Global Land Use Changes due to the U.S. Cellulosic Biofuel Program Simulated with the GTAP Model

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1. Introduction

The land use consequences of US biofuel programs and their contributions to GHG emissions have been the focal point of many debates and research studies in recent years. However, most of these studies focused on the land use emissions due to first generation biofuels such as corn ethanol, sugarcane ethanol, and biodiesel (e.g. [1, 2] [3, 4]). A quick literature review indicates that only a few attempts have been made to estimate these emissions for second generation biofuels which convert cellulosic materials into liquid fuels.

Gurgel, Reilly, and Paltsev [5] introduced two biomass energy sectors (Bios-Electric and Bio-Oil) into a highly aggregated computational general equilibrium (CGE) model, known as the MIT Emissions Prediction and Policy Analysis (EPPA), to evaluate land use consequences of producing biofuels from biomass feedstocks. That model ignores first generation biofuels, aggregates all agricultural products in one sector thereby over-simplifying the competition for land among its alternative uses, and relies on an old data set which represents the world economy in 1999. Those authors predicted that producing energy from biomass requires a considerable amount of land, about 0.5 hectares per 1,000 gallons of ethanol. They did not calculate the land use emissions due to production of energy from cellulosic materials.

In a preliminary work, Tyner, Taheripour, and Han [6] used farm level and partial equilibrium models and showed that producing ethanol from corn stover may have insignificant land use implications. The authors also concluded that the US idled and cropland pasture can support considerable volumes of biofuel production without imposing a major impact on other crop activities on cropland.

More recently, the United States Environmental Protection Agency (EPA) released its emissions assessments for alternative biofuels including ethanol produced from corn stover and a dedicated crop (switchgrass) [7]. To provide these assessments, EPA mainly relied on the FASOM and FARPRI partial equilibrium models to evaluate domestic and international land use impacts of the US biofuel production targets. The simulation results obtained from these models showed that producing ethanol from corn stover has insignificant land use impacts. However, producing ethanol from switchgrass will cause major land use changes in the US and other countries across the world. The EPA results indicated that producing 7.9 billion gallons of ethanol from switchgrass will increase global cropland area by about 3 million hectares, of which 1.7 million hectares will occur in the US. In addition, according to the EPA estimates, producing ethanol from switchgrass will curb acreages of US soybeans, wheat, hay, and a variety of other crops by 3.36 million hectares. The EPA results indicated that producing ethanol from switchgrass reduces the US land use emissions, because producing switchgrass deposits carbon into the soil. According to this report, producing ethanol from switchgrass reduces GHGs by 2.5 kg CO_2 equivalent per million BTU of ethanol produced due to the land use changes and soil carbon sequestration within US (about 190 grams CO_2 equivalent per gallon of ethanol). On the other hand, producing ethanol from switchgrass causes about 15 kg CO_2 equivalent per million BTU due to the land use changes in the rest of the world (about 1,140 grams CO_2 equivalent per gallon of ethanol). Hence, according to the EPA report the net land use emissions of producing ethanol from switchgrass are about 12.5 kg CO_2 equivalent per million BTU (about 950 grams CO_2 per gallon of ethanol).

The existing limited literature on land use impacts of producing biofuels from crop and forest residues provides enough evidence to confirm that producing these fuels from agricultural and forest residues causes insignificant land use impacts. However, this picture is cloudy for dedicated energy crops. As mentioned above, some studies argue that it is possible to produce dedicated energy crops on marginal and idled croplands, and therefore it will not cause significant land use impacts. On the other hand, other studies indicate that this argument could be misleading and that producing dedicated crops could lead to major land use changes.

Estimating the land use impacts of producing biofuels from dedicated energy crops is more complicated in many ways than that from corn ethanol. Production of dedicated crops for significant volumes of biofuels could alter relative prices of crops and their profitability leading farmers to produce them on their existing active croplands or convert their idled or marginal croplands (e.g. cropland pasture) to produce these crops. Even marginal lands are often used in some way for livestock production, so that competition must be taken into account. Given that these crops are not produced at a commercial level yet, and it is not clear how farmers will react when they become profitable, it is important to provide a comprehensive analytical framework to assess a wide range of alternative possible cases which may come about in the future.

This paper provides an analysis of the land use changes induced by biofuel production from cellulosic feedstocks. It develops an economy-wide computational general equilibrium (CGE) model based on the modeling framework developed at Purdue University’s Center for Global Trade Analysis Project (GTAP) to assess the land use consequences of producing biofuels from cellulosic materials including corn stover and dedicated energy crops. In particular, we extend the model developed in Tyner et al. [4], known as GTAP-BIO-ADV, in several directions. The new model is based on the latest version of GTAP database (version 7), which depicts the world economy in 2004. It handles production, consumption and trade of the first and second generation biofuels, and its land use components allow competition among traditional crops and dedicated energy crops for idled land and cropland pasture.

In what follows we first describe the model and data changes in the following sections:

- Introducing biofuels into the 2004 version 7 GTAP data base,
- Introducing advanced biofuels into the GTAP modeling framework,
- Land supply nesting structure,
- Adding greater flexibility in acreage switching among different crops in response to price changes,
- Including an endogenous yield adjustment for cropland pasture in response to changes in cropland pasture rent.

We describe each of these changes to the basic modeling and data structure. Details of the changes are provided in the appendices A, B, and C. Then we introduce the experiments which are designed to simulate the land use impacts of biofuels mandates. Finally, we provide estimates for the land use implications of alternative biofuel pathways (both ethanol and bio-gasoline) from corn, corn stover, miscanthus, and switchgrass and their associated emissions.

2. Introducing Biofuels into the 2004 Version 7 of GTAP Database

The first version of GTAP-BIO database was built based on the GTAP standard database version 6 which represented the world economy in 2001 [8]. That database covers global production, consumption, and trade of the first generation of biofuels including ethanol from grains (*eth1*), ethanol from sugarcane (*eth2*), and biodiesel (*biod*) in 2001. Recently, version 7 of GTAP database, which depicts the world economy in 2004 was published [9]. However, this database does not include biofuel industries. To take advantage of this new database we introduced global production, consumption, and trade of first generation biofuels in 2004 into this database. In addition, we introduced several new industries into the data base to expand the space of biofuel alternatives to second generation of biofuels as well (see Appendix A). In particular, we introduced three feedstock industries (Miscanthus, Switchgrass, and Corn stover) and six advanced biofuel industries (Miscanthus bio-gasoline (AdvfB_Misc), Switchgrass bio-gasoline (AdvfB_Swit), Corn stover bio-gasoline (AdvfB_Stover), Miscanthus ethanol (AdvfE_Misc), Switchgrass ethanol (AdvfE_Swit), and Corn stover ethanol (AdvfE_Stover)) into the database. Given that the advanced cellulosic biofuels are not yet commercially viable, we assigned very small values to the production and consumption of these biofuels in 2004 and we used the most updated information obtained from the literature and expert inputs to define the production technologies for these industries. We also updated the land use, land cover, and land rent headers of the new GTAP-BIO database according to unpublished work done by Avetisyan, Baldos and Hertel [10]. These authors updated the GTAP land use and land cover data set to 2004. The steps and processes which we followed to construct the new database are described in Appendix A of this paper in detail. Here we briefly introduce its major specifications.

The new GTAP-BIO data set represents the world economy in 2004 and covers 69 groups of commodities (including biofuels and their byproducts), 67 industries, and 117 regions. In this paper we aggregated the new database to the commodity and regional aggregation levels which are used in Tyner et al. [4] with minor modifications. Here we collapsed regions, commodities, industries, and endowments into 19 regions, 43 groups of commodities, 41 industries, and 22 groups of endowments. See appendix A of this paper for more details. In this aggregation crops are aggregated into 8 groups (including paddy rice, wheat, coarse grains, oilseeds, sugar crops, other crops, miscanthus, and switchgrass), and biofuels are: ethanol from grains, ethanol from sugar crops, biodiesel from oilseeds, ethanol from corn stover, ethanol from miscanthus, ethanol from switchgrass, bio-gasoline from corn stover, bio-gasoline from miscanthus, and bio-gasoline from switchgrass.

The energy content of bio-gasoline is assumed to be equal to the energy content of conventional gasoline, and the energy content of ethanol is two-thirds that of conventional gasoline. In the advanced biofuel sectors, conversion of cellulosic materials to gasoline-like hydrocarbon fuels follows a thermochemical conversion technology, and conversion of cellulosic materials to ethanol follows a biochemical pathway.

In addition to these new commodities we split the traditional food and vegetable oil industries into new industries of food, feed, crude vegetable oil, refined vegetable oil, and oilseed meals to better represent and model the links and interaction among these industries with crops and biofuel. In the older version of GTAP-BIO database oilseed meals were tradable indirectly through the feed industry. In the new version oilseed meals are directly and indirectly tradable, meaning that the oilseed crushing industry (represented by the crude vegetable oil industry) could sell its oilseed meal outputs to domestic buyers (including livestock and the feed industries) and international markets. This will help us to model production and trade of oilseed meals more accurately and is more consistent with the actual operation of this industry.

The land use and land cover categories and definitions used in this dataset are very similar to those in the old version. However, we revised the rent values we assigned to each type of land to make them more consistent with independently available information in this area. The previous model did not have physical outputs for cropland pasture. Because cropland pasture will take on much more importance in this version, we created output values that resulted in yields somewhat less than hay yields on cropland. This was done for both the U.S. and Brazil. This change plays an important role in analyzing the land use impacts of producing biofuels from dedicated energy crops.

To introduce cellulosic biofuels we assumed that several regions including the U.S., the EU and Brazil produce tiny volumes of cellulosic biofuels in the base year. For the U.S. we assumed that miscanthus and switchgrass will be produced in AEZs 7 to 12, mostly in AEZs 10, 11, and 12 (see Figure 1). These AEZs are endowed with large areas of cropland pasture suitable for producing dedicated energy crops such as miscanthus and switchgrass.

