub-product and equation (15) denotes demand for inputs into the capital-energy sub-production. Burniaux and Truong (2002) mention that in order to ensure capital and energy are complements in the short-run, and substitutes in the long-run, the elasticity σ_{ELKE} must be lower than the elasticity between capital and other commodities in the value added nest.

In the value-added-energy nest, the price of the sub-product *vaen* is determined by equation (16) and the demand for inputs in the VAE nest is implied by equation (17).

$$pf("vaen", j,r) = \sum_{k \in VAEN\_COMM} \{\Psi_{CSHVAEN}(k, j,r) * [pf(k, j,r) - af(k, j,r)]\} \tag{16}$$

$$\begin{aligned} qf(i, j,r) = -af(i, j,r) + qf("vaen", j,r) - \sigma_{ESUBVA}(j,r) \\ *[pf(i, j,r) - af(i, j,r) - pf("vaen", j,r)] \end{aligned} \tag{17}$$

where i, k $\in$ *VAEN_COMM* and j $\in$ *PROD_COMM ;* $\Psi_{CSHVAEN}$ is the share of *i* in cost to *j* of value-added-energy sub-product; the CES substitution elasticity (σ_{ESUBVA}) to combine the primary factors of production.

At the top-level nest, the firm combines value-added and intermediate inputs with an elasticity of substitution (σ_{ESUBT}) equal to 0.

$$\begin{aligned} qf(i, j,r) = -af(i, j,r) + qo(j,r) - ao(j,r) - \sigma_{ESUBT}(j) \\ *[pf(i, j,r) - af(i, j,r) - ps(j,r) - ao(j,r)] \end{aligned} \tag{18}$$

where i, k $\in$ *TOP_COMM* and j $\in$ *PROD_COMM; af(i,j,r)* is the input augmenting technical change and *ao(j,r)* is the Hicks-neutral technical change. Following Keeney and Hertel (2008), we assume a medium run crop-yield-response which is used to calibrate the elasticity of substitution for primary factors (σ_{ESUBVA}) and the elasticity of intermediate input substitution (σ_{ESUBT}) for the five crop sectors.

3.2 Modeling Land Use change for Biofuels

The growing importance of biofuels has created a huge demand for bio-feedstock. The energy demand coupled with demand for food have put tremendous pressure on land which can result in intensification and change in cropping patterns as well as steer additional land from forest and pasture lands for agricultural use. Several studies have raised concerns on environmental and social impacts of biofuel programs. Kelly (2007) predicts that the increased biofuels production in the US could lead to a shift in cropping patterns towards corn and it could bring marginal land prone to erosion, forest, pasture land etc. under corn[5]. Any tendency towards importing foreign-grown feedstocks could also result in massive displacement of agriculture and rain forest in the developing

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[5] For example, Kelly (2007) reports that California's state law stipulates to increase the share of alternative fuels from the current 6% to 20% by 2020 and 30% by 2030 which might require cutting down distant forests to grow biofuel feedstocks consequently exacerbating the global warming.

countries. Leahy (2007) reports that biofuels are causing deforestation in Indonesia, Malaysia, and Thailand due to monocultures of oil palm[6]. Buckland (2005) estimated that, development of oil-palm plantations of about 16 million acres across Sumatra and Borneo during 1985-2000, was responsible for 87% of deforestation (about 25 million acres of rainforest).

The potential for displacement of fossil fuels by biofuels could result in significant land-use change, with possible unfavorable impacts on the environment. Therefore in order to capture these potential land use changes due to biofuel programs, we adopt the GTAP-AEZ framework (Lee *et al*., 2008). In the original GTAP model, land is regarded as a sluggish endowment which can be re-allocated, based on relative land rents. However, not all crops are taken up in all parts of a country due to constraints on their adaptability. Owing to this limitation Lee *et al*. (2005) disaggregate national land endowment in GTAP into 18 Agro-Ecological-Zones (AEZs) as per U.N. Food and Agricultural Organization convention. In the GTAP land use data, the land used by the GTAP land-based sectors are distinguished by agro-ecological zones. Their 2001 crop and forest data has adopted the "length of growing period" data which is derived by combining information on moisture and temperature regimes, soil type, topography, and knowledge on crop requirements[7]. The AEZ data are derived based on six categories of 60 day interval growth period in the world subdivided into three climatic zones (tropical, temperate, and boreal) using criteria based on absolute minimum temperature and growing degree days.

The global land use database developed by Lee *et al.* (2008) involves three land use databases: (i) the land cover data from Ramankutty *et al.* (2008) which distinguishes forest, pastureland, and cropland cover types, (ii) data on harvested land cover and yields from Monfreda *et al*. (2008a, 2008b), and (iii) database which maps forestry activity in the 18 AEZs as documented in Sohngen *et al*. (2008). Lee *et al*. (2008) utilizes these

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[6] Palm oil is a low-cost vegetable oil highly efficient in biodiesel production. As FAPRI (2007) reports Malaysia and Indonesia are the major producers accounting for 88% of total world palm oil production and China, India, and EU-25 are the major importers.

[7] For detailed discussion on construction of this data base, refer to Lee *et al*. (2005). The GTAP-AEZ database is also useful for assessing the mitigation potential of land-based emissions as illustrated in Hertel *et al*. (2008).

land use components and disaggregates land rents in the GTAP data base on the basis on prices and yields. The detailed discussion on this aspect is given in the volume edited by Hertel, Rose, and Tol (2008). Therefore, incorporating aforementioned rich land-use AEZ level database into the biofuels module would yield better, and close to accurate presentation of sectoral competition for land due to biofuel production.

3.2.1 Structure of AEZs

In order to allow for substitutability among the AEZs, we incorporate a CES sub-product nest in the value-added-energy nest of the production structure (Figure 3). In the value-added nest, "land" is the composite good (sub-product) which allows for substitution between AEZs for a given use.

$$pf(\text{"}land\text{"}, j, r) = \sum_{k \in AEZ\_COMM} \{\Psi_{CSHAEZ}(k, j, r) * [pf(k, j, r) - af(k, j, r)]\} \tag{19}$$

$$\begin{aligned} qf(i, j, r) = -af(i, j, r) + qf(\text{"}land\text{"}, j, r) - \sigma_{ESAEZ}(j, r) \\ * [pf(i, j, r) - af(i, j, r) - pf(\text{"}land\text{"}, j, r)] \end{aligned} \tag{20}$$

where i, k $\in$ *AEZ_COMM* and j $\in$ *PROD_COMM;* Ψ_{CSHAEZ} is the share of k^{th} AEZ in cost to *j* of AEZ sub-product nest. The equations (19) and (20) determine the price of AEZ sub-product and demand for inputs in AEZ sub-production. The degree of substitution is determined by the parameter, σ_{ESAEZ}, which we assume to be very high (σ_{ESAEZ} = 20). This is dictated by the homogeneity of the products being produced on the different land types (Hertel *et al*., 2008).

Since crops grown are climate and soil specific, Lee *et al*. (2005) made an assumption while applying AEZ classification that, the land is mobile across uses within an AEZ, but immobile across the 18 AEZs. In line with Hertel *et al*. (2008), the land mobility is effectively restricted across alternative uses within a given AEZ, by using a Constant Elasticity of Transformation (CET) frontier analogous to CES function with one proviso, the convex revenue function implying that land owners maximize total returns by optimal mix among crops. As structured in Hertel *et al.* (2008), we adopt a nested CET function which allocates land in two tiers (refer to AEZ nest in Figure 3); with the assumption of homothetic separability on the revenue function. The land-owner makes optimal allocation of a given parcel of land under crops, pasture or commercial forest in the first stage, while the choice of crops is made in the second stage. Given that any increase in biofuel production would necessitate an increase in the supply of feedstock, which has to come from diversion of feedstock from other uses, increased yields and/or expansion of land area under that feedstock crop. Keeney and Hertel (2008) examine the issue of crop yield response in greater detail. They recommend a long-run yield response to price of 0.4, which we adopt here and calibrate to reach this targeted yield response by adjusting the elasticity of substitution in crop production.

The supply of land-AEZ endowment across the sectors is determined by the following equation (in percentage change form):

$$qo_{cropland}(i,r) = qo(i,r) - \omega(i,r) + \Omega_1 * [pm_{land}(i,r) - pm_{cropland}(i,r)] \tag{21}$$

The composite price for AEZ-land endowments is given by:

$$pm_{land}(i,r) = \sum_k \Psi_1(i,k,r) * pm_{es}(i,k,r) \tag{22}$$

The market price of AEZ-land endowment allocated to different crops

$$pm_{cropland}(i,r) = \sum_k \Psi_2(i,k,r) * pm_{es}(i,k,r) \tag{23}$$

where i, $k \in$ *AEZ_COMM*; $\omega(i,r)$ is the slack variable in endowment market clearing condition; $\Psi_1(i,k,r)$ is the revenue share of ith AEZ in kth land using sector (LAND_COMM); $\Psi_1(i,k,r)$ is the revenue share of ith AEZ in kth crop sector using land (CROP_COMM); $pm_{es}(i,k,r)$ is the market price of AEZ-land endowment *i* used by producing sector *j* in region *r*.

The sensitivity of land allocation across the three cover types is determined by the elasticity, Ω_1, in equation (21). For this parameter, we rely on Ahmed, Hertel, and Lubowski (2008) who recommend a value of -0.2 (for roughly a decade-long land cover transformation) based on a study on land use elasticities by Lubowski, Plantinga, and Stavins (2006). The solution for $qo_{cropland}(i,r)$ obtained from (21) is distributed across non-crop land (forestry and pasture lands) in as below:

$$qoes(i,j,r) = qo(i,r) - \omega(i,r) + \Omega_1 * [pm_{land}(i,r) - pm_{es}(i,j,r)] \tag{24}$$

where i, $\in$ *AEZ_COMM*; j $\in$ NCROP_COMM.

The supply of cropland is allocated across crops as given by equation (25).

$$qoes(i, j, r) = qo_{cropland}(i, r) - \omega(i, r) + \Omega_2 * [pm_{cropland}(i, r) - pm_{es}(i, j, r)] \tag{25}$$

where i $\in$ *AEZ_COMM*; j $\in$ CROP_COMM; Ω_2 is the elasticity of transformation across crops, taken as -0.5 (FAPRI, 2004) which is the maximum acreage response elasticity for corn across different regions in the United States. The CET parameters Ω_1 and Ω_2 are non-positive and their absolute value increases in absolute terms as the degree of sluggishness diminishes possibly driving the rental rates across alternative uses together (Hertel *et al.*, 1997). For instance an increase in ethanol production in the US would boost demand for corn, and the resulting increase in corn prices is shared among all the factors of production. Thereby, an increase in land rents attracts more land into corn production taken out from alternative uses.

4. Database for Biofuels

Given that the liquid biofuels industry has only recently emerged onto the global economic scene in a large way (outside of Brazil), it presents a unique modeling challenge. The GTAP data base (Dimaranan, ed., 2007) does not include explicit biofuels sectors. Taheripour *et al*. (2007) deal with this challenge by incorporating biofuel sectors into the GTAP data base using the available information on the patterns of sales and purchases for these sectors. As noted previously, the biofuel industry included in this study[8] constitutes three distinct sectors: ethanol-1, ethanol-2, and biodiesel based on the type of feedstock used to produce them.

In order to break out the three biofuel sectors, Taheripour *et al*. (2007) made use of 'SplitCom' software developed by Horridge (2005). As depicted in Figure 4, there are 57 sectors and 87 regions in the version 6 of GTAP data base. Thus, those authors generate: the grain based ethanol-1 sector from the food products sector (ofd) receiving inputs from the cereal grains sector (gro), the sugar based ethanol-2 sector out of

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[8] Since the focus of our study is implications of biofuels on agricultural and land use markets, we ignore the carbon module in the GTAP-E model and hence CO_2 emission from biofuels is not included in the database.

chemicals sector (crp) with inputs from sugar-cane-beet (c_b) sector; and biodiesel sector is created from the vegetable oils and fats (vol) sector which gets input from the oil-seeds (osd) sector. Thus the final disaggregated level has 60 sectors[9] and 87 regions. The sales of biofuels are channeled through household as well as intermediate demand. As discussed in the earlier section, we use information on land rents from GTAP-AEZ database (Lee *et al*., 2005; Lee *et al*., 2008) to disaggregate land endowment data across 18 AEZs. The GTAP version 6 data base and the AEZ data depict the global economy for the year 2001.

This data base is aggregated to permit focus on the sectors and regions of particular interest. For implementing the biofuels boom analysis, we aggregate the database into 20 economic sectors and 18 regions (Table 2). The sectors are aggregated such that we could focus on the linkages among feedstock, biofuels, energy commodities, and other important sectors. The regions are aggregated such that each continent is broadly divided into three categories: major energy consuming countries, major energy exporting countries, and all remaining countries in the continent.

