Land Use Changes and Consequent CO_2 Emissions due to US Corn Ethanol Production: A Comprehensive Analysis*

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July 2010

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FINAL REPORT

(revised)**

* The research underlying this report was partially funded by Argonne National Laboratory. We are deeply indebted to Dr. Michael Wang for his many contributions to this research. Throughout the process, he has consistently posed excellent questions that have stimulated more thinking and modifications on our part. Also, for this final paper, he provided an excellent set of insightful suggestions and comments that have improved the paper significantly. Of course, the authors are solely responsible for the content of and any errors in the report.

**The original April report was revised because in the review process errors were found in the magnitudes of the EU and Brazil ethanol shocks in moving from the 2001 data base to the updated 2006 data base. The impacts of the errors were small. However, we revised the report to reflect the corrected shocks. The model versions posted on the web include the corrected values and are consistent with this report.

Executive Summary

The basic objective of this research was to estimate land use changes associated with US corn ethanol production up to the 15 billion gallon Renewable Fuel Standard level implied by the Energy Independence and Security Act of 2007. We also used the estimated land use changes to calculate Greenhouse Gas Emissions associated with the corn ethanol production.

The main model that was used for the analysis is a special version of the Global Trade Analysis Project (GTAP) model. It is a computable general equilibrium model that is global in scope. The version used for this analysis has up to 87 world regions and 57 economic sectors plus the biofuel sectors that were added for this analysis. There are many different versions of the GTAP model. It is used by thousands of economists around the world for analysis of trade, energy, climate change, and environmental policy issues. The model is publically available with documentation of the model and data base at www.gtap.org. The version used in this analysis contains energy and GHG emissions (GTAP-E) and also has land use (GTAP-AEZ). The name for the special version created for this work is GTAP-BIO-ADV and encompasses many changes to improve the analysis of corn ethanol:

- The three major biofuels have been incorporated into the model: corn ethanol, sugarcane ethanol, and biodiesel.
- Cropland pasture in the US and Brazil and Conservation Reserve Program lands have been added to the model.
- The energy sector demand and supply elasticities have been re-estimated and calibrated to the 2006 reality. Current demand responses are more inelastic than previously.
- Corn ethanol co-product (DDGS) has been added to the model. The treatment of production, consumption, and trade of DDGS is significantly improved.
- The structure of the livestock sector has been modified to better reflect the functioning of this important sector.
- Corn yield response to higher corn prices has been estimated econometrically and included in the model.
- The method of treating the productivity of marginal cropland has been changed so that it is now based on the ratio of net primary productivity of new cropland to existing cropland in each country and AEZ.

There are many other changes both in data and model structure, which are detailed in the report, but these are the major model and data modifications.

To evaluate the land use implications of US ethanol production we develop three groups of simulations. In the first group we calculate the land use implications of US ethanol production off of the 2001 database. This approach isolates impacts of US ethanol production from other changes which shape the world economy. In the second group of simulations, we first construct a baseline which represents changes in the world economy during the time period of 2001-2006. Then we calculate the land use impact of the US ethanol production off of the updated 2006 database, while we follow the principles of the first group of simulations for the time period of 2006-20015. Finally, in the third group of simulations we use the updated 2006 database obtained from the second group of simulations but we assume that during the time period of 2006-2015 population and crop yields will continue to grow.

In this summary, we will first report the land use changes for the third group of simulations. Then we present emissions obtained for the three groups of simulations. Tables 1 and 2 provide the estimated land use changes broken down by US and rest of world (Table 1) and the forest pasture split (Table 2). On average 24.4% of the land use change occurs in the US, and 75.6% in the rest of the world. Forest reduction accounts for 32.5% of the change and pasture 67.5%. On average 0.13 hectares of land are needed to produce 1000 gallons of ethanol.

Table1. Simulated global land use changes due to the US ethanol production: with yield and population growth after 2006

Changes in US corn ethanol production	Land use changes (hectares)			Distribution of Land Use changes (%)			Hectares per 1000 Gallons
	Within US	Other Regions	World	Within US	Other Regions	World	
3.085 BG (2001 to 2006)	106870	360397	467268	22.9	77.1	100.0	0.15
2.145 BG (2006 to 7 BG)	58373	175123	233496	25.0	75.0	100.0	0.11
2.000 BG (7 to 9 BG)	57966	177186	235151	24.7	75.3	100.0	0.12
2.000 BG (9 to 11 BG)	60830	184916	245746	24.8	75.2	100.0	0.12
2.000 BG (11 to 13 BG)	65116	199837	264953	24.6	75.4	100.0	0.13
2.000 BG (13 to 15 BG)	70656	206057	276713	25.5	74.5	100.0	0.14
13.23 BG (2001 to 15 BG)	419811	1303516	1723327	24.4	75.6	100.0	0.13

Table 2. Simulated global land use changes due to the US ethanol production: With yield and population growth after 2006