3. Introducing Advanced Biofuels into the GTAP Modeling Framework

To add second generation biofuels we adopt as the starting point for the new model, the model reported in Tyner et al. [4] and known as GTAP-BIO-ADV. We made several changes and modifications in the GTAP codes and its associated parameters to introduce the advanced biofuels into GTAP modeling framework. These changes and modifications are outlined in detail in Appendices A and B. Here we describe major characteristics of the new model, which henceforth we refer to it as the GTAP-BIO_ADVFUEL.

As noted earlier in this report, we first defined six industries to handle production processes of the two new biofuels commodities – bio-gasoline and ethanol for each of the three feedstocks. Then we introduced the new biofuels into the household demand structure and the derived demand of firms for liquid fuels. To support production of the new biofuels we defined three new industries (stover, miscanthus, and switchgrass) which provide feedstocks for the new biofuel industries. The stover industry collects corn stover and ships its output (collected corn stover) to the stover ethanol or bio-gasoline industry. This industry uses inputs including fuel, fertilizer (to maintain productivity of croplands where nutrients in stover are removed), transportation, capital, labor, and other goods and services to collect, bail, store and ship corn stover to the stover processing industry. The miscanthus and switchgrass industries are different from the stover industry. These industries produce miscanthus or switchgrass and sell their products to the processing industries. The miscanthus and switchgrass industries compete with crop producers for cropland. It is important to note that we are not simulating miscanthus and switchgrass together. We simulate either miscanthus or switchgrass, separately.

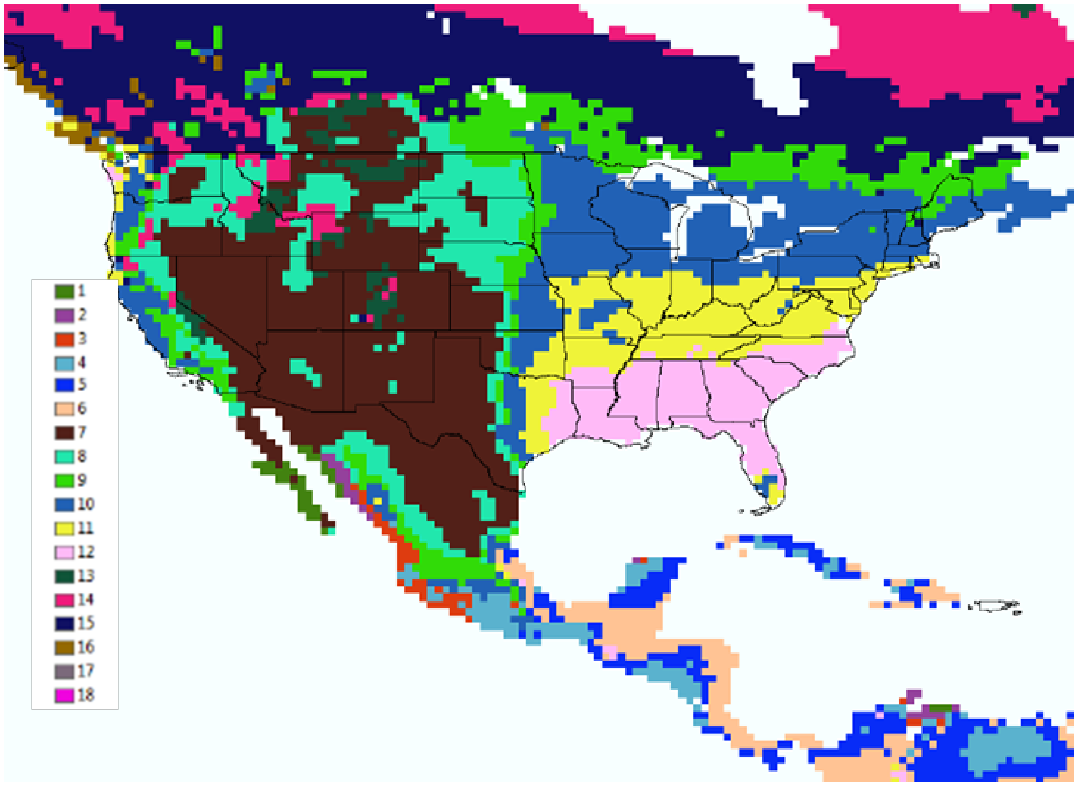

Figure 1. Distribution of AEZs in the U.S.

4. Land Supply Nesting Structure

In our earlier work the land supply module consisted of a two-level nesting structure. In this nesting format the lowest level allocates land supply among three land cover categories of forestry, pastureland, and cropland, and the upper level allocates croplands among crop activities including the Conservation and Reserve Program (CRP) land and cropland-pasture. In the two-level nesting structure only one parameter (ETL2) governs allocation of cropland supply among all types of crops. In this work we extended the land supply structure into three levels. We made this change because it more closely represents the agronomic and economic reality. Dedicated energy crops such as miscanthus and switchgrass are much more likely to compete with cropland pasture than they are to compete with much more productive cropland used for corn, soybeans, etc. Thus, the new structure better reflects what would likely emerge in this new production activity. The lowest level of the new land supply model is the same as what we had before. The second level divides cropland supply into two main crop categories. The first group covers all traditional crops including rice, wheat, coarse grains, oilseeds, vegetable and fruits, sugar crops, other crops, and CRP land (not used in this analysis). The second group covers miscanthus, switchgrass, and cropland-pasture. The top level of this three-level nesting structure determines supply of cropland to every crop activity. This nesting structure allows us to assign different land transformation elasticities among the first and second groups of crops (see Figure 3 in appendix B).

5. Adding Greater Flexibility in Acreage Switching Among Different Crops in Response to Price Changes

In our previous work we and others observed that GTAP does not seem to have as much acreage responsiveness as we experienced in the decade 2000-09. Indeed, it is the case that in previous decades, crop acreages (distribution of cropland among alternative crops) were much more responsive to changes in government programs, as these seemed to be more important drivers than commodity prices. Chavas and Holt [11] used 1945-1985 annual time-series data for U.S. corn and soybean acreage decisions, they found the own-price elasticities for corn and soybeans to be very low, 0.158 and 0.441 respectively, which were also confirmed by Gallagher [12], Lee and Helmberger [13], Tegene, Huffman and Miranowski [14]. The small elasticities were due to the government intervention in corn and soybean markets.

Houck and Ryan [15] evaluated the impact of government programs on corn and concluded that more than 95% of variation in U.S. corn acreage during 1949-1969 can be associated with variables that represent government intervention. Duffy, Kasazi and Kinnucan [16] also used corn and soybean 1955-1988 annual time-series data to estimate acreage response under farm programs. Their results showed that risk variability affected soybeans to some extent but price variability in corn had little effect on planting provisions due to extensive farm programs for corn to mitigate the effects of market volatility. Houck and Subtonik [17], Chembezi and Womack [18], de Gorter and Paddock [19], and Mclntosh and Shideed [20] also concluded that government programs' impact on corn and soybean's acreage response to be the most important one and dominated other impacts. Clearly, prior to 2000, prices were less important in determining acreage shifts. The GTAP parameter which governs the extent of acreage shift among alternative cropping industries in response to relative crop prices was calibrated on historical data. Given the recent observations on crop acreages, it seems that farmers now respond to the relative crop prices more than what we observed in the past (prior to 2000). In this analysis, we asked the question of whether there is any difference in farmers reactions to crop price changes in the past decade and earlier periods. To answer this question we estimated acreage response to changes in soybean and corn returns per acre over different decades prior to 2000 and for 2000-2010. The following regression shows the results for the time period of 2000-2010:

ΔHarvesed corn area (acres) = 1.388 + 0.084 ΔCorn revenue/acre(t-1) – 0.138 ΔSoybean revenue/acre(t-1)

The independent variable *t* values are 2.9 and 3.0 respectively, and the adjusted R^2 is 0.44. For the 2000-2010 period, changes in corn and soybean revenues were a major driver of changes in corn acres. We did the same regressions for prior periods and found no significant relationship. As the literature suggests, in prior periods, government policy was a major driver, and now it is commodity prices and revenue. For these reasons, we increased the magnitude of the land supply transformation elasticity among the traditional crops from -0.5 to -0.75. In the future, we will continue to test the sensitivity of this parameter. A complete description of the new nesting structure and associated elasticities is provided in Appendix B.

6. Endogenous Cropland Pasture Yield Change

Producing dedicated energy crops on cropland pasture will increase the opportunity costs of using these lands as an input in livestock industry, which consequently will lead farmers to improve productivity of their cropland pasture. Cropland pasture today is used largely as an input to the livestock industry. We received comments on our previous work suggesting that the increased use of land for biofuels would lead to investments in increased productivity as land rents increased. This led us to define a module to link productivity of cropland pasture with its rent. Rent is a residual reflecting the underlying value of the land derived from its revenue streams. This module determines changes in productivity of cropland pasture according to its rent and an elasticity parameter which is added to the model parameters. This elasticity governs cropland pasture yield change with respect to changes in the rent of cropland pasture. The equation which represents the endogenous productivity increase is as follows:

$$af(i,r) = \alpha[1 + \beta \cdot \varphi] pf(i,r)$$

Where

Af(i, r): Cropland pasture augmenting technical change in Agro Ecological Zone *i* of region *r*,

α: Scalar yield elasticity,

β: Scalar yield adjustment factor,

φ: Share of dedicated energy crop in total area of cropland pasture,

pf (i, r): Percent change in the rent of cropland pasture in Agro Ecological Zone *i* in region *r*.