5. Historical Analysis

Typically validation of a model involves testing if it can track historical developments in the economy. In the same spirit, we verify the model by projecting[10] the biofuel economy from 2001 baseline (database) to depict 2006 scenario and compare the share of feedstock in biofuels and related sectors to the historical evidence. In doing so, we consider three key factors of the US biofuels boom: rise in petroleum prices, the replacement of MTBE[11] by ethanol as gasoline additive, and the subsidies to the ethanol and biodiesel industries in the US and EU. Each of these key factors is discussed in detail in the following sections.

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[9] In this study, we do not include the by-products from biofuel sectors in the database.

[10] As Keeney and Hertel (2005) rightly point out, validating a GE model is fundamentally difficult as in principle the GE model endogenously determines all variables. Many disruptions in the world such as wars, droughts, financial crises, trade policy changes etc. though very important, it is virtually impracticable to include them in the model. Here we focus only on three key elements that are responsible for biofuels boom during 2001-2006 and ignore all other exogenous changes in the global economy during this period.

[11] Methyl tertiary-butyl ether (MTBE), a petroleum derived additive used as octane enhancer in the oil industry, was banned recently due to its highly toxic nature.

5.1 Crude oil price shock

The biofuels industry has a close linkage with petroleum products. The price of biofuels is implicitly dictated by the price of the crude oil for which it substitutes. Higher crude oil prices act as an incentive for increased biofuels consumption and consequently, the usage of feedstocks has implications on trade and welfare. In a GTAP-based study, McDonald, Robinson, and Thierfelder (2006) showed substitution of biomass for crude oil in the US could lead to a decline in the world crude oil price, thereby benefitting oil importers through terms of trade improvements. The study further indicated that the substitution will have indirect effects on the global agricultural markets due to exchange rate linkages. As seen from Table 3, the average annual real price (in 2006$ using GDP deflator) of crude oil was $25.3/barrel during 2001 and it took a steep jump to reach $78 in August 2006, thereafter dropping back to attain an average price of $59.7/barrel for the year 2006, which was an increase of 136% over 2001. Crude oil accounts for 55% of gasoline cost and the higher prices for crude oil would translate directly into higher prices for gasoline (Behrens and Glover, 2006). It is clear from the table that not all the crude oil price shock had been transferred to gasoline market by 2006, as crude oil prices rose by 136% while the average real price of gasoline has increased by 78%. The rise in gasoline prices has also driven the price of ethanol in the US, which has increased by about 74%, but the biodiesel price increased by only 31.8% over this same period.

In this paper we focus on a key underlying driver of biofuel demand – namely the crude oil price – shocking this by the historically observed amount, and asking the model to predict the impacts on gasoline prices and hence biofuel demands. In practice, the reasons for the oil price increase over this period are quite complex and modeling oil price formation over time would take us well beyond the scope of this technical paper. Therefore, we adopt a simple, transparent approach to achieving the oil price rise, since we are primarily interested in the consequences of the price hike, not the causes. Specifically, to achieve the world price change in crude oil, we swap *pxwcom*("Oil")[12] with exogenous *aosec*("Oil"), the rate of technical change of the oil sector worldwide, in

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[12] *pxwcom* is the price index of global crude oil exports.

the closure[13]. Thus, the model reduces oil production world-wide by an amount sufficient to cause world crude oil prices to rise by 136%. This is expected to boost the demand for liquid biofuels as a substitute for gasoline, and it comprises the first piece of our historical validation experiment.

5.2 Phasing out of MTBE in the US

With the passing of the US Clean Air Act of 1990, the vendors were required to have a minimum oxygen percentage in gasoline. Although ethanol and MTBE were the two recognized additives, the petroleum derived MTBE gained predominance during 1990s due to its lower cost of production. While it played an important role in reducing ozone emissions in the US, MTBE was found to be a serious ground water contaminant. This led to a ban of MTBE by 20 States by 1999. The Energy Policy Act (EPA) of 2005 removed the oxygen requirements giving the oil companies freedom to meet the clean air rules subject to their discretion and the US Environmental Protection Agency eliminated the oxygen requirement as of May 8, 2006, which removed the oil companies' legal cover on MTBE-based ground water contamination. This was the death knell for MTBE as an additive, and led to its replacement with ethanol (Tyner, 2008). Production of biofuels has increased even in the net energy exporting countries due to mandatory use of ethanol as an octane enhancer[14]. For example, many Latin American countries, including the major energy exporter, Venezuela, have been importing ethanol from Brazil and recently began to develop a large scale production of sugarcane-based ethanol domestically. So in order to blend with gasoline, several countries have started to produce or import ethanol to abate the pollution due to the petroleum based non-biodegradable MTBE.

As seen from Table 3, production of MTBE oxygenates plummeted from 3.26 billion gallons in 2001 to 1.29 billion gallons in 2006, following the legislation to phase out MTBE. The mirror image of this decline in share of MTBE in the additive market from 65% in 2001 to 21% in 2006 is the rising share of ethanol in the additive market which escalated from 35% (1.76 billion gallons) in 2001 to 79% (4.86 billion gallons) in 2006, which is about 125% increase during the six year period. However, with the

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[13] The closure used in this model is the standard general equilibrium closure, which allows full adjustment within each country (Appendix-1).

[14] The octane number of ethanol is 112 and that of standard gasoline is 87 (Tyner, 2007).

removal of the oxygen requirement, the oil companies were free to meet the clean air rules either by using ethanol or reformulated gasoline. Thus, there are two effects occurring simultaneously from two policies which have led to an increase in use of ethanol as an additive in the US gasoline industry (oil_pcts). To figure out this effect, consider the intermediate demand equation (18) discussed earlier. Assuming the elasticity of substitution among intermediate inputs in oil_pcts sector (σ_{ESUBT}) = 0, and no change output augmenting technical change in the oil_pcts industry ($ao(j,r)$ = 0), the equation (18) takes the form:

$$qf(i,j,r) = -af(i,j,r) + qo(j,r) \tag{26}$$

where *i* and *j* refer to ethanol-1 and oil_pcts sectors, respectively in the *r* region (US); $qf(i,j,r)$ is the demand for ethanol-1 in the oil_pcts sector in the US; $qf(i,j,r)$ is the factor i (ethanol-1) augmenting technical change in sector j (oil_pcts) in the US; and $qo(j,r)$ being the output of oil_pcts in the US. Equation (26) is in the percentage change form and its levels form is as below:

$$AF(i,j,r) = \frac{QO(j,r)}{QF(i,j,r)} \tag{27}$$

From equation (27) we compute change of AF from 2001 (AF^0) to AF in 2006 (AF^1). During the 2001 to 2006, decline in MTBE in the oil_pcts sector (QF^1) was 1.97 billion gallons (Table 3). That means, if we index output to 1.0, then AF^1= 1/1.97 = 0.51 (assuming no change in oil_pcts output QO) and AF0 in the initial period is 1. Therefore, percent change in AF = ((0.51 - 1)/1)* 100 = - 49%. This change in average intensity of ethanol-1 use due to MTBE ban in the oil_pcts sector is incorporated by shocking the factor augmenting technical change (*af*) variable by -49%. With this additive shock, we expect ethanol-1 production in the US to go up and also the production of feedstock (corn).

5.3 Subsidies for Biofuels

The rising popularity of biofuels is primarily attributed to the subsidies and other incentives that the national governments offer to this infant industry. The biofuel industry in the US thrived mainly because of the steady government subsidy being offered to the industry for the past three decades. The Energy Tax Act of 1978 started a tax exemption of 40 cents per gallon for ethanol and it rose to 60 cents per gallon under Tax Reforms Act in 1984. Eventually this federal subsidy came down to the present rate of 51 cents per gallon. Until 2004, the excise tax exemption policy has prevailed in the ethanol industry, but this was replaced by a blenders' credit of $0.51 per gallon; both the policies essentially have the same effect. Similarly, biodiesel in the US gets a blender's tax credit of $1 per gallon. The feedstock costs for biodiesel are generally higher than ethanol, which has led to a higher level of subsidy for biodiesel (Gray, 2006).

Tyner (2008) discusses the historical changes in ethanol subsidies and argues that the recent ethanol boom is an unintended consequence of a fixed ethanol subsidy which was calibrated to $20 per barrel crude oil prices. Though the success of ethanol industry relies on relative corn and oil prices, the subsidy has remained fixed irrespective of the hike in crude oil and corn prices. As Tyner and Quear (2006) argue, instead of a price invariant fixed subsidy, a subsidy that varies with ethanol prices or input costs could stimulate greater ethanol production through substantial risk reduction.

Apart from the US Federal subsidy, 38 states offer several incentive schemes such as excise-tax reductions or producer payments, production tax credits, statewide mandates for use of biofuels, etc. (Kojima, Mitchell, and Ward, 2007). Koplow (2006) estimated the per gallon aggregate subsidy as $1.05 for ethanol and $ 1.54 for biodiesel for the year 2006. As seen from Table 3, the real ethanol price has gone up from $1.48 per gallon in 2001 to $2.58 in 2006, which is an increase by 74%. Given the ethanol prices, we compute the power of the *ad valorem* equivalent (ADV) of $0.51 fixed subsidy[15], which was found to be 1.34 in 2001 and declined to 1.20 in 2006, by 10.93%. This is the reduction in economic impact of subsidy which acts as a disincentive for the ethanol producers. Therefore we shock the output subsidy variable (*to*) in the US by -10.93. Similarly, the power of ADV for biodiesel in the US has declined from 1.41 to 1.31, by 7% during 2001-06.

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[15] In GTAP jargon, the power of the *ad valorem* tax or subsidy (TO_i) = 1+ t_i, where t_i is the *ad valorem* tax or subsidy rate expressed in percentage (Hertel, 1997).

The EU-27 has emerged as the largest producer of biodiesel in recent years. The major impetus behind this boom is the tax credit given to biofuel industry by the members states (MS). The EU directive allows MS a legal framework to differentiate taxation of energy products and this has resulted in implementing different levels of tax credits by the MS (Bendz, 2007). Germany was the first country to implement tax incentives for biofuels, which started only after 2002, and later other MS adopted different levels of biofuel tax credits. We compute a production weighted average of these tax credits in major biofuels producing countries in the EU-27. The ADV equivalent of tax credit for ethanol was found to be 1.508 for 2006 which is an increase of 50.77% over 2001 (ADV equivalent of no tax credit is 1) and that of biodiesel was 81.18% (Table 3). Interestingly, German government started collecting $0.34 per gallon tax on biodiesel from January 1, 2008 as it was losing large tax revenue from fossil diesel. This tax is will likely to increase to more than $2.46 per gallon in 2012 (Godoy, 2007). Since we focus on the 2001-2006 historical period for validation, we ignore the very recent developments in the biofuel industry.

In order to project the global economy in time, we need to shock all the exogenous variables in time. However it is practically infeasible to obtain the observed data for all the exogenous variables on a global scale, we shock only the key biofuel drivers responsible for biofuel boom in the US and EU, and focus only on the higher petroleum prices in the case of Brazil. We implement all the six experiments discussed above simultaneously and calibrate the parameters to predict historical experience – focusing on the composition of the energy sector and the ensuing impacts on agriculture.

5.4 Calibration of Substitution Parameters

In our biofuels extension of the GTAP-E model, we have added a new parameter – the elasticity of substitution between petroleum products and liquid biofuels in final demand ($\sigma_{ELHBIOIL}$). Unfortunately, we do not have estimates for this parameter, which obviously plays a key role in our analysis. Ideally, we would like to estimate this using an econometric approach. However, the lack of adequate time-series or cross-section data on biofuels limits us to adopt a simpler, calibration approach for obtaining these elasticities of substitution.

We have assembled historical data on biofuel use for our three focus regions: US, EU and Brazil. By choosing the values for $\sigma_{ELHBIOIL}$ of 3.95, 1.65 and 1.35 for these three regions, we are able to successfully reproduce the increase in biofuel output in these three regions, based on the three shocks above. Note the relatively lower value for Brazil, which has a much higher market penetration of biofuels. The model is telling us that, at this point, the potential for increasing biofuel use in response to higher fuel prices is more limited than in the US and the EU, where there is still scope for displacing fuel use in conventional vehicles. In the other regions of the world, we adopt the default value for this parameter of 2.0 (Table 4). In our subsequent analysis, we will not be changing biofuel policies in these other countries, so the importance of this parameter is less pronounced.

Note that the elasticity of substitution between biofuels and petroleum products, $\sigma_{ELBIOOIL}$, in the petroleum sector is zero, by assumption (see above). This is because this portion of the biofuel demand is explicitly recognized as additive demand in the model. Tokgoz and Elobeid (2006) elucidate that complementarity relationship between ethanol and gasoline dominates over substitution relationship, mainly due to current blending at 10% and the FFVs market form negligible portion of the US vehicle fleet. They further assume that the substitution effect will continue to be limited until the FFVs dominate the market.