Changes in US corn ethanol output	Land use changes (hectares)			Distribution of land use changes (%)		
	Forest	Grassland	Crop*	Forest	Grassland	Total*
3.085 BG (2001 to 2006)	-151706	-315487	467268	32.5	67.5	100.0
2.145 BG (2006 to 7 BG)	-75942	-157560	233496	32.5	67.5	100.0
2.000 BG (7 BG to 9 BG)	-76424	-158735	235151	32.5	67.5	100.0
2.000 BG (9 BG to 11 BG)	-79870	-165871	245746	32.5	67.5	100.0
2.000 BG (11 BG to 13 BG)	-86227	-178732	264953	32.5	67.5	100.0
2.000 BG (13 BG to 15 BG)	-89932	-186782	276713	32.5	67.5	100.0
13.23 BG (2001 to 15 BG)	-560101	-1163167	1723327	32.5	67.5	100.0

*The difference between the changes in cropland and the sum of forest and grassland is due to rounding

We now consider estimated emissions induced by US ethanol production. Table 3 summarizes the emissions results from the three sets of simulations, and Table 4 provides the estimated ethanol and gasoline emissions in grams per gallon of gasoline equivalent.

Table 3. Estimated land use change emissions due to U.S. ethanol production (Figures are annual CO_2 emissions in grams per gallon of ethanol)

GTAP results off of 2001 database	Average emissions	1676
	Marginal emissions	1846
GTAP results off of 2006 database	Average emissions	1426
	Marginal emissions	1467
GTAP results off of 2006 plus population & yield growth	Average emissions	1167
	Marginal emissions	1159

Table 4. Estimated well-to-wheel ethanol and gasoline emissions for average land use changes (emissions are in grams per gallon of gasoline equivalent)

Description	Ethanol Emissions	Gasoline Emissions	Ethanol GHGs vs Gasoline (percent)
Simulations Off of 2001	10342	11428	90.5
Simulations Off of 2006	9961	11428	87.2
Simulations Off of 2006 Plus population & yield growth	9568	11428	83.7

Land use change and the associated GHG emissions is a very controversial topic. Some argue it is impossible to measure such changes. Others argue that failure to measure the land use changes and the consequent GHG emissions would lead us to incorrect policy conclusions. After working on this topic for over two years, we come out between these extremes. First, with almost a third of the US corn crop today going to ethanol, it is simply not credible to argue that there are no land use change implications of corn ethanol. The valid question to ask is to what extent land use changes would occur. Second, our experience with modeling, data, and parameter estimation and assumptions leads us to conclude that one cannot escape the conclusion that modeling land use change is quite uncertain. Of course, all economic modeling is uncertain, but it is important to point out that we are dealing with a relatively wide range of estimation differences.

In some cases, the results are fairly stable regardless of the simulation. For example, the percentage of land that comes from forest ranges between 25 and 32.5 percent depending on the model and assumptions being used. Similarly, the fraction of land use change that occurs in the U.S. ranges between 24 and 34 percent. However, the land needed to meet the ethanol mandate ranges between 0.13 and 0.22 hectares/1000 gallons, which is a fairly wide range. The land use ethanol CO_2 emissions per gallon range between 1167 and 1676, also a fairly large range. Total ethanol CO_2 emissions due to production and consumption of gasoline (including land use) range between 78.1 g/MJ and 84.4 g/MJ. Ethanol emissions as a fraction of gasoline emissions range between 83.7 and 90.5 percent. We cannot say whether or not corn ethanol would meet a 20 percent standard given the inherent uncertainty in the analysis, and potential improvement in direct emissions associated with corn farming and ethanol production.

Analysis such as that undertaken here is very complex and is limited by data availability, validity of parameters, and other modeling constraints. Economic models, like other models, are abstractions from reality. They can never perfectly depict all the forces and drivers of changes in an economy. However, the basic model used for this analysis, GTAP, has withstood the test of time and peer review. Hundreds of peer reviewed articles have been published using the GTAP data base and analytical framework. In this project, we have made many changes in the model and data base to improve its usefulness for evaluating the land use change impacts of large scale biofuels programs. Yet, uncertainties remain. In this paper, we have described the evolution of the modeling and analysis and present openly the evolution of the results. We believe quite strongly that analysis of this type must be done with models and data bases that are available to others. Replicability and innovation are critical factors for progress in science. They also are important for credibility in policy analysis.

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1. Introduction

US ethanol production has increased sharply from 1.7 billion gallons (BGs) in 2001 to about 10 BGs in 2009. According to the Renewable Fuel Standard (RFS) in the US Energy Independence and Security Act of 2007 (CRS RL34294), 2007, US corn ethanol production will reach 15 BGs in 2015. This level of ethanol production will affect agricultural activities within the US and around the world. In particular, it can cause land use changes anywhere in the world, and the implications of land use changes are complex and controversial. A sizeable ethanol production program has the potential to increase corn price, corn yield per unit of land, affect corn consumption, change corn trade, and encourage livestock producers to use byproducts of ethanol production in their animal feed rations. Land use changes associated with increased corn ethanol production are important because the land use changes can affect the CO_2 emissions associated with ethanol production and consumption.