In the simulations presented in this report, we assigned a value of 0.4 to the scalar yield elasticity (i.e. $\alpha=0.4$) and assigned different values to the scalar yield adjustment factor (β) to establish the following relationship between the area of cropland pasture moved to the production of dedicated crops (ΔA) and the percentage change in the average yield of cropland pasture (p_yield):

$$p\_yield = 4.15\Delta A.$$

In other words, for each simulation, the value of β was calibrated to hold this relationship constant. The productivity changes obtained from the scenarios which simulate the land use impacts of producing biofuels from dedicated crops vary from about 15% for miscanthus bio-gasoline to 35% for switchgrass ethanol.

Another interpretation of the productivity increase is that it is the productivity increase required to obtain the land use change results provided in this report. In other words, with no productivity increase, more land would be needed than is calculated with the productivity increase. We have no clear empirical basis for the parameters used in this analysis. As indicated above, we had clear and consistent feedback from reviewers that by assuming no productivity increase, we were over-estimating the land use change. Whether these results over or under estimate land use change associated with dedicated energy crops is an open question.

7. Biofuel Scenarios for Simulation

To assess the land use emissions due to production and consumption of the second generation of biofuels we defined the following seven experiments:

a. An increase in corn ethanol production from its 2004 level (3.41 billion gallons [BG]) to 15 BG, using the 2004 database,

b. An increase in production and consumption of Bio-Gasoline produced from corn stover (i.e. AdvfB-Stover) by 6 BG (or 9 BG ethanol equivalent), on top of 15 BG corn ethanol,

c. An increase in production and consumption of Bio-Gasoline produced from miscanthus (i.e. AdvfB-Misc) by 4.7 BG (or 7 BG ethanol equivalent), on top of 15 BG corn ethanol,

d. An increase in production and consumption of Bio-Gasoline produced from switchgrass (i.e. AdvfB-Swit) by 4.7 BG (or 7 BG ethanol equivalent) on top of 15 BG corn ethanol,

e. An increase in production and consumption of ethanol from corn stover (i.e. AdvfE-Stover) by 9 BG, on top of 15 BG corn ethanol,

f. An increase in production and consumption of ethanol from miscanthus (i.e. AdvfE-Misc) by 7 BG, on top of 15 BG corn ethanol,

g. An increase in production and consumption of ethanol from switchgrass (i.e. AdvfE-Swit) by 7 BG, on top of 15 BG corn ethanol.

These experiments are designed based on the targets which are defined in the Renewable Fuel Standard (RFS2) and are explained in Appendix C.

8. Land Use Impacts

The land use impacts obtained from the experiments defined in the previous section are presented in Table 1. This table indicates that producing 11.59 BG corn ethanol increases global cropland area by 2.1 million hectares (0.18 hectares per 1000 gallons of ethanol). About 47% of this additional land requirement is expected to occur in the U.S., and the share of forest in this land requirement is about 11%. In general, the normalized additional land requirement obtained from this experiment (0.18) is in between the corresponding figures reported for the second and third group of experiments presented in Tyner et al. [4]. However, the share of forest in land conversion obtained from the new experiment (11%) is smaller than the corresponding figures obtained from the second and third groups of that report. Simulation results obtained from experiment (a) indicates that also about 1.4 million hectares of cropland pasture will be converted to cropland globally due to the corn ethanol shock. Cropland pasture is included in the cropland cover classification. Cropland pasture is defined as land that as some point in history was in cropland but is not today. It is not land considered converted from natural land now. However, the data is available separately for this category, so alternative assumptions can be applied. Cropland pasture land changes are reported in Table 2.

The results obtained from experiment (b) show that producing bio-gasoline from corn stover causes insignificant land use impacts. This result does not include any associated soil carbon change.

Table 1. Land Use Impacts of First and Second Generation Biofuels (1000 hectares)*

Case	Scenario	Land cover	US	EU	Brazil	Others	Total
(a)	15 BG ETH Off of 2004	Forest	-331	-80	42	144	-226
		Crop	971	126	82	899	2,078
		Pasture	-639	-46	-123	-1,043	-1,852
(b)	6 BG Stover Bio-Gasoline	Forest	8	2	0	47	56
		Crop	-13	-2	-2	-15	-32
		Pasture	5	0	2	-32	-24
(c)	4.7 BG Miscanthus Bio-Gasoline	Forest	-153	-16	8	24	-137
		Crop	106	25	15	173	319
		Pasture	47	-9	-23	-197	-183
(d)	4.7 BG Switchgrass Bio-Gasoline	Forest	-550	-45	20	-16	-590
		Crop	223	65	40	447	775
		Pasture	327	-20	-60	-431	-185
(e)	9 BG Stover Ethanol	Forest	19	3	0	52	74
		Crop	-13	-4	-3	-25	-44
		Pasture	-6	1	3	-28	-30
(f)	7 BG Miscanthus Ethanol	Forest	-221	-21	11	26	-205
		Crop	134	32	20	222	408
		Pasture	88	-11	-31	-249	-202
(g)	7 BG Switchgrass Ethanol	Forest	-784	-61	28	-29	-845
		Crop	301	89	54	610	1,054
		Pasture	483	-28	-82	-581	-208

*Cases (b) to (g) are in addition to case (a). The crop category includes both traditional crops and dedicated energy crops.

Producing bio-gasoline from miscanthus requires a considerable amount of land (in terms of new land plus cropland pasture moved to miscanthus). The result of experiment (c) shows that producing 4.7 billion gallons of bio-gasoline from miscanthus (equivalent to 7 BG ethanol) increases global cropland area (i.e. new cropland) by about 0.3 million hectares. About 33% of this new land requirement will occur in the US, and globally forest has a share of 43% in this new land conversion. The normalized additional land requirement of producing 4.7 BG bio-gasoline from miscanthus is about 0.07 hectares per 1000 gallons of bio-gasoline or 0.05 ha per 1000 gal. of ethanol equivalent, considerably less than the requirement for corn ethanol. In general about 3.7 million hectares of land are needed to produce 4.7 BG bio-gasoline from miscanthus. However, this land requirement is mainly obtained from cropland pasture (see Table 2). To support this shift the yield of cropland pasture would need to be increased by about 15%. Producing miscanthus for biofuel transfers also some cropland pasture to production of other crops and moderately affects allocation of cropland among crop activities.

The results from experiment (d) show that producing 4.7 BG of bio-gasoline from switchgrass requires more land than miscanthus because the yield is considerably lower. Global cropland area (i.e. new cropland) increases by about 0.8 million hectares, and 29% of that is in the US. Forest is 76% of the global total. The land requirement per 1000 gallons of bio-gasoline is 0.16 hectares (0.11 per 1000 gal. ethanol equivalent), less than the requirement for corn ethanol, but much higher than miscanthus. About 7.1 million hectares of land is needed for switchgrass, as shown in Table 2 most of which comes from cropland pasture. To support this shift the yield of cropland pasture would need to be increased by about 29%. The large amount of land needed also explains why such a large share comes from forest. With a large amount of cropland pasture needed for switchgrass, the livestock sector must go to other land categories. Given the low productivity of pasture, it opts to get more forest land.

Table 2. Changes in Area of Cropland Pasture due to Biofuel Production (1000 hectares)

Biofuel Case		Changes in Cropland Pasture		Net Moved to Traditional Crops		Net Moved to Dedicated Energy Crops	
		US	Brazil	US	Brazil	US	Brazil
(a)	15 BG Corn Ethanol Off of 2004	-1,169	-238	1,169	238	0	0
(b)	6 BG Stover Bio-Gasoline	0	6	0	-6	0	0
(c)	4.7 BG Miscanthus Bio-Gasoline	-3,719	-43	52	43	3,667	0
(d)	4.7 BG Switchgrass Bio-Gasoline	-6,915	-113	-177	113	7,092	0
(e)	9 BG Stover Ethanol	-9	8	9	-8	0	0
(f)	7 BG Miscanthus Ethanol	-4,590	-56	195	56	4,395	0
(g)	7 BG Switchgrass Ethanol	-8,278	-154	-228	154	8,506	0

Experiments (e) through (g) involve production of ethanol from cellulosic feedstocks. Experiment (e) is production of 9 BG of ethanol from corn stover. There are virtually no land use impacts associated with this pathway.

Experiment (f) is 7 BG of ethanol from miscanthus. Global cropland (i.e. new cropland) increases by about 0.4 million hectares, about 33% of which is in the U.S. Forest represents 50% of the land conversion. The land requirement per 1000 gallons of ethanol is 0.06 hectares. About 4.4 million hectares of miscanthus is needed, considerably more than the 3.7 million needed for the equivalent amount of bio-gasoline (experiment c). To support this large shift from cropland pasture to miscanthus production an increase of 19% in the productivity of cropland pasture is needed.

Finally experiment (g) simulates production of 7 BG of ethanol from switchgrass. It requires about 1 million hectares of new cropland globally (table 1), 29% of which is in the US. Forest constitutes 80% of the converted land. The land requirement per 1000 gallons of ethanol is 0.15, close to the requirement for corn ethanol. Globally, 8.5 million hectares of cropland pasture (table 2) are needed to support production of 7 BG of ethanol from switchgrass. To support this large shift from cropland pasture to switchgrass production, a sizeable increase of 35% in the productivity of cropland pasture is needed.

Table 3 summarizes the land needed per 1000 gallons of bio-gasoline or ethanol for each of the cases. Three important conclusions emerge from this table. First, switchgrass needs more land than miscanthus in all cases. This conclusion derives from the assumed lower yield of switchgrass compared with miscanthus. Clearly, dedicated energy crop yield is key to deriving the land use changes associated with these feedstocks. Second, ethanol requires more land in all cases than bio-gasoline (in ethanol equivalents) because the conversion efficiency is assumed to be higher for the thermochemical process to produce bio-gasoline than for the ethanol bio-chemical process. Third, both conversion processes produce negligible land use changes when corn stover is the feedstock. The detailed land use changes among cropland, forest, and pasture and in different global regions needed for GREET and other model applications are available upon request from the authors.