Another important set of parameters that drive the biofuels economy are the land-use parameters (Table 4), which are adopted from various studies discussed in the earlier sections. With these parameter values, we analyze the impact of six shocks performed simultaneously and compare model results with historical evidence.

5.5 Validation of the Model

Having fully specified the biofuels model, we ask how well it does in capturing the observed changes over the period: 2001-2006. Of course, since we have calibrated the elasticity of substitution in consumption to give us the desired increase in biofuel production, examination of that variable is not a test of model performance. However, it is information to ask how well the model has predicted other changes in the structure of the economy. Since we have not projected the entire economy forward in time, we will focus on the *composition* of the economy, not on the *level* of prices or quantities in the new equilibrium.

6. Impact of Biofuel Drivers on the Global Economy

In this section, we discuss the impact of the key biofuel drivers (see previous section) on some of the variables interested to biofuel economy. After running the three shocks together as discussed in the earlier sections, the results are presented in Table 5 in comparison with the corresponding historical data (recall that we are only simulating the impact of the bio-fuel related shocks, not all of the other developments that occurred over this period). Ethanol production in the US increased from 1.7 billion gallons in 2001 to 7.1 billion gallons in 2006, which is about 174% increase. Our calibrated model faithfully reproduces this change (177% during the same period).

Historically, the area under corn, the key feedstock in the US, has increased only by 3.5%, but production has gone up by 11% which indicates a significant improvement in yield due to a combination of technology and weather. The model prediction of coarse grain production is about 7% over this same period. An important criterion to assess the performance of the model is the change in the share of feedstock going to biofuels. As seen from the table, the model predicted corn share[16] going to ethanol in the 2001 database is about 6.8%, and it increased to 17% in 2006. This share is comparable with the historical shares of 6.5% and 20.2% for 2001 and 2006 respectively.

Interestingly, the share of corn exports has increased historically by 5.5% over the period of 2001-06, but the model prediction indicates a decline in export share[17] by about 9%. The model prediction must be negative, given the economic logic of the model, since price rises and export demand is downward sloping. However, over this historical period, in spite of increased usage of corn for ethanol production, US corn exports have grown moderately due to factors that are not included in our simulation. These include

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[16] As presented in Table 5, the model predicted share distinguishes domestic production and exports separately. The reason for not combining the domestic and exports together is, the historic share includes only domestic production in the total.

[17] The above explanation applies to the differences in historic and predicted share of corn exports as well.

rapid economic growth in Asia and depreciation of the US dollar. This discrepancy between predicted and observed exports also helps to explain the divergence between predicted and actual production of corn. Similarly, the other grains sector, which constitutes paddy rice and wheat, is predicted to see a decline of 3% in production, which is less than the actual decline in production for these crops. However, if we closely look at the historical data, there are huge annual fluctuations in area and production of these grains.

Moving down to the next section of Table 5, we see the predicted and historical results for Brazil. Here, we see that historical production of sugar-based ethanol (ethanol-2) in Brazil went up from 3.6 billion gallons in 2001 to 4.5 billion gallons in 2006, which is an increase of 24%. The corresponding model predicted value is 39% which is larger than the historic data. On the contrary, the historic increase in sugarcane production is about 32%, but the equivalent value from the model is only 17%. However, the model predicted the share of sugarcane in ethanol production matches the historical data quite well: 43.5% in 2001 and 51.6% in 2006. Furthermore, the model predicts a huge increase of (605 %) sugarcane based ethanol from Brazil over the six year period.

The last panel of Table 5 compares the model predictions and historical observation for the European Union. Biodiesel production in the EU increased from 288 million gallons to 1.47 billion gallons during 2001-06, an increase by 410%, which is reproduced by the model (increase of 431%). Unfortunately, we could not find the historical data on the share of oilseeds used for biodiesel production for the entire European Union, but our model showed an astonishing increase from 6.5% in 2001 to 27.6% in 2006. The model predicts that this 20+ percentage point increase in share comes from a 17% increase in oilseed production, a 6% decline in oilseeds exports from the EU, and from a 10% increase in oilseed imports. To mention again, we have not shocked the entire 2001 economy forward in time – just the biofuel drivers. Therefore we cannot expect that the six shocks that we have included here should predict accurate output levels. With the exception of the discrepancies noted above, overall the model predicts the stylized facts about the structure of the energy, biofuel and agricultural economy reasonably well.

6.1 Decomposition of Change in Output and Prices

A substantial increase in world crude oil price along with US and EU specific biofuel incentive shocks can result in economy wide impacts across countries. Table 6 depicts the percent change in output in terms of domestic and export components across various agricultural sectors. The impact of the three shocks on agricultural output in the United States reveals that the production increase for coarse grains comes from a 7.5% increase in domestic demand combined with a small (-0.9%) decline in exports. If we look at the drivers behind the increase in coarse grains production, interestingly it is the crude oil price (5.6%) first and additive demand for ethanol (2.4%) secondly which contributed to the increase in coarse grains production. The subsidy shock (declining *ad valorem* equivalent of subsidy) acts as a disincentive to the ethanol industry and leads to a 1 percent decline in coarse grains, while outputs in all other sectors go up by small amounts. The production of all other agricultural commodities went down slightly, except for oilseeds. Production in the other grains sector drops by 3.2%, the majority of which was due to decline in exports (2.7%). Since we ran four (subsidies to ethanol and biodiesel are combined together in Table 6) simulations simultaneously, the changes attributed to each shock may be examined for the United States. These *subtotals*[18] for each shock (Table 6) reveal that the hike in oil price has a major impact on output of the non-coarse grains commodities.

The output changes in the European Union and Brazil are mainly due to the crude oil price shock. The other two shocks specific to the US biofuel industry did not have any direct effect on agricultural markets in other regions. With the rise in crude oil price, oil seed production goes up substantially (17.5%) in the EU which mainly comes from a 19% increase in domestic demand and 1% reduction in exports. Besides, production of other grains goes down by 1%, and all other sectors also experience a small production slump in the EU.

Banse *et al*. (2007) indicate that higher crude oil prices would make the feedstock more competitive in petroleum production in the EU. In the case of Brazil, though all

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[18] The concept of *subtotals* in GEMPACK jargon is defined as decomposing the total effect of a group of shocks into contribution made by each individual shock. The theory of subtotals is given in Harrison, Horridge, and Pearson (2000).

the agricultural sectors experience a decline in production except for sugarcane (17% increase) as expected, it is interesting to note that the domestic demand for oilseeds goes down by 0.5%, while exports rise by 2.2%. From these results, we can conclude that higher crude oil prices have played an important role in boosting biofuels and their feedstock production, but have led to deterioration in the production of other competing crops and forestry sectors.

A glance at Table 7 shows the impact of biofuel drivers on the market price across the sectors for the period 2001-06. The *total* effect of the biofuel drivers is that the medium run market prices for the biofuel feedstock go up by 9% for coarse grains in the US, 10% for oilseeds in the EU, and 11% for sugarcane in Brazil. Interestingly, the price of ethanol and biodiesel went up by 17% and 13%, respectively in the US (which is much less relative to the crude oil price increase of 136%), while the same declined in the EU. The table also lists the change in market price in some of the major energy exporting regions as they experienced a little stronger pinch in prices, possibly due to increase in demand as their disposable income goes up following the hike in oil price[19]. The change in consumer price index (CPI) as also given at the bottom of the table which indicates that the general rise in price level was lower in the biofuel producing regions compared to that of energy exporting regions.

6.2 Land Use and Land Cover Change across AEZs

The rise in feedstock demand brings in more land under cultivation of that feedstock. The additional pressure to increase the feedstock output can lead to intensification of the crop that could bring higher yield. Figure 5 shows the percentage change in land area under coarse grains across the AEZs in the world during 2001-06

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[19] Though several studies have indicated about substantial increase in food prices due to biofuel boom, interestingly our model does not capture this occurrence. Since the last quarter of 2006 and up until the first quarter of 2008, world has been witnessing considerable increase in agricultural commodity prices often attributed to increase in biofuel production (Alexander and Hurt, 2007; Westcott, 2007; von Braun, 2008). For example, when tortilla prices skyrocketed in Mexico in January 2007, some market analysts attributed the price hike to bio-ethanol-related corn shortages (Caesar, Riese, and Seitz, 2007). However, though U.S. corn prices due to biofuel production could bare an explanation, the real reason behind the tortilla price hike was the concentration in the Mexican corn flour and tortilla industry, and failure of trade policies that allowed dumping of corn into Mexico over time (Spieldoch, 2007). Along these lines, there are several reasons such as drought in New Zealand and Australia, increase in global demand for dairy products, etc which are attributable to increase in food and feed prices. Since we have not projected the economy for 2006, the model predicted change in market prices could be insignificant.

following the biofuels boom. The largest changes in coarse grain acreage (up to 10%) are in less-productive AEZs which contribute little to national coarse grain output. The productivity-adjusted change in land cover and crop harvested area over the period 2001-06 is given in Table 8. The total change in crop land cover was 2.1% which came from a 0.5% and 1.6% decline in commercial forest and pasture land, respectively in the US The productivity-weighted acreage change in land-use for the coarse grains is about 5%, which comes from contribution of land from all other crop sectors. The major decline was observed in other grains sector with -3.4% changes in acreage. Figures 6-9 plot the land use changes by region and AEZ for oilseeds, sugar crops, other grains, other agri-goods sectors and Figures 10-11 depict the change in land cover under commercial forest and pasture land, respectively.

Table 8 reports that the impact of these biofuels drivers on oilseed acreage in the European Union is quite large -- 15%, which mainly comes at the cost of all other land-using sectors. The land-cover under crops rises by 4.4% in the EU (which is entirely due to oilseeds acreage expansion) and this comes from decline of 2.1% each in forest and pasture land-cover area. Depending on the AEZ, the overall productivity-weighted average for land used in oilseeds increased from 0.05% to 19% (Figure 6). This trend confirms Tyner and Caffe (2007) who estimate that non-food rapeseed area in France would increase from 1.5 million acres to more than 4 million acres by 2010, whereas the same will decrease from 2.2 million acres to 1.6 million acres for food purposes.

The acreage under sugar crops (sugarcane and sugar beet) in Brazil expands by 15% under this biofuel experiment, with the land mainly coming from pasture, forestry, and other agri-good sectors. The increase in demand for sugar crops pushed the productivity-weighted average change from 0.49% to more than 18%, depending on the AEZ (Figure 7). With 6% increase in crop land-cover in Brazil, about 4.7% of which came from pasture land-cover and about 1% from forest land. As seen from Figure 8, the forestry sector gave up its acreage in all the regions except for Canada and Rest of the World. Brazil is the main region with productivity-weighted acreage loss of up to -7% each in forest land (Figure 10) and in pasture land (Figure 11) depending on the AEZs.

As discussed above, the major acreage loss is under other grains (paddy and wheat). As seen from Figure 8, reductions in productivity-weighted acreage range from -12% and the gain across some AEZs is by only 6%. It is clear from Table 8 that, overall, paddy and wheat are the crops which lose acreage and production heavily in most of the regions except for Oceania countries and India. Figure 9 depicts percent change in land area under agri-goods sectors, which registers a decline of about 11% of land used across AEZs in each of these sectors. Overall, the Other Agri-goods sector gave up land for producing biofuel feedstock crops.

6.3 Impact on Trade

Apart from understanding the domestic impacts of biofuel production, it is important to investigate the possible repercussions around the world. The impact of biofuel drivers on bilateral trade is presented as change in import volume for coarse grains, oilseeds, and other food products by the US, EU and all other regions combined, in Table 9. As seen from the table, the US coarse grain exports decline by $178 million but the other regions fill this gap in exports and in fact, the total volume of global trade in coarse grains rises by $54 million. US exports of coarse grains to EU declines only by $4 million, while trade with rest of the world gets affected to a greater extent ($174 million). The middle panel of the table gives the change in import volume for oilseeds which increases by $395 million. The EU-27 region imports oilseeds from all other regions, the majority of which comes from Brazil and the US. The US and EU exports of oilseeds to rest of the world decline sharply. India and Eastern Europe also emerge as net oilseed exporters in this experiment. Interestingly, trade in the Other Food Products sector increases heavily by $1.29 billion. The increase in US imports mainly comes from rest of the Southeast and South Asia, and EU-27. However, EU imports from most of the regions decline drastically (by $1.65 billion), whereas, the RoW imports increase by $2.71 billion.

The commodity trade balance, by region, owing to the biofuel drivers is presented in Table 10. Macro-economic trade balance requires that the current account must be equated to the capital account in each region. Any change in trade due to biofuel production is offset and the capital account adjusts. The main impact on the trade balance is to reduce oil imports, which can be clearly seen from the table as the oil and oil products portion of the trade balance improves. The trade balance in aggregate deteriorates for the US, with the largest contributors being manufacturing and services (-$77 billion) and oil and oil products (-$66 billion – due to the higher oil prices). The trade balance improves in the US in the case of oilseed and coarse grain exports. In contrast, the scenario for the European Union is quite different than that of the United States. EU trade balance improves in aggregate which mainly comes from exports in manufacturing and services sector ($151 billion). The agricultural trade balance particularly in the oilseeds sector deteriorates as imports surge in response to the strong demand by the biodiesel sector. Brazil has a modest trade balance with positive numbers coming from export of ethanol mainly to the US and EU. Brazil gains by exporting a larger share of oilseeds to the EU. All the oil exporting regions exhibit a solid trade balance in the oil and oil products sector.

6.4 Impact on Terms of Trade

The terms of trade (ToT) effect reported in Table 11, is negative for both the US and the EU. The welfare effect from ToT loss is due to the transfer of wealth from the consuming region to the producing region. The ToT loss in the US mainly comes from oil and oil products sector (-$54 billion) and also from the other sectors in a smaller scale. The European Union also loses about $77 billion by ToT effect in the oil and oil products sector. The only sectors with positive ToT effect in the EU region are other primary sectors and to a smaller extent, oilseeds, other grains, and coarse grains sectors.

The effect of the six shocks on ToT basically depends on the magnitude of the change in oil price relative to the change in the export prices. A decomposition of ToT as contribution of change in world price, export price, and the import prices would be helpful. In the US, the world price interaction with oil and oil products was the major component contributing towards ToT loss. Although change in export price interaction is positive for most of the sectors particularly for coarse grains and other agri-sectors, it is of a smaller magnitude. But the change in import price component was relatively much smaller for all the sectors. Thus, we can see that these changes in the price interactions contributed towards to the ToT effect. The ToT decomposition for the EU indicated that world price interaction with oil and oil products contribute to a ToT loss of $76.9 billion. Interestingly, the export price component at the aggregate level was negative and quite large. But the import price interaction was positive, the larger part of which was from manufacturing and services sector.

7. Conclusions and Directions for Future Research

Biofuels have been receiving greater attention in the recent years from researchers, industrialists, environmentalists, and national governments across the world. In order to analyze the linkages between biofuels and agricultural markets, we use a global, general equilibrium model. The GTAP-E model, supplemented to include biofuels, is useful in assessing the impact of the growing importance of biofuels on global changes in crop production, utilization, prices, factor movements, trade, etc. In this study we incorporate biofuels into the GTAP-Energy data base and to the production and consumption structure of the model. We also apply agro-ecological zones (AEZs) information for each of the land using sectors. For validation of the model, we project the biofuel economy forward in time from 2001 to 2006, and compare the model predictions with historical evidence. Since it is not possible to introduce all the changes to the global economy over this period, we focus on three key issues which are responsible for biofuel boom in recent years: the hike in crude oil prices, replacement of MTBE by ethanol in gasoline additives, subsidies for ethanol and biodiesel in the US and EU. Using this historical simulation, we calibrate some of key elasticities of energy substitution between biofuels and petroleum products in each region.

Based on only the six types of shocks related to biofuels, the model predictions match reasonably well with key historical evidence in the major biofuel producing regions. The results from the historical simulation revealed, that with higher crude oil prices biofuels are substituted for petroleum products. The biofuel drivers have driven up the demand for feedstocks in the three major producing regions, United States, Brazil and EU. As a result there is change in acreage towards corn in the US, oilseeds in EU, and sugarcane in Brazil, affecting the land area under paddy and wheat in all the regions. Brazil emerges as a leading oilseed exporter to the European Union.

Since the biofuel industry is very dynamic, there are several elements of the global production and trade in this sector which are hard to replicate in the model. For example, the GTAP data base used in this study pertains to 2001 data, whereas several countries have started producing biofuels at a large scale only in the recent years, which is not possible to capture in our database. Many developing countries have started producing new biofuel feedstocks such as palm oil, jatropa, etc. for which we have not yet established linkages with biofuel sectors. Byproducts of biofuels are also crucial in determining global impacts of biofuel programs. Taheripour *et al*. (2008) introduce byproducts of corn-ethanol and biodiesel into the earlier version of this model and found that the model without byproducts overstates the impacts of biofuels on feedstock production and land use. This must be borne in mind when using the version of the model documented in this paper. Of course the specific nature of the biofuel by-products and their use varies across feedstocks and proper incorporation of them into a model is a large exercise in its own right. Future work will focus on extending this model to incorporate key types of cellulosic ethanol, as well as incorporating CO_2 and other GHG emissions to permit a comprehensive assessment of the environmental impact of biofuels. In addition to looking at the GHG emissions impacts of biofuels, we plan to analyze their impact on poverty, as they provide a double-edged sword for the world’s poor – on the one hand raising food prices, while on the other, enhancing earnings opportunities in agriculture.

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Tables and Figures

Table 1. The Major Biofuel Producers in the World during 2006

Ethanol Production			**Biodiesel Production**		
	Million gallons	*Share (%)*		*Million gallons*	*Share (%)*
United States	4,856	37.3	Germany	799	41.4
Brazil	4,763	36.5	United States	385	20.0
China	1,083	8.3	France	223	11.6
India	486	3.7	Italy	134	7.0
France	251	1.9	United Kingdom	58	3.0
Germany	202	1.5	Austria	37	1.9
Russia	171	1.3	Poland	35	1.8
Canada	153	1.2	Czech Republic	32	1.7
Other countries	1,068	8.2	Other countries	227	11.8
World	**13,033**	100	**World**	**1,929**	100

Data sources: Earth Policy Institute, 2006; Renewable Fuels Association, 2007; European Biodiesel Board, 2007.

Table 2. Aggregation of Sectors and Regions used in the Model

No	**New Code**	**Sector Description**	**GTAP old sectors**	**No.**	**New Code**	**Region Description**	**Comprising GTAP old regions**
1	CrGrains	Cereal grains	gro	1	USA	United States	usa
2	OthGrains	Paddy and Wheat	pdr wht	2	CAN	Canada	can
3	Oilseeds	Oil seeds	osd	3	EU27	European Union 27	aut bel dnk fin fra deu gbr grc irl ita lux nld prt esp swe bgr cyp cze hun mlt pol rom svk svn est lva ltu
4	Sugarcane	Sugar cane, sugar beet	c_b	4	BRAZIL	Brazil	bra
5	Livestock	Cattle,Animal pdts,Milk,Wool	ctl oap rmk wol	5	JAPAN	Japan	jpn
6	Forestry	Forestry	frs	6	CHIHKG	China, Hong Kong	chn hkg
7	Ethanol1	Ethanol1 (corn based)	eth1	7	INDIA	India	ind
8	Ethanol2	Ethanol2 (sugarcane based)	eth2	8	LAEEX	Latin AmericanEnergy Exporters	mex col ven arg
9	Biodiesel	Biodiesel	biod	9	RoLAC	Rest of LatinAmerica+Caribbean	xna per xap chl ury xsm xca xfa xcb
10	OthFoodPdts	Other Food Products	voln ofdn	10	EEFSUEX	EE & FSU Energy Exp	xef rus xsu
11	ProcLivestoc	Meat, Dairy products	cmt omt mil	11	RoE	Rest of Europe	che xer alb hrv tur
12	OthAgri	other agriculture goods	v_f pfb ocr pcr sgr b_t	12	MEASTNAEX	Middle Eastern N Africa E Exp	xme tun xnf bwa
13	OthPrimSect	OtherPrimary:Fishery & Mining	fsh omn	13	SSAEX	Sub Saharan Energy Exporters	xsc mwi moz tza zwe xsd mdg uga xss
14	Coal	Coal	coa	14	RoAFR	Rest of North Africa & SSA	mar zaf zmb
15	Oil	Crude Oil	oil	15	SASIAEEX	South Asian Energy Exporters	idn mys vnm xse
16	Gas	Natural gas	gas gdt	16	RoHIA	Rest of High Income Asia	kor twn
17	oil_pcts	Petroleum, coal products	p_c	17	RoASIA	Rest of Southeast & South Asia	xea phl sgp tha bgd lka xsa
18	electricity	Electricity	ely	18	Oceania	Oceania countries	aus nzl xoc
19	En_Int_Ind	Energy intensive Industries	crpn i_s nfm				
20	Oth_Ind_Se	Other industry and services	tex wap lea lum ppp nmm fmp mvh otn ele ome omf wtr cns trd otp wtp atp cmn ofi isr obs ros osg dwe				

Table 3. Major Drivers of Ethanol Boom in the US and EU-27

	Units	**2001**	**2006**	**Change 2001-2006**
Average crude oil price	*2006 $ / barrel*	25.29	59.69	**136.0%**
United States				
Average gasoline price[1]:	*2006 $ / gallon*	1.20	2.13	77.5%
Fuel ethanol oxygenate production:	*billion gallons*	1.76	4.86	3.10
MTBE oxygenate production:	*billion gallons*	3.26	1.29	-1.97
Additives = Ethanol + MTBE:	*billion gallons*	5.02	6.15	
Share of MTBE to additives:		65%	21%	-68%
Share of ethanol to additives:		35%	79%	125%
Decline in MTBE additive demand:	= 1/-1.97			0.51
Increase in ethanol additive demand (-*af*)	= ((0.51 -1)/1) *100			**-49.24%**
Ethanol:				
Average price	*$ / gallon*	1.48	2.58	74.3%
Federal Subsidy	$ / gallon	0.51	0.51	
ADV equivalent of subsidy[2]	%	1.34	1.20	**-10.9%**
Biodiesel:				
Average price	*$ / gallon*	2.45	3.23	31.8%
Federal Subsidy	$ / gallon	1	1	
ADV equivalent of subsidy[2]		1.41	1.31	**-7.0%**
EU-27				
Ethanol[3] :				
Average Price	$ / gallon	1.48	1.96	32.4%
Tax credit	$ / gallon	-	0.995	
ADV equivalent of tax credit[2]	%	1.00	1.508	**50.77%**
Biodiesel[4] :				
Average Price	$ / gallon	2.33	2.34	0.6%
Tax credit	$ / gallon	-	1.898	
ADV equivalent of tax credit[2]	%	1.00	1.812	**81.18%**

Note: [1] Gasoline prices exclusive of taxes.

[2] *Ad valorem* equivalent of federal subsidy in the US and tax credit in the EU-27.

[3] Ethanol price and the tax credit in the EU refers to France market.

[4] Biodiesel price and tax credits are production share weighted averages of major biodiesel producing countries in the EU-27.

Data Sources: Energy Information Administration (EIA) and Energy Efficiency and Renewal Energy (EERE), US Department of Energy; Nebraska Ethanol Board, Lincoln, NE. Nebraska Energy Office, Lincoln, NE.

Table 4. Key Elasticities of Substitution in Biofuels and Land Use Module.

Regions	ELHBIOIL	Key Parameters	Constant across all regions and sectors
US	3.95		
Canada	2	Elasticity of substitution in Bio-Oil composite in production nest (ELBIOOIL)	0
EU-27	1.65		
Brazil	1.35		
Japan	2	Elasticity of substitution in AEZ production nest (ESAEZ)	20
China-Hong Kong	2		
India	2		
Latin American Energy Exporters	2	Scalar yield elasticity target (YDE_Target)	0.4
Rest of Latin America & Caribbean	2	Elasticity of transformation for sluggish primary factor endowments (ETRAE)	-0.0001
EE & FSU Energy exporters	2		
Rest of Europe	2	Elasticity of transformation for land cover at the bottom of land supply tree (ETRAE1)	-0.2
Middle Eastern N Africa energy exporters	2		
Sub Saharan Energy exporters	2	Elasticity. of transformation for crop land in supply tree (ETRAEL2)	-0.5
Rest of North Africa & SSA	2		
South Asian Energy exporters	2		
Rest of High Income Asia	2		
Rest of Southeast & South Asia	2		
Oceania countries	2		

Note: ELHBIOIL refers to elasticity of substitution in Bio-Oil energy composite in private demand.

Table 5. Validation of the Model from Historical Evidence in the US, Brazil, and EU-27.