Table 3. New Cropland Needed for the Different Cases

Biofuel Case		Biofuel Produced (billion gallon)	New Cropland Needed (1000 ha.)	New Cropland Needed (ha./1000 gallons of biofuel)	New Cropland Needed (ha./1000 gallons of ethanol eq.)
(a)	Corn Ethanol	11.59	2078	0.18	0.18
(b)	Stover Bio-gasoline	6	-32	-0.005	-0.004
(c)	Miscanthus Bio-gasoline	4.7	319	0.07	0.05
(d)	Switchgrass Bio-gasoline	4.7	775	0.16	0.11
(e)	Stover Ethanol	9	-44	-0.005	-0.005
(f)	Miscanthus Ethanol	7	408	0.06	0.06
(g)	Switchgrass Ethanol	7	1054	0.15	0.15

9. Conclusions

These results suggest that corn stover (and by implication other crop residues) have no significant induced land use change associated with biofuel production. The results suggest that use of dedicated energy crops induces land use change and transfers natural land (in particular forest) to crop production. Producing biofuels from dedicated crops also transfers a major portion of cropland pasture to the production of these crops. The size of this land transformation varies with the type of biofuel produced, and it ranges between 16% and 35 % of the existing areas of US cropland pasture prior to biofuel production. Our results indicate that producing bio-gasoline from miscanthus generates the lowest land requirement across all alterative pathways which convert dedicated crops to biofuels. This pathway needs about 0.07 hectares of new natural land per 1000 gallons of bio-gasoline (or 0.05 hectares per 1000 gallons of ethanol equivalent). The largest land requirement is associated with the switchgrass. This pathway needs about 0.15 hectares of new natural land per 1000 gallons of ethanol. These results indicate that the land requirements for switchgrass are considerably higher. The difference is due largely to the assumed yields of switchgrass and miscanthus in this analysis. If switchgrass yields turn out to be higher, then this difference would narrow.

These results indicate that recent articles which imply little or no land use impacts from dedicated energy crops could be misleading. The land use impacts of producing biofuels from dedicated crops is not zero because the opportunity costs of using cropland pasture is not zero. Livestock producers will not give up their cropland pasture with no compensation. The fact is that there is little completely idled land, especially in the U.S. We have not used CRP acreage in these estimates. Also, these results for dedicated energy crops depend upon the assumption of productivity increase in cropland pasture as more and more of it is used for dedicated energy crops. We believe that some measure of productivity increase is appropriate, but the magnitude needs more research.

In future research, we intend to present emission results of the simulated land use changes using emission factors that are currently under development by our group and others.

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Appendix A

Introducing the First and Second Generations of Biofuels into the GTAP Database Version 7

The first version of GTAP-BIO database was built based on the GTAP standard database version 6 which represented the world economy in 2001 [8]. That database covers global production, consumption, and trade of the first generation of biofuels including ethanol from grains (*eth1*), ethanol from sugarcane (*eth2*), and biodiesel (*biod*) in 2001.

This standard GTAP database version 7, recently published, also does not cover biofuel industries. Following Taheripour et al. [8] we first introduce the first generation of biofuels into this database. Then we define a process to introduce the second generation of biofuels into this newer data base as well.

1. Introducing Biofuels into GTAP Version 7

To introduce *eth1*, *eth2* and *biod* into the new database we replicate the original work done by Taheripour et al. [8]. Hence in this section we briefly explain the steps which we followed and the data items which we used. In addition, we highlight differences between the new database and the original one.

1.1. Step One; Production and Trade of Biofuels in 2004

We collected data on consumption and trade of biofuels in 2004 from several sources including the U.S. Department of Energy (DOE), the U.S. Department of Agriculture (USDA), the Renewable Fuel Association (RFA), European Union of Ethanol Producers, European Biodiesel Board, and others. Table A1 represents production of grain-based ethanol, sugarcane-based ethanol, and biodiesel across the world in 2004. Figures reported in this table are introduced into the GTAP-BIO database version 7 as productions of *eth1*, *eth2*, and *biodiesel* in 2004.

In 2004 Brazil was the leading ethanol exporter in the world. Table A2 shows 2004 Brazilian exports. This data was introduced in the GTAP-BIO database version 7 for the trade of *eht2*. In this year trade of *eht1* and *biod* were negligible.

Table A1. Global Biofuel Production in 2004 (million gallons)

Country Code in GTAP V7	Country Name	Grain Based Ethanol (eth1)	Sugarcane Based Ethanol (eth2)	Biodiesel
BRA	Brazil	0.0	3989.0	0.0
USA	USA	3410.0	0.0	28.0
CHN	China	100.5	0.0	0.0
ESP	Spain	67.1	0.0	3.9
CAN	Canada	52.8	0.0	0.0
IND	India	0.0	42.5	0.0
FRA	France	26.7	0.0	104.5
SWE	Sweden	18.8	0.0	0.4
THA	Thailand	0.0	14.8	0.0
POL	Poland	12.7	0.0	0.0
ARG	Argentina	0.0	8.4	0.0
XCB	Caribbean	0.0	7.4	0.0
DEU	Germany	6.6	0.0	310.7
AUS	Australia	0.0	6.6	0.0
JPN	Japan	6.2	0.0	0.0
PHL	Philippines	0.0	4.4	0.0
NLD	Netherland	3.7	0.0	0.0
LVA	Latvia	3.2	0.0	0.0
FIN	Finland	0.8	0.0	0.0
ITA	Italy	0.0	0.0	96.1
DNK	Denmark	0.0	0.0	21.0
CZE	Czech Republic	0.0	0.0	18.0
AUT	Austria	0.0	0.0	17.1
SVK	Slovakia	0.0	0.0	4.5
BGR	United Kingdom	0.0	0.0	2.7
LTU	Lithuania	0.0	0.0	1.5

Sources: DOE, USDA, the Renewable Fuel Association, European Union of Ethanol Producers, and European Biodiesel Board.

1.2. Step Two; Sectors to Be Split and Biofuels Plant Level Models

Following the original work reported in Taheripour et al. [8], the new industries of *eht1*, *eth2*, and *biod* are taken from the GTAP sectors of *ofd*, *crp*, and *vol*, respectively. The production technologies of ethanol industries are also similar to our original work.

However, a new technology was introduced for biodiesel production. In the original GTAP-BIO database the biodiesel industry was using oilseeds to produce biodiesel (as the main product) and oilseed meal as the by-product. The biodiesel industry in the new database uses crude vegetable oil and only produces biodiesel. Hence, in the new database, the biodiesel industry does not produce any by-products. Instead, as explained later on in this report, we defined a new industry which uses oilseeds to produce crude vegetable oil and oilseed meals. The new approach models the role of oilseed meals in an economy with biofuels more precisely.

Table A2. Brazil Ethanol Exports by Importing Countries
(million gallons)

Country Code in GTAP V7	Country Name	Imports from Brazil
CHL	Chile	0.5
CRI	Costa Rica	30.5
XCA	El Salvador	7.5
IND	India	125.1
XCB	Jamaica	35.1
JPN	Japan	58.4
MEX	Mexico	1.0
NLD	Netherlands	43.6
NGA	Nigeria	28.2
XSM	Others	68.5
KOR	South Korea	72.8
SWE	Sweden	44.0
TUR	Turkey	3.2
USA	U.S.A.	111.0
VEN	Venezuela	0.1
	Total	629.671

Source: [21]

While the cost structure of the *eth1*, e*th2*, and *biod* activities are the same as before, their levels are tuned to the price levels of 2004. For the revenue side we assume that the price of ethanol was about $1.69 per gallon (this was the US average ethanol price in 2004). The price of biodiesel is determined according to its energy content compared with the energy content of ethanol. In constructing the new database we take into account the following subsidies and tariffs as well:

- U.S. ethanol subsidy of 0.51 cents per gallon,
- U.S. biodiesel subsidy of 100 cents per gallon,
- US ethanol tariff (2.5% ad valorem plus 54 cents/gal. specific),

We sequentially used the *SplitCom* program to split the original and parent sectors of *ofd*, *crp*, and *vol* to the new sectors of *eth1*, *eth2*, *biod*, *ofdn*, *crpn*, and *voln*. These processes are explained in detail in Taheripour et al.[8]. Table A3 represents global production of biofuels introduced.

1.3. Split of Ethanol Between the Additive and Final Fuel

In this step we split ethanol consumption between two parts: ethanol as an additive to gasoline and ethanol as a fuel extender. Following the original work we assigned 75% of ethanol production to the additive role and the rest as a fuel consumed by consumers. The database obtained from the above steps corresponds to the GTAP-BIO version 6. Henceforth we refer to this database as **GTAP-BIO_V7**. This database will be available for GTAP users. In the next sections we describe the modifications to the commodity structure to better highlight the links among the crop, biofuels, food, feed, and livestock industries.

2. Split of Standard GTAP Food Industry into Food and Feed Industries

In the GTAP-BIO databases the *ofdn* industry[1] covers production of all processed foods and animal feeds [22]. This aggregated industry has major forward and backward links with many industries. It buys raw materials from crop, livestock, processed livestock, and vegetable oil industries and sells its products to several sectors as intermediate inputs and to households as final products. Indeed the *ofdn* covers two major industries of processed food and processed feed. To better understand the implications of biofuel production for these industries we split the *ofdn* industry into two distinct activities of "*food*" and "*feed*". To accomplish this task we pursued the following assumptions and steps:

[1] This sector is known as *ofd* in the GTAP standard database.