US.	Ethanol-1 Production Million gallons	Model Prediction[1]: Ethanol Production ($ million)	Corn Area Million hectares	Corn Production Million tonnes	Model Prediction[1]: Coarse Grain Production ($ million)	Share of Corn for Ethanol	Model Prediction[1]: Corn Share for Ethanol (% share)	Share of Corn for Exports	Model Prediction[1]: Corn Share for Exports (% share)
2001	1770	2489.30	30.28	241.38	20936.5	6.5%	6.8%	19.4%	27.6%
2002	2130		31.56	227.77		7.5%		17.5%	
2003	2800		31.44	256.28		11.0%		18.8%	
2004	3400		32.37	299.92		11.7%		15.3%	
2005	3900		32.71	282.31		14.5%		19.5%	
2006	4855	6886.80	31.33	267.60	22335.0	20.2%	17.0%	20.5%	25.1%
2007*	7123		37.15	316.50		23.0%			
%Ch 2001-06	**174.29**	**176.66**	**3.47**	**10.86**	**6.68**	**209.05**	**150.0**	**5.50**	**-9.06**
%Ch 2000-07*	*46.71*		*18.58*	*18.27*					

US	Wheat Area Million hectares	Wheat Production Million tonnes	Rice Area Million hectares	Rice Production Million tonnes	Model Prediction[1]: Other Grain Production ($ million)	Soybean Area Million hectares	Soybean Production Million tonnes	Model Prediction[1]: Oilseed Production ($ million)	Model Prediction[1]: Ch in Coarse Grain exports ($ million)
2001	23.77	53.00	1.33	10.59	7304.8	29.63	78.67	12772.2	5779.3
2002	24.13	43.70	1.30	10.38		29.59	75.01		
2003	24.86	63.81	1.21	9.84		29.36	66.78		
2004	23.87	58.74	1.34	11.43		30.08	85.01		
2005	22.89	57.28	1.35	10.99		28.86	84.00		
2006	22.94	49.32	1.14	9.51	7070.8	30.21	86.69	12857.3	5601.1
2007*						25.63	71.30		
%Ch 2001-06	**-3.52**	**-6.95**	**-14.79**	**-10.21**	**-3.20**	**1.95**	**10.20**	**0.67**	**-3.08**
%Ch 2000-07*						*-15.15*	*-17.75*		

Continued…

BRAZIL	Ethanol-2 Production Million gallons	Model Prediction[1]: Ethanol Production ($ million)	Sugarcane Area Million hectares	Sugarcane Production: Million tonnes	Model Prediction[1]: Sugarcane Production ($ million)	Share of Sugarcane for Ethanol production	Model Prediction[1]: Sugarcane Share for Ethanol	Share of Sugarcane for Sugar production	Model Prediction[1]: Sugarcane Share for Sugar	Model Prediction[1]: Ch in Ethanol-2 Exports ($ million)
2001	3609.0	5341.7	4.88	326.1	3189.4	43.3%	43.5%	55.7%	44.3%	137.7
2002	3760.0		5.02	344.3		45.2%		53.8%		
2003	4336.0		5.1	363.7		46.2%		52.8%		
2004	4443.0		5.5	416.6		49.1%		49.9%		
2005	4467.0		5.69	421.8		53.0%		46.0%		
2006	4491.0	7420.4	5.87	431.4	3737.4	51.0%	51.6%	48.0%	37.1%	970.7
%Ch 2001-06	**24.44**	**38.91**	**20.29**	**32.29**	**17.18**	**17.67**	**18.51**	**-13.76**	**-16.29**	**604.88**

EU-27	Biodiesel Production: Million gallons	Model Prediction[1]: Biodiesel Production ($ million)	Oilseeds Area: Million hectares	Oilseeds Production: Million tonnes	Model Prediction[1]: Oilseed production ($ million)	Model Prediction[1]: Oilseed Share for Biodiesel	Oilseed Imports: Million tonnes	Oilseed Exports: Million tonnes	Model Prediction[1]: Ch in Oilseed imports ($ million)	Model Prediction[1]: Ch in Oilseed exports ($ million)
2001	288	513.69	14.21	33.5	6905.1	6.50%	26.14	6.40	5440.41	1329.5
2002	384		14.13	31.5			25.27	6.76		
2003	503		15.06	34.4			24.45	6.46		
2004	708		14.83	38.6			21.69	7.00		
2005	815		15.02	36.5			24.87	6.60		
2006	1467	2729.56	15.82	37.9	8111.1	27.60%	28.05	6.19	5996.5	1243.9
%Ch 2001-06	**409.38**	**431.37**	**11.3**	**13.1**	**17.47**	**324.62**	**7.29**	**-3.38**	**10.22**	**-6.44**

Note: [1] Model prediction values refer to results from crude oil price in all regions, additive demand in the US, and biofuel subsidy shocks in the US and EU, performed together. The model predictions for 2001 are the pre-shock values (from the basedata) and 2006 values are post-shock values.
Data Sources: Food and Agriculture Organization online database ; Economic Research Service, United States Dept of Agriculture; Renewable Fuels Association; European Biodiesel Board; The São Paulo Sugar Cane Agro-industry Union (UNICA).

Table 6. Impact of Biofuel Drivers on the Agricultural Production in the US, EU, and Brazil: 2001-2006 (*% change in output by sector)*

	Total Change (%)	Decomposed by Demand		Decomposed by Driver			
		Domestic	Exports	Additives	Oil Price	Subsidy-US	Subsidy-EU
US							
Ethanol-1	176.7	176.7	0.0	63.9	148.0	-34.9	-0.3
Coarse Grains	6.7	7.5	-0.9	2.4	5.6	-1.3	0.0
Other Grains	-3.2	-0.5	-2.7	-1.1	-2.8	0.6	0.1
Oilseeds	0.7	0.1	0.6	-0.7	0.2	0.3	0.8
Sugarcane	-0.9	-0.8	0.0	-0.2	-0.8	0.1	0.0
Other Agri	-0.8	-0.7	-0.1	-0.2	-0.7	0.1	0.0
Livestock	-1.2	-1.0	-0.1	-0.1	-1.1	0.1	0.0
Forestry	-0.3	-0.3	0.0	-0.2	-0.3	0.1	0.0
EU-27							
Biodiesel	431.4	431.4	0.0	-0.7	184.5	0.4	247.1
Coarse Grains	0.8	0.6	0.2	0.1	0.6	-0.1	0.2
Other Grains	-1.1	-1.0	-0.1	0.1	-0.1	0.0	-1.1
Oilseeds	17.5	18.7	-1.2	0.2	7.8	-0.1	9.6
Sugarcane	-0.5	-0.5	0.0	0.0	-0.2	0.0	-0.2
Other Agri	-0.3	-0.6	0.3	0.0	0.0	0.0	-0.3
Livestock	-0.5	-0.5	0.0	0.0	-0.4	0.0	-0.1
Forestry	-1.5	-1.3	-0.2	0.0	-1.0	0.0	-0.5
Brazil							
Ethanol-2	38.9	23.3	15.6	0.2	38.8	0.1	-0.2
Coarse Grains	0.7	-0.4	1.1	0.2	0.7	-0.1	-0.1
Other Grains	0.3	0.3	0.0	0.0	0.8	0.0	-0.5
Oilseeds	1.7	-0.5	2.2	0.2	-0.2	-0.2	1.8
Sugarcane	17.2	17.2	0.0	0.1	17.2	0.1	-0.1
Other Agri	-1.8	-1.1	-0.7	0.0	-1.6	0.0	-0.1
Livestock	0.1	0.1	0.0	0.0	0.2	0.0	0.0
Forestry	-2.0	-1.8	-0.2	0.0	-1.9	0.0	-0.1

Table 7. Impact of Biofuel Drivers on Market Price across Selected Regions: 2001-2006

% Change in Market Price	US	EU-27	Brazil	Latin American Energy Exporters	Middle Eastern North African Energy Exporters	Sub-Saharan Energy Exporters
Coarse Grains	8.68	6.98	5.9	6.32	13.54	10.03
Other Grains	6.35	6.39	5.43	6.77	12.63	9.04
Oilseeds	5.85	9.55	6.41	6.76	13.56	9.5
Sugarcane	5.08	5.48	10.96	5.81	14.47	9.07
Livestock	3.44	3.1	2.75	4.86	10.78	9.81
Forestry	4.19	7.00	8.29	5.13	17.77	16.71
Ethanol-1	16.87	-33.51	1.51	3.91	10.37	7.42
Ethanol-2	3.88	6.67	3.27	6.83	18.22	9.62
Biodiesel	12.75	-40.9	3.27	4.35	11.39	7.91
Other Food Products	1.92	-0.09	1.84	3.98	10.42	7.45
Processed Livestock	2.41	0.29	1.43	4.11	10.17	7.97
Other Agri Commodities	2.68	1.66	3.72	4.62	13.1	8.54
Other Primary sectors	2.62	3.27	3.44	5.51	11.69	8.55
Consumer Price Index (% ch)	2.99	2.71	3.01	5.40	12.22	8.93

Table 8. Change in Land Cover and Crop Area due to Biofuel Drivers: 2001-2006

Region	*Land Cover (% ch)*			*Crop Harvested Area Change (%)*				
	Crops	Forest	Pasture	Coarse Grains	Oilseeds	Sugar-cane	Other Grains	Other Agri
US	1.3	-0.3	-0.4	5.0	-0.6	-2.0	-3.3	-1.2
Canada	0.8	-0.1	-0.1	1.4	-0.1	-0.4	0.8	0.1
EU-27	1.9	-1.1	-1.2	-0.4	15.0	-1.4	-2.1	-0.8
Brazil	2.8	-0.5	-0.4	-0.3	0.7	15.5	-1.0	-2.1
Japan	0.4	-0.1	0.0	3.9	1.4	-0.8	0.6	-0.7
China-Hong Kong	0.0	0.5	-0.2	0.0	2.0	-0.4	-0.5	-0.5
India	0.4	-0.6	-1.9	-0.7	0.0	-0.5	1.0	0.2
Latin American Energy Exporters	-0.1	-0.2	0.1	0.9	-0.9	0.3	-0.1	-0.2
Rest of Latin America & Caribbean	0.8	0.1	-0.3	0.5	1.6	0.6	1.1	-0.4
EE & FSU Energy Exp	-0.3	0.1	0.1	-0.7	1.1	-2.0	0.3	-0.3
Rest of Europe	-0.2	0.7	-0.6	-0.7	0.7	-0.2	0.2	-0.2
Middle Eastern N Africa energy exporters	0.9	-2.0	-0.2	1.2	-1.1	1.1	-0.6	1.7
Sub Saharan Energy exporters	-1.9	-0.5	0.7	1.2	-2.0	-0.8	-3.5	-1.7
Rest of North Africa & SSA	1.3	0.2	-0.3	-0.1	2.6	-0.3	2.1	-0.4
South Asian Energy exporters	0.3	-0.3	0.3	-0.1	0.7	-0.3	0.0	0.0
Rest of High Income Asia	-0.4	0.2	-0.8	-0.4	3.4	-18.8	0.1	-0.9
Rest of Southeast & South Asia	0.8	-0.8	-0.3	-0.3	0.8	-0.6	0.5	-0.2
Oceania countries	1.1	-0.1	-0.1	1.6	2.7	-1.5	3.9	-1.6

Table 9. Impact of Biofuel Drivers on Bilateral Trade (change in import volume): 2001-2006 ($ millions)

	Exporters:	Coarse Grains				Oilseeds				Other Food Products			
		US	EU	RoW	Total Exports	US	EU	RoW	Total Exports	US	EU	RoW	Total Exports
1	US	0	-4	-174	-178	0	158	-81	77	0	-129	-85	-214
2	Canada	6	1	2	9	-3	19	-14	2	89	-9	14	93
3	EU-27	0	0	23	23	0	0	-130	-130	135	0	2667	2801
4	Brazil	0	4	22	26	0	179	-42	137	-8	-144	40	-112
5	Japan	0	0	0	0	0	0	0	1	8	-2	13	20
6	China-Hong Kong	0	1	40	42	1	49	52	102	29	-4	96	121
7	India	0	1	5	6	9	31	72	112	54	43	292	389
8	Latin American Energy Exporters	0	3	22	25	-2	23	-72	-51	-168	-347	-264	-779
9	Rest of Latin America & Caribbean	7	4	10	22	1	31	20	51	37	-41	110	106
10	EE & FSU Energy Exp	0	6	32	38	1	63	7	70	-19	-206	-170	-395
11	Rest of Europe	0	0	3	3	0	8	2	10	5	-28	105	82
12	Middle Eastern N Africa energy exporters	-1	-2	-7	-9	-1	-7	-5	-13	-41	-191	-215	-447
13	Sub Saharan Energy exporters	-1	-2	-4	-6	-1	-2	-20	-23	-19	-487	-154	-660
14	Rest of North Africa & SSA	0	1	19	20	0	4	3	8	-1	-39	89	49
15	South Asian Energy exporters	0	0	1	1	0	2	3	5	8	-54	42	-4
16	Rest of High Income Asia	0	0	0	0	0	0	0	1	-10	-10	-90	-111
17	Rest of Southeast & South Asia	0	0	6	6	0	2	15	17	138	8	251	398
18	Oceania countries	0	0	28	28	2	13	5	20	1	-14	-32	-45
	Total	**14**	**13**	**27**	**54**	**7**	**574**	**-185**	**395**	**238**	**-1654**	**2709**	**1293**

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 10. Performance of Trade Balance due to Biofuel Drivers ($ billion).

Trading Regions / Trading Sectors	1 USA	2 CAN	3 EU27	4 BRAZIL	5 JAPAN	6 CHIHKG	7 INDIA	8 LAEEX	9 RoLAC	10 EEFSUEX	11 RoE	12 MEASTNAEX	13 SSAEX	14 RoAFR	15 SASIAEEX	16 RoHIA	17 RoASIA	18 Oceania	Total
Coarse Grains	0.26	0.02	0.04	0.07	-0.13	0.04	0.01	-0.01	0.00	0.05	0.00	-0.39	-0.02	0.02	-0.01	-0.02	0.01	0.05	-0.01
Other Grains	0.02	0.21	-0.04	-0.04	0.12	0.06	0.41	0.05	0.04	0.15	0.04	-1.47	-0.17	0.04	0.01	0.09	0.20	0.22	-0.06
Oilseeds	0.40	0.05	-0.89	0.32	-0.07	0.01	0.11	-0.04	0.07	0.08	0.01	-0.12	0.00	0.01	-0.01	-0.01	0.04	0.04	-0.03
Sugarcane	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Livestock	-0.16	0.09	-0.07	0.00	0.01	0.25	0.11	-0.08	0.03	-0.01	0.11	-0.49	-0.07	0.03	0.00	-0.02	0.07	0.14	-0.07
Forestry	0.04	-0.01	-0.13	0.00	-0.04	0.10	0.12	0.00	0.02	0.13	0.06	-0.07	-0.34	0.02	0.07	0.00	0.05	0.02	0.04
Ethanol-1	-0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ethanol-2	-0.78	-0.07	-0.02	0.86	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biodiesel	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other Food Products	-0.36	0.12	3.02	-0.04	0.09	0.23	0.45	-0.78	0.19	-0.57	0.13	-2.08	-1.07	0.09	0.06	-0.06	0.53	-0.03	-0.08
Processed Livestock	-0.76	0.21	2.28	0.24	0.19	0.27	0.23	-0.54	0.19	-0.29	0.16	-2.34	-0.57	0.06	0.09	0.02	0.37	0.06	-0.14
Other Agri Commodities	-0.39	0.03	1.72	-0.02	0.18	0.45	0.75	-0.54	0.53	-0.34	0.51	-2.84	-1.75	0.20	0.06	0.22	1.06	0.05	-0.12
Oil & Oil Products	-66.09	2.35	-62.45	-1.36	-29.29	-8.04	-8.24	29.20	-3.15	48.79	-6.18	115.12	20.09	-2.11	6.07	-18.34	-12.3	-1.45	2.64
Other Primary sectors	-0.26	-0.56	4.37	0.24	0.72	-0.58	0.22	-0.34	0.22	-0.20	0.21	-2.62	-0.18	-0.66	-0.12	1.10	0.19	-1.05	0.71
Manufacturing & services	-76.59	0.04	151.43	0.03	27.49	5.35	7.96	-41.35	1.49	-12.30	22.88	-99.38	-17.87	3.20	-4.90	18.43	11.37	-0.13	-2.88
Total	-144.7	2.50	99.25	0.30	-0.74	-1.89	2.12	-14.4	-0.4	35.48	17.92	3.33	-1.97	0.89	1.32	1.42	1.62	-2.1	0.00

Note: For abbreviations of the regions, please refer to the corresponding serial numbers in Table 9.

Table 11. Decomposition of Terms of Trade for the US and EU ($ million).

	US				**EU-27**			
	World Price	**Export Price**	**Import Price**	**Total**	**World Price**	**Export Price**	**Import Price**	**Total**
Coarse Grains	20	113	4	137	0	1	4	6
Other Grains	-54	45	0	-9	-3	44	-19	22
Oilseeds	-41	-7	2	-46	25	45	-28	43
Other Food Products	-221	153	3	-65	258	-656	212	-186
Processed Livestock	-316	161	-11	-166	-297	-256	174	-379
Other Agri Sectors	-105	56	0	-49	429	-423	-25	-19
Biofuels	8	0	-12	-4	1	-16	16	1
Oil & Oil Products	-53989	110	295	-53583	-76985	-133	-328	-77446
Other Primary sectors	457	26	-48	435	2948	-115	31	2864
Manufacturing & services	-880	9462	-2518	6064	-7582	-20025	5575	-22032
Total	**-55122**	**10120**	**-2284**	**-47286**	**-81206**	**-21532**	**5612**	**-97126**

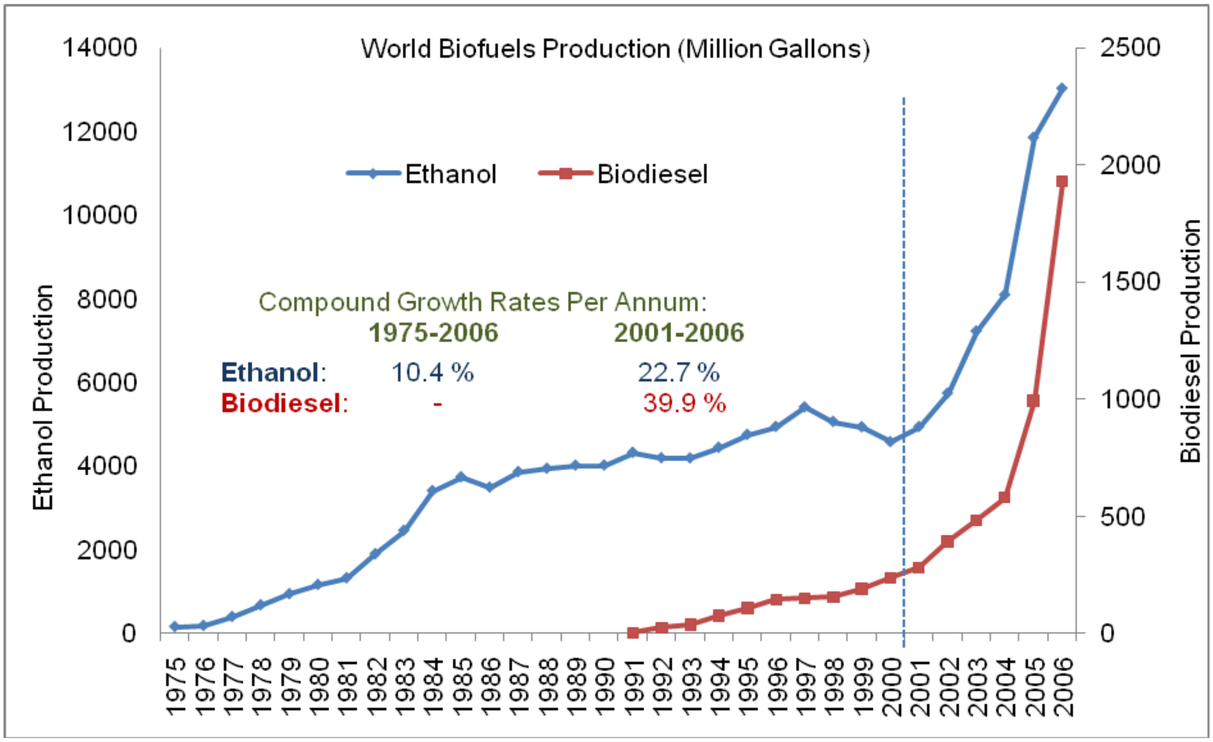


Figure 1. World Production of Ethanol and Biodiesel (million gallons)
(Data sources: Earth Policy Institute, 2006; FAPRI, 2007)

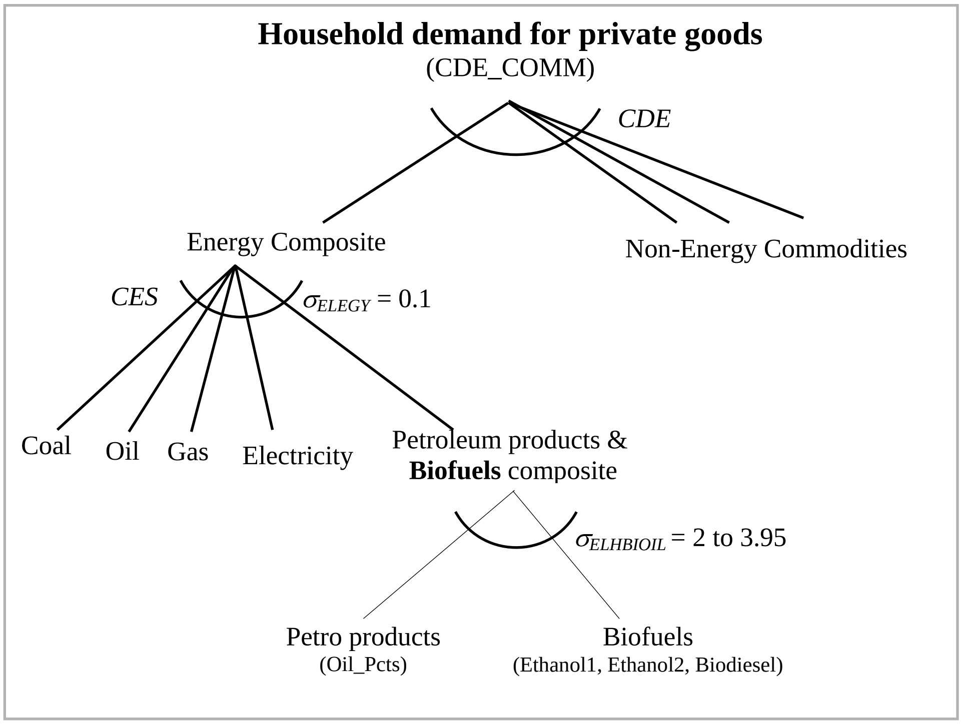


Figure 2. Modification of Consumption Structure in the GTAP-E Model

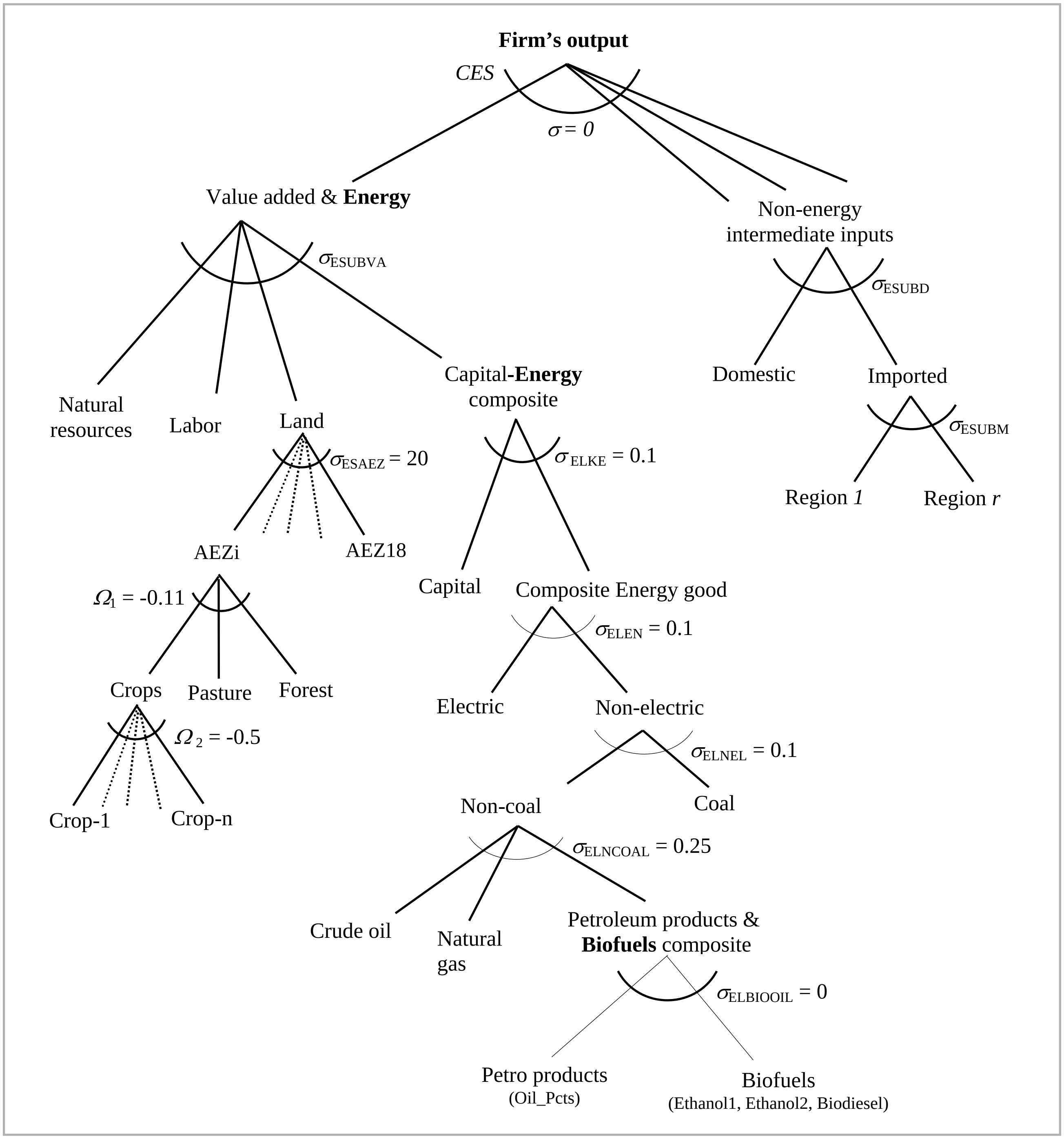
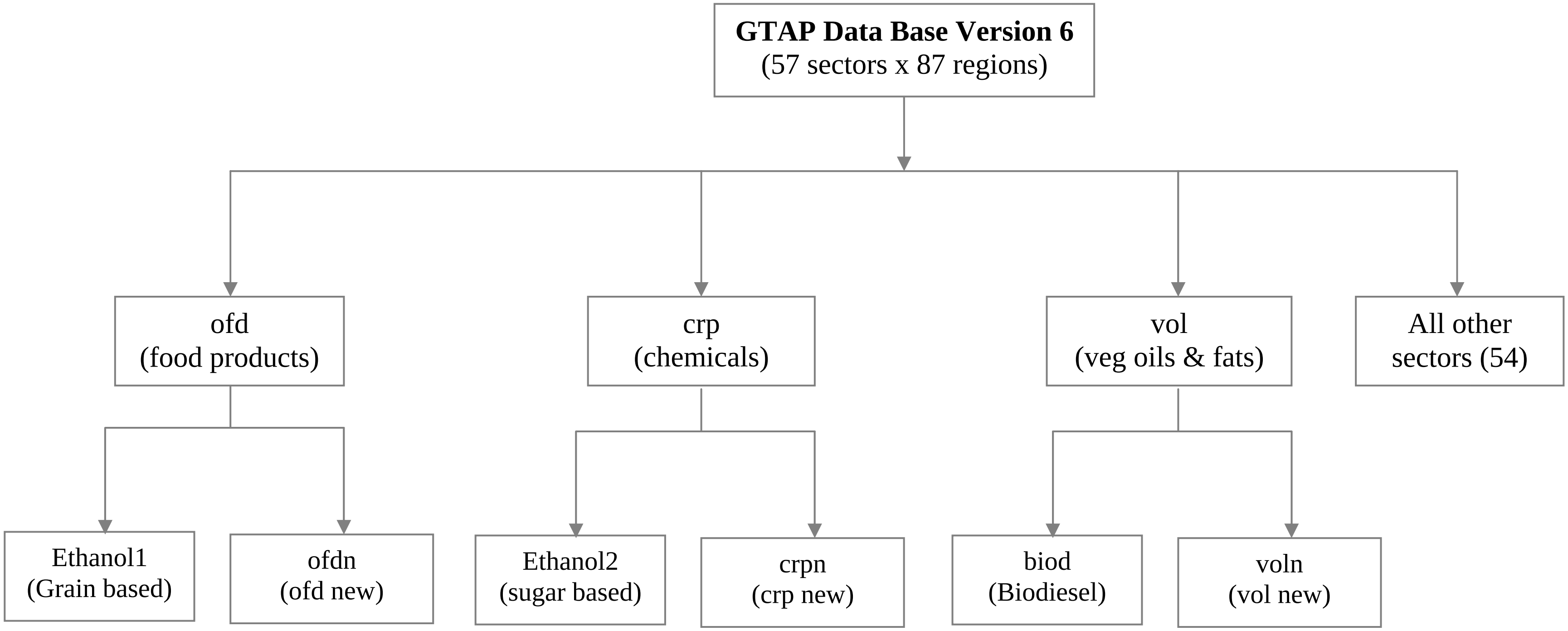