Table A3. Monetary Values of Outputs of Food and Feed Industries in GTAP-BIO V7 at Market Prices (U.S. million dollars)

Region*	Food	Feed
1 USA	247,252	41,246
2 EU27	732,996	62,195
3 BRAZIL	26,513	3,617
4 CAN	25,271	4,152
5 JAPAN	151,209	16,371
6 CHIHKG	67,136	20,259
7 INDIA	27,405	2,064
8 C_C_Amer	62,133	5,248
9 S_o_Amer	29,358	5,115
10 E_Asia	21,988	5,702
11 Mala_Indo	20,877	3,161
12 R_SE_Asia	21,083	2,802
13 R_S_Asia	4,474	887
14 Russia	15,400	2,701
15 Oth_CEE_CIS	24,667	2,892
16 Oth_Europe	18,983	1,660
17 MEAS_NAfr	27,062	3,185
18 S_S_AFR	28,008	3,626
19 Oceania	21,886	2,331
Total	1,573,701	189,213

* Members of these regions are shown in Table A10.

a. All sale items of the o*fdn* industry to the livestock industries (i.e. *ctl*, *oap*, *rmk*, and *wol*) are assumed to be processed feed products. These items are considered as sales of the *feed* industry. We applied the same rule for the imported sales as well.

b. According to the very detailed U.S. 1997 input-output table obtained from The Bureau of Economic Analysis of the U.S. Departments of Commerce, we defined column shares to split the intermediate and primary inputs used by the *ofdn* industry between the *food* and *feed* industries.

Given these assumptions we defined column, row, and cross shares for the splitting process in each region. We introduced the column, row and cross shares into the *Split.com* program to split the *ofdn* industry into two new industries. We allowed the

S*plit.com* program to determine the trade shares as the residual. Table A3 represents the monetary values of outputs of these new industries at market prices by region in the new database.

3. Split of Standard GTAP Vegetable Oil Industry into Crude and Refined Vegetable Oil Industries

In the GTAP-BIO database the "*voln*" industry[2] covers production of all types of vegetable oils and fats (for details see Karen Huff et al., 2000). This industry produces crude and refined vegetable oils; animal and vegetable fats; and all types of oilseed meals, oil cakes, and other residues resulting from the extraction of vegetable oils and fats. This industry buys all types of oilseeds and animal fats along with other inputs and sells its products mainly to the livestock and processed livestock industries, food industries, processed animal feed industries, chemical industries, services (restaurants and fast food), and households. In an economy with biofuels, the *vol* industry interacts with the biofuel industry as well.

To better represent the forward and backward links between crop, vegetable oil, livestock, food, feed and biofuel industries and follow the stream of commodities among these industries, we split the *voln* sector into two distinct industries of crude vegetable oil (*cvoln)* and refined vegetable oil (*rvoln*). The former industry crushes oilseeds and produces two commodities: crude vegetable oil and oilseed by-products. The latter industry uses crude vegetable oil and produces refined vegetable oil. To divide the *voln* industry into the new sectors we pursued the following steps and assumptions:

a. All sale items of the *voln* industry to the livestock and feed industries (i.e. *ctl, oap, rmk, wol, and feed)* are assumed to be animal feed. These items are mainly oilseed meals, oil cakes, and other residues resulting from the extraction of vegetable oils and fats. These items are considered as sales of the *cvoln* industry. We applied the same rule for the imported sales as well.
b. The self use of the *voln* industry (mainly crude vegetable oil) is considered as an intermediate input for the *rvoln* industry. This item is also included in the sale items of the *cvoln* industry.

[2] This sector is known as *vol* in the GTAP standard database.

c. In biodiesel producing regions, sales of *vol* to the biodiesel industry are transferred to the *cvoln* industry.
d. All crop and livestock commodities purchased by the *vol* industry are transferred to the *cvoln* industry.
e. Other cost items of the *voln* industry are mainly divided between the *cvoln* and *rvoln* based on the sale shares of these two industries in total sale of the *voln* industry. In some cases we modified the cost shares according to the cost shares obtained from the U.S. input-output table.

Given these assumptions we defined column, row, and cross shares for the split process in each region. We introduced the column, row and cross shares into the *Split.com* program to split the *voln* industry into two new industries. We allowed the S*plit.com* program to determine the trade shares as the residual. In some cases we altered the trade shares to match the results with real observation obtained from the Oil World database [23]. Table A4 represents the monetary values of outputs of these two new industries at market prices by region in the new database.

4. Introducing By-Products into the Database

Here we introduce two by-products into the database. The first by-product is Dried Distillers' Grains with Solubles (*DDGS*), produced jointly with ethanol from grains. The second by-product is oilseed meals (*VOBP*). To introduce *DDGS* we determined the volume of *DDGS* produced in each region according to ethanol production in each region. Then, we assessed the monetary value of the *DDGS* produced in each region according to the average price of *DDGS* in the U.S. in 2004. In that year the U.S. was the main exporter of DDGS. Hence we introduced U.S. DDGS exports to other regions for the trade of this commodity. As noted earlier in this report we distinguished oilseed meals produced by the *cvoln* industry in section "3.a" of this report. Here, we just explicitly separated them out from the main product and referred to them as *VOBP*. Table A5 represent monetary values of DDGS and VOBP at market prices by region in the new database.

Table A4. Monetary Values of Outputs of Crude and Refined Vegetable Oil Industries in GTAP-BIO V7 at Market Prices (U.S. million dollars)

Region	Cveg	Rveg
1 USA	7,657	8,546
2 EU27	6,989	28,890
3 BRAZIL	5,686	6,094
4 CAN	1,130	2,243
5 JAPAN	1,672	3,931
6 CHIHKG	3,515	3,963
7 INDIA	2,456	5,870
8 C_C_Amer	859	3,397
9 S_o_Amer	5,865	6,792
10 E_Asia	892	1,179
11 Mala_Indo	7,428	11,173
12 R_SE_Asia	801	2,546
13 R_S_Asia	911	2,544
14 Russia	506	1,704
15 Oth_CEE_CIS	1,030	3,740
16 Oth_Europe	147	635
17 MEAS_NAfr	1,016	2,879
18 S_S_AFR	937	2,666
19 Oceania	427	2,109
Total	49,924	100,899

* Members of these regions are shown in Table A10.

5. Introducing Cellulosic Feedstock Industries into the Database

The following feedstock industries are introduced into the database to support production of advance biofuels:

- Corn stover industry, which collects corn stover from croplands and delivers the collected corn stover to the cellulosic biofuel industries,
- Miscanthus industry, which produces miscanthus and delivers its output to the cellulosic biofuel industries,
- Switchgrass industry, which produces switchgrass and delivers its output to the cellulosic biofuel industries.

Table A5. Monetary Values of Outputs of DDGS and VOBP in GTAP-BIO V7 at Market Prices (U.S. million dollars)

Region	DDGS	VOBP
1 USA	1,157	4,517
2 EU27	48	1,761
3 BRAZIL	0	1,210
4 CAN	18	508
5 JAPAN	2	727
6 CHIHKG	34	2,048
7 INDIA	0	883
8 C_C_Amer	0	281
9 S_o_Amer	0	1,158
10 E_Asia	0	455
11 Mala_Indo	0	1,112
12 R_SE_Asia	0	132
13 R_S_Asia	0	497
14 Russia	0	58
15 Oth_CEE_CIS	0	161
16 Oth_Europe	0	37
17 MEAS_NAfr	0	217
18 S_S_AFR	0	220
19 Oceania	0	44
Total	1,259	16,026

* Members of these regions are shown in Table A10.

Since these new industries do not operate in real world, we used the most updated information available in the literature and inputs from experts to define the cost structures of these industries and their production technologies. The literature has wide ranges of estimates regarding dedicated energy crop yields, crop production costs, conversion technology costs, and conversion yields. We were fortunate to have assistance from experts at Argonne national Laboratory and the National Renewable Energy Laboratory to assist in developing a reasonable and consistent set of assumptions to use in the analysis. All the data that follows comes from literature and discussions with that group.[3] The production costs of corn stover, miscanthus, and switchgrass are shown in Table A6. The assumed annual yields are 1.5, 8.7, and 4.5 dry short tons per acre for corn stover,

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[3] The collaborators from Argonne and National Renewable Energy Laboratory were Andy Aden, Jennifer Dunn, Ignasi Palou-Rivera, and May Wu. Many thanks for their assistance.

miscanthus, and switchgrass, respectively. For corn stover, we assumed that 33 percent of the available stover could be removed and the rest left on the field to prevent erosion and loss of soil carbon.

Table A6. Production Costs of Corn Stover, Miscanthus and Switchgrass at 2010 Prices (U.S. dollars per dry short ton)

Cost item	Stover	Miscanthus	Switchgrass
Fertilizer	20.34	16.47	16.47
Harvesting costs:	20.19	35.56	35.56
Fuel	3.06	5.39	5.39
Labor	3.31	5.83	5.83
Equipment	7.38	13.00	13.00
Other	6.44	11.34	11.34
Transport:	30.00	30.00	30.00
Labor	15.00	15.00	15.00
Equipment	10.00	10.00	10.00
Fuel	5.00	5.00	5.00
Storage	18.94	13.00	13.00
Seeding	0.00	19.69	4.52
Land rent	0.00	11.31	21.82
Total cost with no rent	89.47	114.71	99.55
Total cost with rent	89.47	126.03	121.37

Source: Authors' estimates in consultation with Argonne and National Renewable Energy Laboratory.

Then using the U.S. GDP deflator we adjusted these cost items (except for land rent) to the price level of 2004 to make them consistent with the price level of GTAP database. For land we followed a different method to adjust its value to 2004. This method is explained later in this section. According to our calculations, corn stover, miscanthus, and switchgrass are priced at $78, $103.12, and $92.45 per short ton respectively at 2004 prices. We converted cost items noted in Table A6 in terms of cost items in GTAP database. These cost structures are shown in Table A7. This table indicates that capital is a major cost item in these new industries. This table also shows that items such as transportation, fertilizer, and labor have significant shares in the cost structures of these new industries. As shown in Tables A6 and A7, unlike the corn stover industry, the miscanthus and switchgrass industries use land as an input in the production process. The costs of land for miscanthus and switchgrass industries are determined based on yield of 8.7 and 4.5 short tons per acre for miscanthus and switchgrass, respectively. The rent value for land under production of these crops is assumed to be about $60 per hectare ($24.3 per acre) in 2004. This value is obtained according to the average of land rents in wheat, coarse grains, oilseeds, and livestock industries in GTAP 2004 database.

To introduce the corn stover, miscanthus, and switchgrass industries into the database, we assumed that some regions including the U.S., Brazil, China, France, Germany, and the U.K. produce tiny amounts of these products in 2004 and converts them to advance biofuels. The *SplitCom* program was used to introduce these industries into the new database.

Table A7. Cost Structures of Corn Stover, Miscanthus, and Switchgrass Sctivities (percentages of total costs)

Cost Items	Corn Stover	Miscanthus	Switchgrass
Fertilizer	22.7	14.0	15.6
Transportation	33.5	25.4	28.4
Fuel	3.4	4.6	5.1
Payments to seed company	0.0	6.7	1.7
Other costs	7.0	7.5	8.0
Labor	10.0	10.7	11.5
Land	0.0	2.7	5.8
Capital (including profit)	23.3	28.5	23.9
Total	100.0	100.0	100.0

Source: Authors' estimates.

6. Introducing Advanced Cellulosic Biofuels into the Database

Six cellulosic biofuel producers which convert cellulosic feedstocks to advanced biofuels were introduced into the database – three for ethanol and three for bio-gasoline. In other words, there is a separate industry for each feedstock (stover, miscanthus, and switchgrass). For bio-gasoline, the industries are identical. For ethanol, the stover industry is somewhat different from the dedicated energy crop industry as shown in the base production cost data in Table A8. The conversion yield for bio-gasoline is 60 gallons of bio-gasoline per dry ton (regardless of feedstock). For ethanol, the conversion yield is 75 gallons of ethanol per dry ton regardless of feedstock. It is also assumed that the price of the advanced biofuels is equal to their production costs.

Table A9 provides the cost structure for the biofuel industries. This table indicates that capital and feedstock are major cost items for biofuel producers. Even though these industries may produce by-products (such as electricity and other energy products), their shares are so small that we ignore here. However, we also assumed that the advanced biofuel producers will get $1.01subsidy per gallon of produced fuel in the base case. The *SplitCom* program was used to introduce these industries into the new GTAP-BIO database.

Table A8. Biofuel Production Costs

Cost Items	FeedStock ($ / dry short ton)	Pathways		
		Thermo - Gasoline	Bio - Ethanol - Stover	Bio - Ethanol - Dedicated Crops
Capital cost ($/gal.)		$1.14	$0.51	$0.57
Operating cost ($/gal.)		$0.49	$1.34	$1.52
Feedstock cost:				
Stover ($/gal)	$89.47	$1.49	$1.19	
Switchgrass ($/gal)	$121.37	$2.02		$1.62
Miscanthus ($/gal)	$126.03	$2.10		$1.68
Total cost - stover		$3.12	$3.05	
Total cost - switchgrass		$3.65		$3.71
Total cost - miscanthus		$3.73		$3.77

Source: Authors' estimates in consultation with Argonne and National Renewable Energy Laboratory.

Table A9. Cost Structures of Advanced Biofuel Producers (percentage of total costs)

Cost items	Bio-gasoline			Ethanol		
	Miscanthus	Switchgrass	Corn stover	Miscanthus	Switchgrass	Corn stover
Feedstock	54.6	51.9	47.7	42.9	40.2	39.2
Chemicals	0.0	0.0	0.0	15.6	16.3	18.8
Energy	1.0	1.0	1.1	4.1	4.2	4.9
Other costs	10.5	11.1	12.1	17.5	18.3	15.0
Labor	2.2	2.4	2.6	4.4	4.6	5.3
Capital	31.8	33.7	36.6	15.6	16.3	16.9
Total	100.0	100.0	100.0	100.0	100.0	100.0

Source: [24, 25]

7. Other Modifications and Components

To support and facilitate research on the economic and environmental consequences of international biofuel programs we added several headers to the GTAP_BIOB_ADF_V7 database. These headers include land use and land cover by country and AEZ in 2004, land rents by country and AEZ in 2004, global liquid biofuel consumption in 2004, emissions data due to production and consumption of all types of energy commodities, and crop production and harvested areas in 2004 by country and AEZ.

8. Aggregation Scheme Used in This Paper

Table A10. Regions and Their Members

Region	Description	Corresponding Countries in GTAP
USA	United States	Usa
EU27	European Union 27	aut, bel, bgr, cyp, cze, deu, dnk, esp, est, fin, fra, gbr, grc, hun, irl, ita, ltu, lux, lva, mlt, nld, pol, prt, rom, svk, svn, swe
BRAZIL	Brazil	Bra
CAN	Canada	Can
JAPAN	Japan	Jpn
CHIHKG	China and Hong Kong	chn, hkg
INDIA	India	Ind
C_C_Amer	Central and Caribbean Americas	mex, xna, xca, xfa, xcb
S_o_Amer	South and Other Americas	col, per, ven, xap, arg, chl, ury, xsm
E_Asia	East Asia	kor, twn, xea
Mala_Indo	Malaysia and Indonesia	ind, mys
R_SE_Asia	Rest of South East Asia	phl, sgp, tha, vnm, xse
R_S_Asia	Rest of South Asia	bgd, lka, xsa
Russia	Russia	Rus
Oth_CEE_CIS	Other East Europe and Rest of Former Soviet Union	xer, alb, hrv, xsu, tur
R_Europe	Rest of European Countries	che, xef
MEAS_NAfr	Middle Eastern and North Africa	xme,mar, tun, xnf
S_S_AFR	Sub Saharan Africa	Bwa, zaf, xsc, mwi, moz, tza, zmb, zwe, xsd, mdg, uga, xss
Oceania	Oceania countries	aus, nzl, xoc

Table A11. List of Industries and Commodities in the New Model

Industry	Commodity	Description	Name in the GTAP_BIOB
Paddy_Rice	Paddy_Rice	Paddy rice	Pdr
Wheat	Wheat	Wheat	Wht
CrGrains	CrGrains	Cereal grains	Gro
Oilseeds	Oilseeds	Oil seeds	Osd
OthAgri	OthAgri	Other agriculture goods	ocr, pfb, v_f
Sugarcane	Sugarcane	Sugar cane and sugar beet	c-b
Miscanthus	Miscanthus	A dedicated crop to be used in biofuel	New
Switchgrass	Switchgrass	A dedicated crop to be used in biofuel	New
Stover	Stover	Collected corn stover to be used in biofuel	New
DairyFarms	DairyFarms	Dairy Products	Rmk
Ruminant	Ruminant	Cattle & ruminant meat production and	Ctl, wol
NonRum	Non-Rum	Non-ruminant meat production	oapl
ProcDairy	ProcDairy	Processed dairy products	Mil
ProcRum	ProcRum	Processed ruminant meat production	Cmt
ProcNonRum	ProcNonRum	Processed non-ruminant meat production	Omt
Forestry	Forestry	Forestry	Frs
Cveg_Oil	Cveg_Oil	Crude vegetable oil	A portion of vol
	VOBP	Oil meals	A portion of vol
Rveg_Oil	Rveg_Oil	Refined vegetable oil	A portion of vol
Proc_Rice	Proc_Rice	Processed rice	Pcr
Bev_Sug	Bev_Sug	Beverages, tobacco, and sugar	b_t, sgr
Proc_Food	Proc_Food	Processed food products	A portion of ofd
Proc_Feed	Proc_Feed	Processed animal feed products	A portion of ofd
OthPrimSect	OthPrimSect	Other Primary products	fsh, omn
Coal	Coal	Coal	Coa
Oil	Oil	Crude Oil	Oil
Gas	Gas	Natural gas	gas, gdt
Oil_Pcts	Oil_Pcts	Petroleum and coal products	p-c
Electricity	Electricity	Electricity	Ely
En_Int_Ind	En_Int_Ind	Energy intensive Industries	crpn, i_s, nfm, fmp
Oth_Ind_Se	Oth_Ind_Se	Other industry and services	atp, cmn, cns, ele, isr, lea, lum, mvh, nmm, obs, ofi, ome, omf, otn, otp, ppp, ros, tex, trd, wap, wtp
NTrdServices	BTrdServices	Services generating Non-C02 Emissions	wtr, osg, dwe
AdvfB-Misc	AdvfB-Misc	Bio-Gasoline produced from miscanthus	New
AdvfB-Swit	AdvfB-Swit	Bio-Gasoline produced from switchgrass	New
AdvfB-Stover	AdvfB-Stover	Bio-Gasoline produced from corn stover	New
AdvfE-Misc	AdvfE-Misc	Ethanol produced from miscanthus	New
AdvfE-Swit	AdvfE-Swit	Ethanol produced from switchgrass	New
AdvfE-Stover	AdvfE-Stover	Ethanol produced from corn stover	New
EthanolC	Ethanol1	Ethanol produced from grains	New
	DDGS	Dried Distillers Grains with Solubles	New
Ethanol2	Ethanol2	Ethanol produced from sugarcane	New
Biodiesel	Biodiesel	Biodiesel produced from vegetable oil	New

Appendix B
Introducing Advanced Biofuels into the GTAP Modeling Framework

1. Modifications in GTAP Modeling Structure

1.1. Demand Side Modifications

On the demand side, we introduced bio-gasoline and ethanol from miscanthus, switchgrass, and corn stover in the demand structure of households and firms as a substitute for fossil fuels and biofuels. Figures B-1 and B-2 represent these demands.