Figure 3. Modification of Production Structure in the GTAP-E Model

Figure 4. Splitting the Three Types of Biofuels in the GTAP Data Base[1]



[1] Please refer to Taheripour *et al*. (2007) for more details.

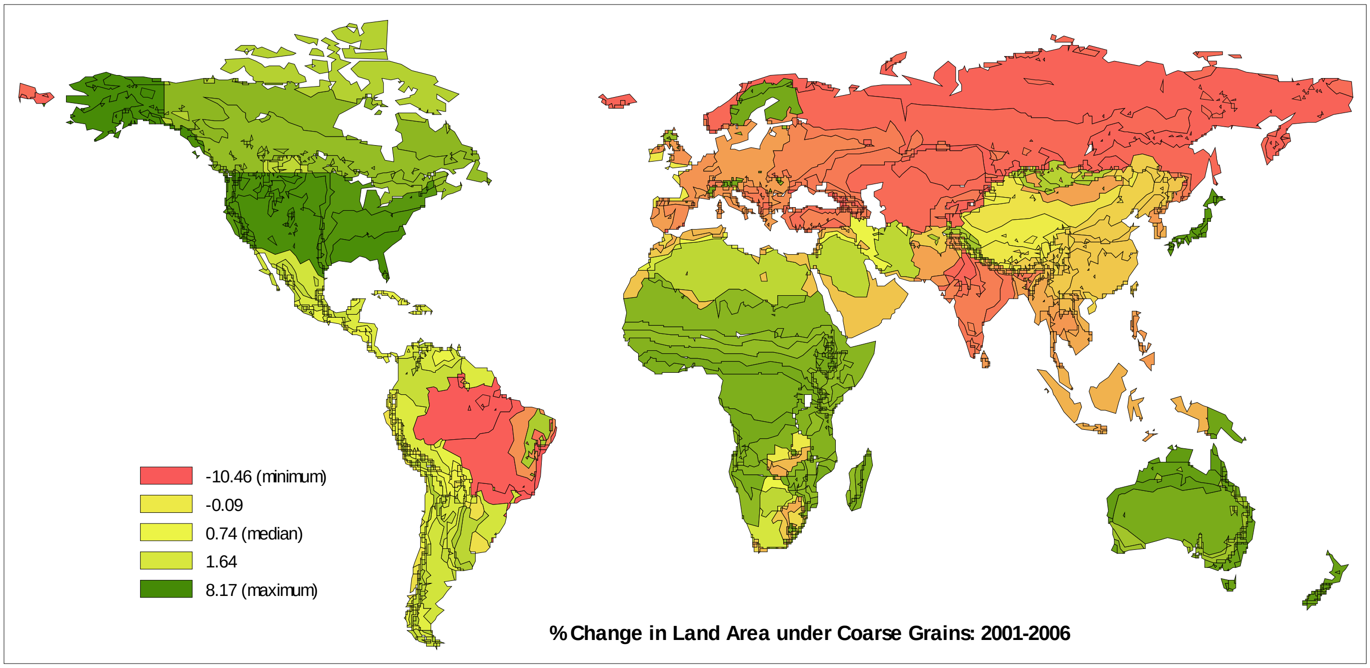


Figure 5. Change in Land Area across AEZs under Coarse Grains: 2001-2006.

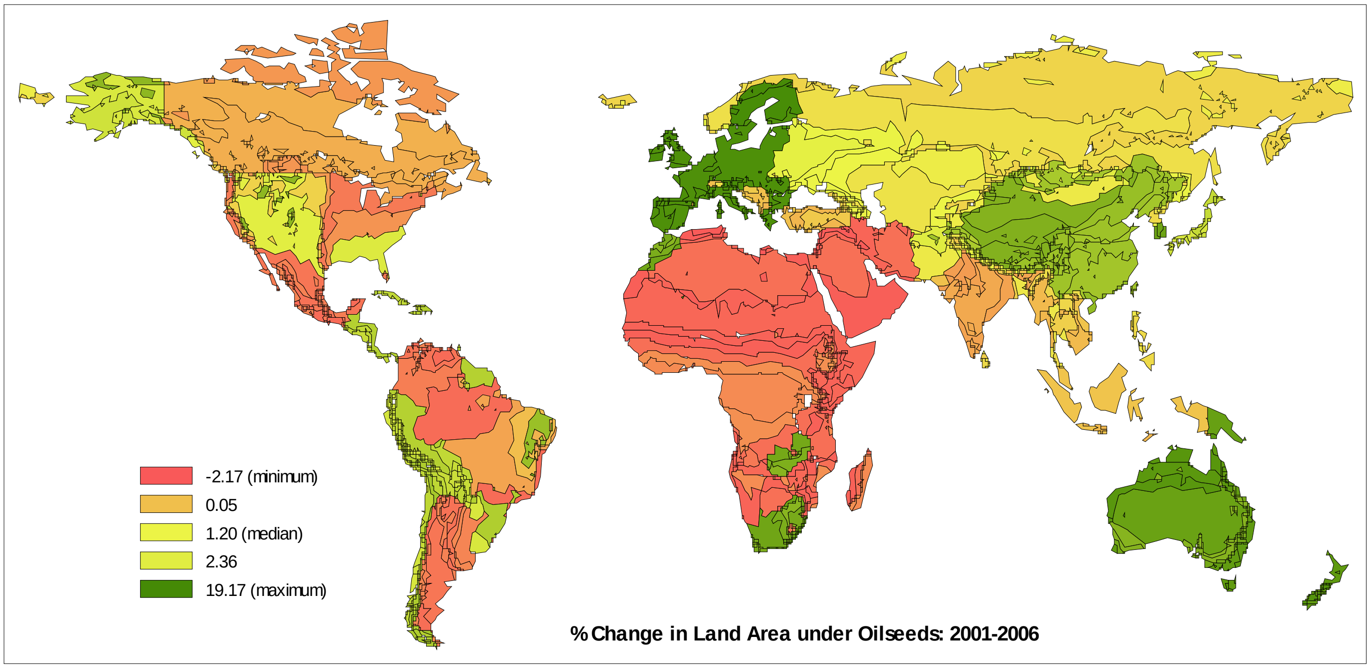


Figure 6. Change in Land Area across AEZs under Oilseeds: 2001-2006.

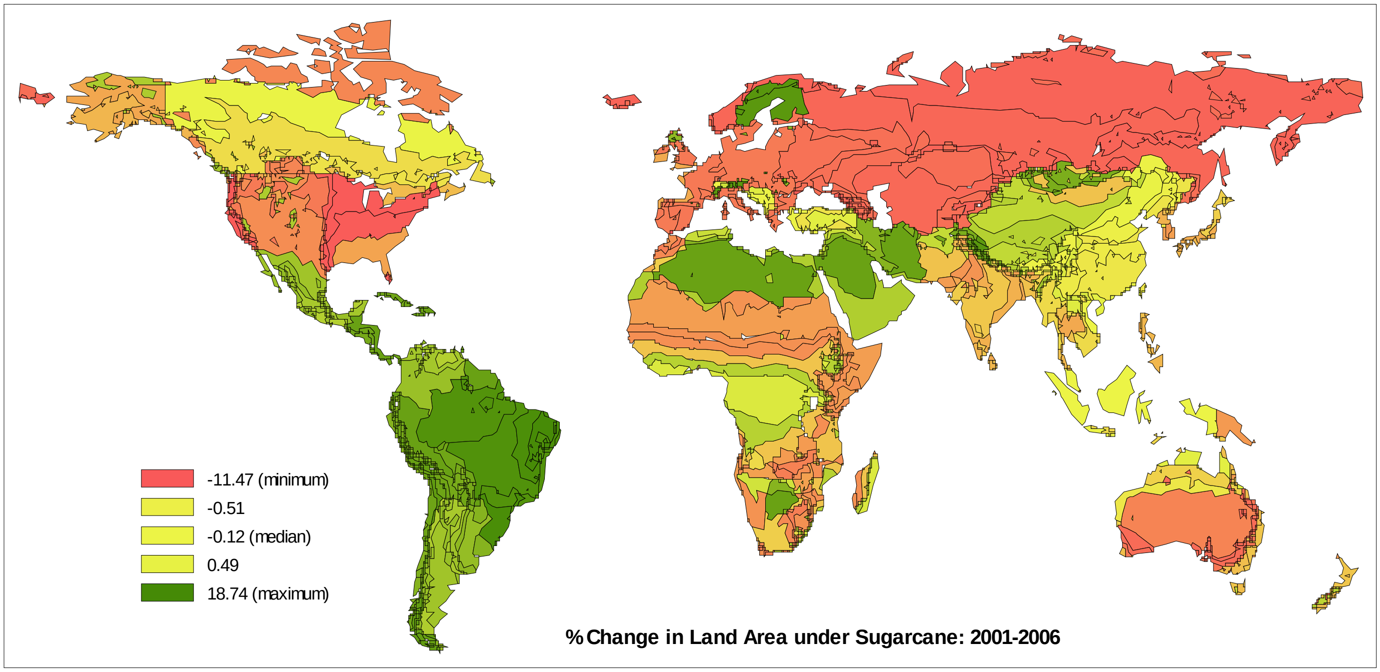


Figure 7. Change in Land Area across AEZs under Sugar Crops: 2001-2006.

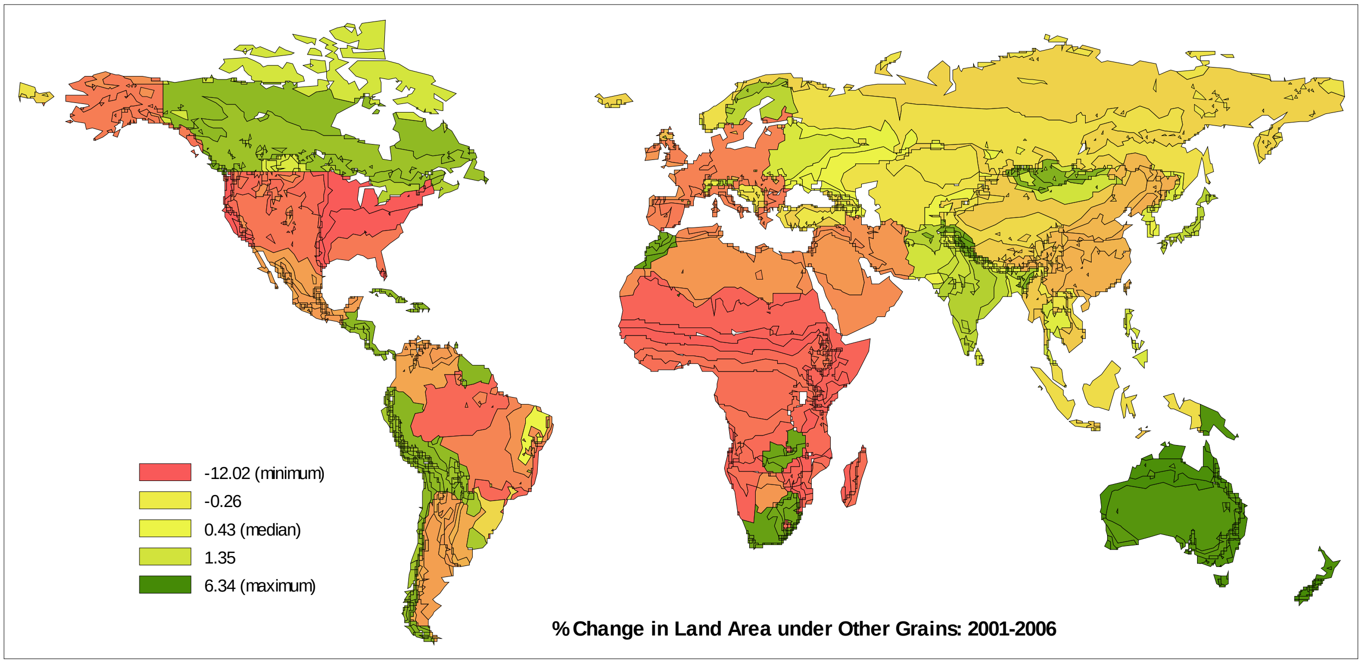


Figure 8. Change in Land Area across AEZs under Other Grains (Paddy & Wheat): 2001-06.

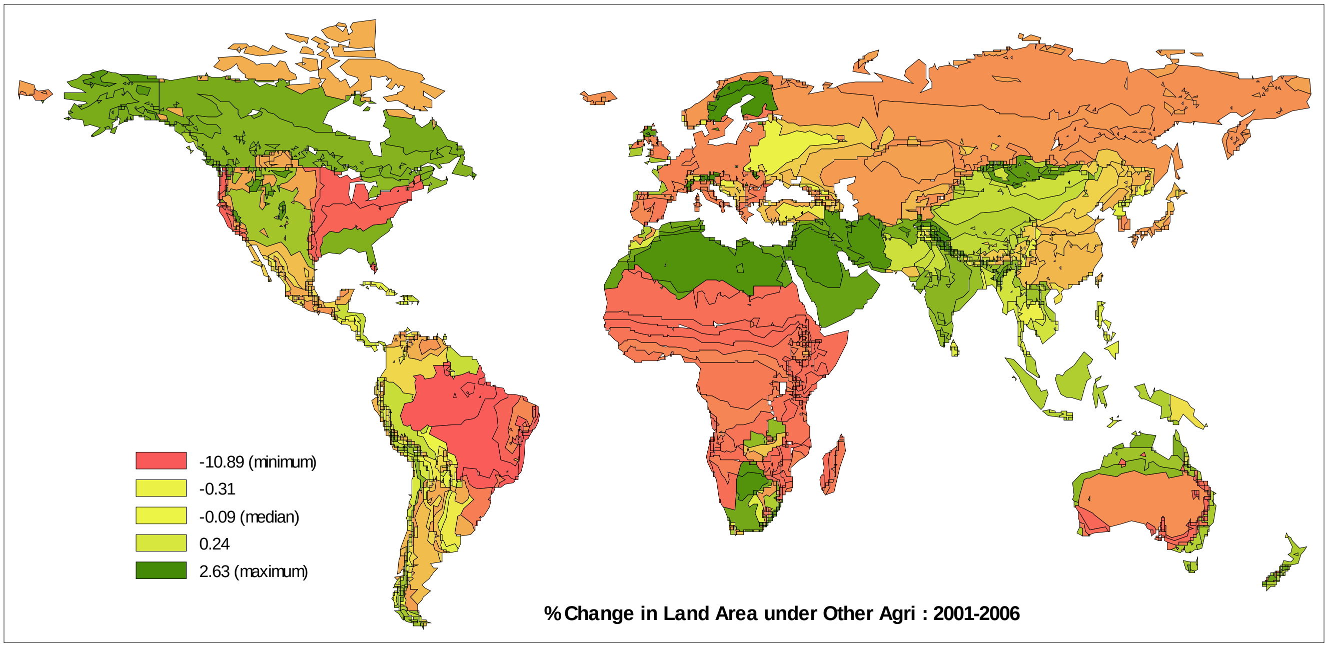


Figure 9. Change in Land Area across AEZs under Other Agri Goods: 2001-2006.

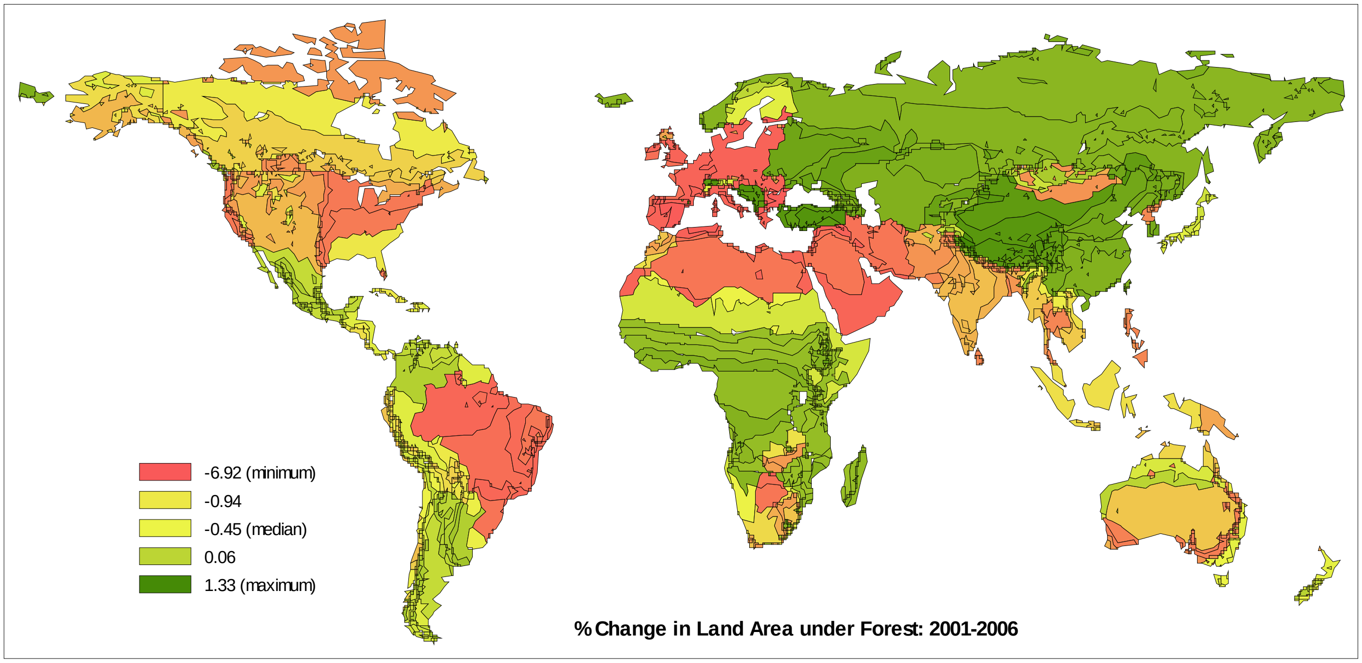


Figure 10. Change in Land Area across AEZs under Forestry: 2001-2006.

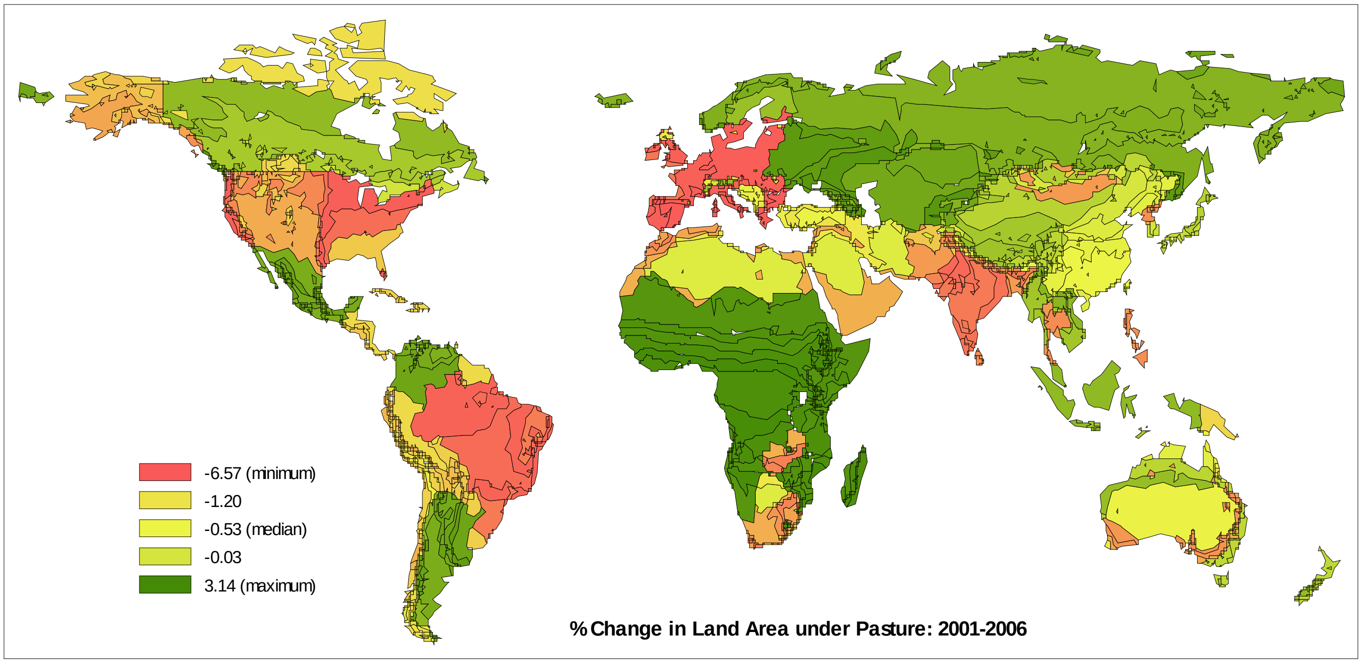


Figure 11. Change in Land Area across AEZs under Pasture cover: 2001-2006.

Appendix-1: Closure and Shocks for Analyzing the Impact of Biofuel Boom

```
! Oil Price, Additive, to - Shocks closure
exogenous
   afall    afcom    afreg    afsec    ams
   aoall    aoreg    aosec
   atd    atf    atm    ats    au
   cgdslack
   dpgov    dppriv    dpsave
   endwslack    incomeslack
   pemp    pfactwld    pop
   profitslack    psaveslack
   qo(ENDW_COMM,REG)
   RCTAXB
   tm    tms    to    tpd     tpm     tp
   tradslack
   tx    txs    ;
Rest Endogenous ;

swap aosec("oil") = pxwcom("oil");
```

***List of Shocks*:**

```
Shock pxwcom("oil") = 136;

Shock afall("ethanol1","Oil_pcts","USA") = -49;

Shock to("Ethanol1","USA") = -10.93;

Shock to("biodiesel","USA") = -7.00;

Shock to("Ethanol1","EU27") = 50.77;

Shock to("biodiesel","EU27") = 81.18;

Subtotal afall = MTBE ban ;
Subtotal pxwcom = World oil price ;
Subtotal to(NSAV_COMM,"USA") = USA subsidies ;
Subtotal to(NSAV_COMM,"EU27") = EU subsidies ;
```