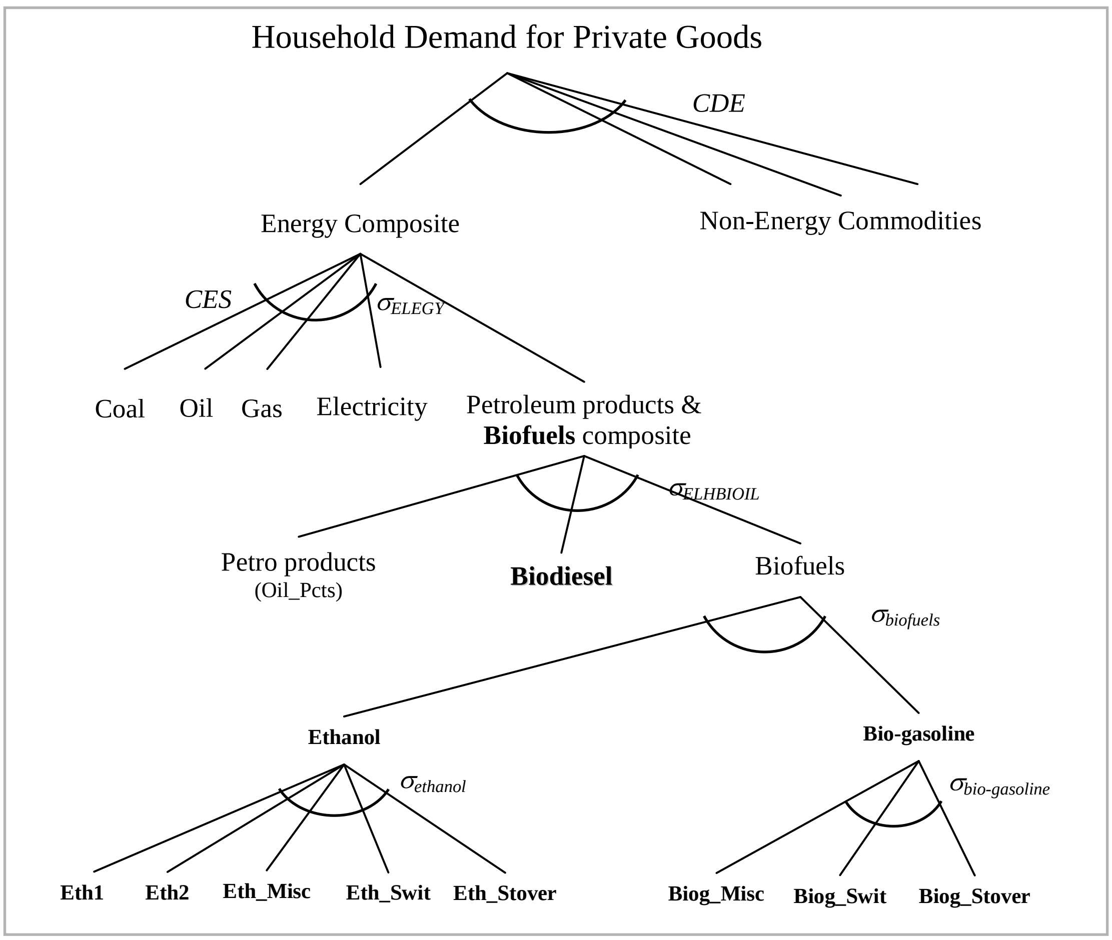

Figure B-1. Household Demand Structure in the GTAP-BIO-ADVFUEL Model

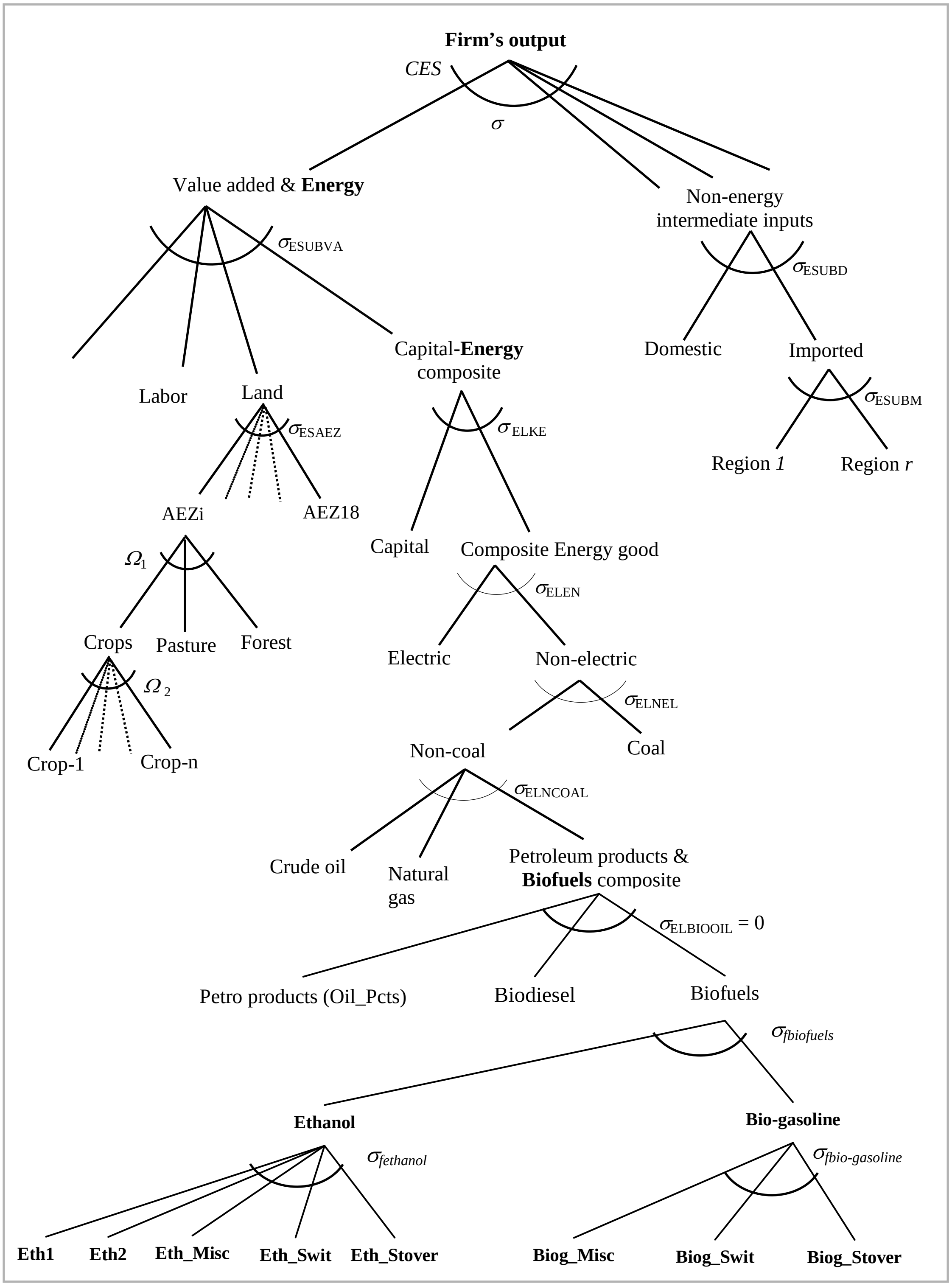

Figure B-2. Demand Structure of Firms for Intermediate and Primary Inputs in the GTAP-BIO-ADVFUEL Model

1.2. Modifications in the Land Market

In our earlier work the land supply module consisted of a two-level nesting structure. In this nesting format the lowest level allocates land supply among three land cover categories of forest, pasture, and cropland, and the upper level allocates croplands among crop activities including CRP and cropland-pastures. In the two-level nesting structure only one parameter (ETL2) governs allocation of cropland supply among all types of crops. In this work we extended the land supply structure to three levels. The lowest level of the new land supply model is the same as what we had before. The second level divides cropland supply into two main crop categories. The first group covers all traditional crops including rice, wheat, coarse grains, oilseeds, vegetable and fruits, sugar crops, other crops, and CRP land. The second group covers dedicated energy crops and cropland-pasture. The top level of this three-level nesting structure determines supply of cropland to each crop industry. This nesting structure allows us to assign different land transformation elasticities among the first and second groups of crops.

Figure B-3 of this appendix represents the new and old land supply structure. We made this change because it more closely represents the agronomic and economic reality. Dedicated energy crops such as miscanthus and switchgrass are much more likely to compete with cropland pasture than they are to compete with much more productive cropland used for corn, soybeans, etc. Thus, the new structure better reflects what would likely emerge in this new production activity. As shown in Figure B-3 in the new model, miscanthus competes with cropland pasture which is an input for the livestock industry. Figure B-3 represents competition in the land market between different agricultural activities in the model. Compared to the earlier model the new land supply structure provides more flexibility in the land market to satisfy the higher demand for miscanthus and switchgrass to meet the production targets for cellulosic biofuels. In addition, for the new model we assigned a larger elasticity of transformation to the crop nests to facilitate conversion of one type of cropland to other types as discussed in the text. In the new land supply structure we applied the following land transformation elasticities:

- Transformation elasticity among forest, pastureland, and cropland = - 0.2 (no change)
- Transformation elasticity among the first and second groups of crops = - 0.75,

- Transformation elasticity among traditional crops = - 0.75
- Transformation elasticity among cropland pasture, miscanthus, and switchgrass = - 10

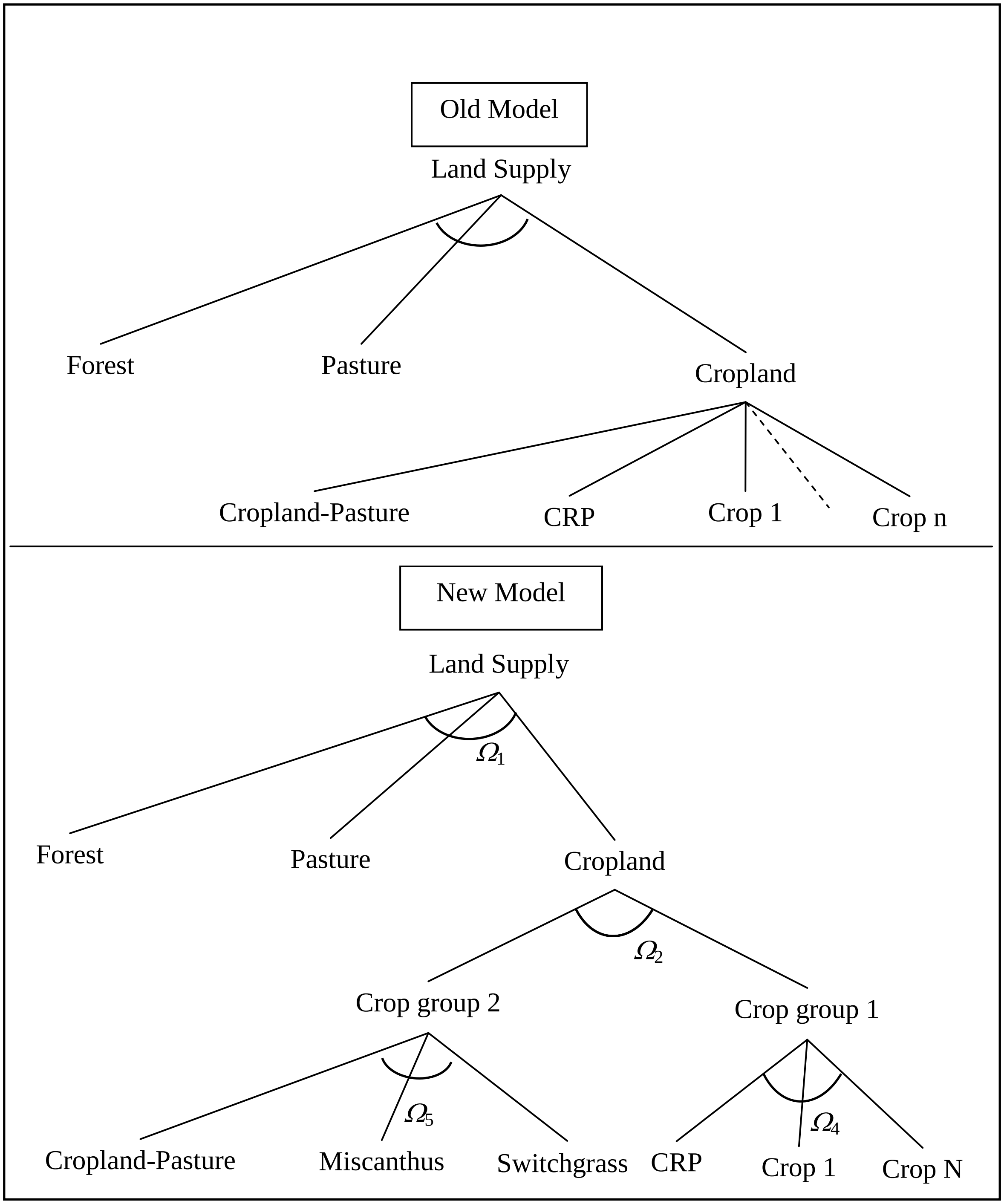

Figure B-3. Land Cover and Land Use Activities in the Old and New GTAP-BIO-ADV

1.3. Other Modifications

We revised all necessary GTAP codes and files to support the new model. That includes revising the main GTAP Table file, GTAP parameter file, and the GTAP set files.

Appendix C
Experiments Used in This Study

Experiment a

The experiment uses the following shocks and swaps to boost U.S. corn ethanol production from its 2004 level (3.41 BGs) to 15 BGs:

To fix the CRP land of the U.S.

Swap *tf(AEZ_COMM,"Oth_Ind_Se","USA") = p_HARVSTAREA_L(AEZ_COMM,"Oth_Ind_Se","USA");*

This swap keeps the area of CRP land unchanged. It swaps changes in CRP land with changes in tax rate on land endowment.

To boost ethanol production

Swap *qo("Ethanol1","USA") = tpd("Ethanol1","USA");*

Shock *qo("Ethanol1","USA") = 339.8826979;*

Here the swap endogenizes subsidy on ethanol consumption and exogenizes ethanol production and then the shock boosts ethanol production according to its expansion from the year of 2004 to 15 BGs ethanol (i.e. *339.8826979*%).

This swap and shock jointly subsidize ethanol production. However, they cause an increase in government subsidies. To offset the impacts of this subsidy we use the following swap to finance the policy through an increase in taxes on biofuel consumption.

To Make the RFS revenue neutral

Swap *del_taxrpcbio("USA") = tpbio("USA");*

Experiment b

In this experiment we shock production of bio-gasoline from corn stover by about 6 BGs. This is identical to 9 BGs of ethanol. The major shocks and swaps used in this experiment are:

To fix the CRP land of the U.S.

Swap *tf(AEZ_COMM,"Oth_Ind_Se","USA") = p_HARVSTAREA_L(AEZ_COMM,"Oth_Ind_Se","USA");*

To boost bio-gasoline production from corn stover

Swap *qo("adv_Stover","USA") = tpd("advf_Stover","USA");*
Shock *qo("advf_Stover","USA") = 777484.822;*

To Make the RFS revenue neutral

Swap *del_taxrpcbio("USA") = tpbio("USA");*

Experiment c

In this experiment we shock production of bio-gasoline from miscanthus by about 4.7 BGs. This is identical to 7.0 BGs of ethanol. The major shocks and swaps used in this experiment are:

To fix the CRP land of the U.S.

Swap *tf(AEZ_COMM,"Oth_Ind_Se","USA") = p_HARVSTAREA_L(AEZ_COMM,"Oth_Ind_Se","USA");*

To boost bio-gasoline production from corn stover

Swap *qo("adv_Misc","USA") = tpd("advf_Misc","USA");*
Shock *qo("advf_Misc","USA") = 609008.110;*

To Make the RFS revenue neutral

Swap *del_taxrpcbio("USA") = tpbio("USA"*

Experiment d

In this experiment we shock production of bio-gasoline from switchgrass by about 4.7 BGs. This is identical to 7.0 BGs of ethanol. The major shocks and swaps used in this experiment are:

To fix the CRP land of the U.S.

Swap *tf(AEZ_COMM,"Oth_Ind_Se","USA") = p_HARVSTAREA_L(AEZ_COMM,"Oth_Ind_Se","USA");*

To boost bio-gasoline production from switchgrass

Swap *qo("advfB_Swit","USA") = tpd("advBf_Swit","USA");*

Shock *qo("advfB_Swit","USA") = 710513.849;*

To Make the RFS revenue neutral

Swap *del_taxrpcbio("USA") = tpbio("USA");*

Experiment e

In this experiment we shock production of ethanol from corn stover by about 9 BGs. The major shocks and swaps used in this experiment are:

To fix the CRP land of the U.S.

Swap *tf(AEZ_COMM,"Oth_Ind_Se","USA") = p_HARVSTAREA_L(AEZ_COMM,"Oth_Ind_Se","USA");*

To boost bio-gasoline production from corn stover

Swap *qo("advfB_Stover","USA") = tpd("advfB_Stover","USA");*

Shock *qo("advfB_Stover","USA") = 1088565.780;*

To Make the RFS revenue neutral

Swap *del_taxrpcbio("USA") = tpbio("USA");*

To adjust the energy content of ethanol to gasoline

shock *afenergy("AdvfE_Stover", "USA")=-33;*

shock *ahenergy("AdvfE_Stover", "USA")=-33;*

Experiment f

In this experiment we shock production of ethanol from miscanthus by about 7 BGs. The major shocks and swaps used in this experiment are:

To fix the CRP land of the U.S.

Swap *tf(AEZ_COMM,"Oth_Ind_Se","USA") = p_HARVSTAREA_L(AEZ_COMM,"Oth_Ind_Se","USA");*

To boost bio-gasoline production from miscanthus

Swap *qo("advfE_Misc","USA") = tpd("advfE_Misc","USA");*

Shock *qo("advfE_Misc","USA") = 846640.051;*

To adjust the energy content of ethanol to gasoline

shock *afenergy("AdvfE_Misc", "USA")=-33;*

shock *ahenergy("AdvfE_Misc", "USA")=-33;*

To Make the RFS revenue neutral

Swap *del_taxrpcbio("USA") = tpbio("USA");*

Experiment g

In this experiment we shock production of ethanol from switchgrass by about 7 BGs. The major shocks and swaps used in this experiment are:

To fix the CRP land of the U.S.

Swap *tf(AEZ_COMM,"Oth_Ind_Se","USA") = p_HARVSTAREA_L(AEZ_COMM,"Oth_Ind_Se","USA");*

To boost ethanol production from switchgrass

Swap *qo("advfE_Swit","USA") = tpd("advfE_Swit","USA");*

Shock *qo("advfE_Swit","USA") = 846640.051;*

To adjust the energy content of ethanol to gasoline

shock *afenergy("AdvfE_Swit", "USA")=-33;*

shock *ahenergy("AdvfE_Swit", "USA")=-33;*

To Make the RFS revenue neutral

Swap *del_taxrpcbio("USA") = tpbio("USA");*