Argonne National Laboratory (ANL) (Wang 1999, Wang et al. 1999, and 2005) has developed a life cycle model (GREET) which estimates the emissions of greenhouse gases (GHGs, including CO2, CH4, and N2O) of corn ethanol production. The GREET model classifies GHG emissions into three categories: 1) feedstock production; 2) fuel production - corn to ethanol in this case; and 3) vehicle operation. The total emissions associated with the ethanol supply chain are then compared with the analogous calculations for gasoline. At present, there is limited data on GHG emissions from direct land use changes due to biofuel production included in the GREET model. The land use consequences of biofuel production and their corresponding emissions were highlighted in the literature. The early papers published in this area show that biofuel production could have extraordinary land use implications (Searchinger et al. 2008[1], Fargione et al. 2008). Because the land use emissions were claimed to be so large, it was deemed important to get different assessments of the possible land use changes and associated emissions. Argonne and Purdue agreed that Purdue would conduct such an analysis using the Global Trade Analysis Project (GTAP) modeling framework and data base. In order to do this analysis with GTAP, several model and data base modifications were required, and these are described in this report.

This report aims to evaluate land use changes and CO_2 emissions induced by US corn ethanol production for several alternative configurations and assumptions. The results of this paper provide information on land use related emissions due to ethanol production that can be combined with the emissions calculated in GREET to produce total green house gas (GHG) emissions associated with corn ethanol production and use. This total can then be compared with gasoline to determine the net gain/loss for corn ethanol production and use compared with gasoline.

To achieve this goal we use three major components. First, we use a computational general equilibrium (CGE) model to assess the economic impacts of ethanol production and its land use implications for the world under alternative sets of assumptions. The CGE model is a special version of the Global Trade Analysis Project (GTAP) model (Hertel, 1997) of the global economy which was recently developed by Taheripour, Hertel, and Tyner (2009) to evaluate impacts of biofuel production for the global livestock industry.

The second component consists of a module which converts land use changes estimated in GTAP to the associated CO_2 emissions. This module generates CO_2 emissions factors which we use to convert land use changes into CO_2 emissions based on the Woods Hole Research Center data set on the soil and land cover carbon profiles. The Woods Hole data set divides the

[1] We will henceforth refer to this paper as SEA

whole world into 10 regions and provides data on the soil and land cover carbon profiles for each region[2].

Finally, we convert the land use related emissions calculated in module two to emissions per gallon of 100% ethanol and add those emissions to those calculated in GREET to get total emissions. This can be done either within the GREET model or by direct calculations. For this paper we have done the calculations directly.

In this report rather than using the terms direct and indirect emissions, as is commonly reported in the literature, we categorize the emissions as those calculated in GREET and associated with use of corn for producing and consuming ethanol and emissions associated with land use changes. By some definitions of the term indirect, these would be labeled indirect emissions, but to avoid confusion we label them emissions associated with induced land use changes.

We should from the outset acknowledge that land use change is a complicated process. It is driven by many factors and varies through time. There are social as well as economic factors involved in the complicated process of evolving land use. The factors vary by culture, region, and economy.[3] Obviously neither this analysis nor any analysis can capture all the factors involved in land use change. What we have attempted to do is to isolate the impacts of a substantial increase in US corn based biofuels production. Since corn is a globally produced and consumed commodity, these impacts will be of necessity global. The impacts will be driven to a

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[2] In our earlier report (Tyner, Taheripour, and Baldos, 2009) we applied the IPCC data set as well. The IPCC data set provides data on the soil and land cover carbon profiles at a global scale with no specification of geographical distribution. The IPCC land use emissions factors are much larger than the regional emissions factors derived from the Woods Hole data set. In this report we only apply the land use emissions factors obtained from the Woods Hole data set. The IPCC data set is too aggregate to be useful in this analysis. Since our results are down to the AEZ and country level, we took advantage of the greater disaggregation in the Woods Hole data.

[3] We are indebted to Gbadebo Oladosu and Keith Kline of Oak Ridge National Laboratory for providing data and useful perspectives on the land use change process.

significant degree by changes in global supply and demand of feed grains. Thus, we have used a global general equilibrium model which can capture many of these market mediated effects.

The rest of this paper is organized as follows. We first introduce the GTAP model and modifications which are made in this model to make it suitable for analyzing economic and environmental consequences of biofuels. Then we explain our simulations and assumptions behind them along with the land use results from these simulations. After that we introduce the land use CO_2 emission factors which we use to convert land use changes into CO_2 emissions. Finally, we present CO_2 emissions induced by US ethanol production due to land use changes and compare these results with results from other studies.

2. Land use changes due to US ethanol production: GTAP model

To evaluate the impacts of the US corn ethanol production on global land use we need a model which is global in scope, and which links global production, consumption and trade. In addition, the model should properly link energy, biofuel, and agricultural markets. Since biofuel, crop, and livestock industries compete through the land market, the model should link these activities through the land market as well. Furthermore, biofuels byproducts, which can be used in animal feedstuffs, bridge these industries through a triangular relationship which alters the nature of competition among these industries. All of this has led us to use a special purpose version of the Global Trade Analysis Project (GTAP) model and its database. GTAP is a computable general equilibrium (CGE) model which considers production, consumption, and trade of goods and services by region and at a global scale. Figure 1 represents an illustrative overview of the GTAP model.

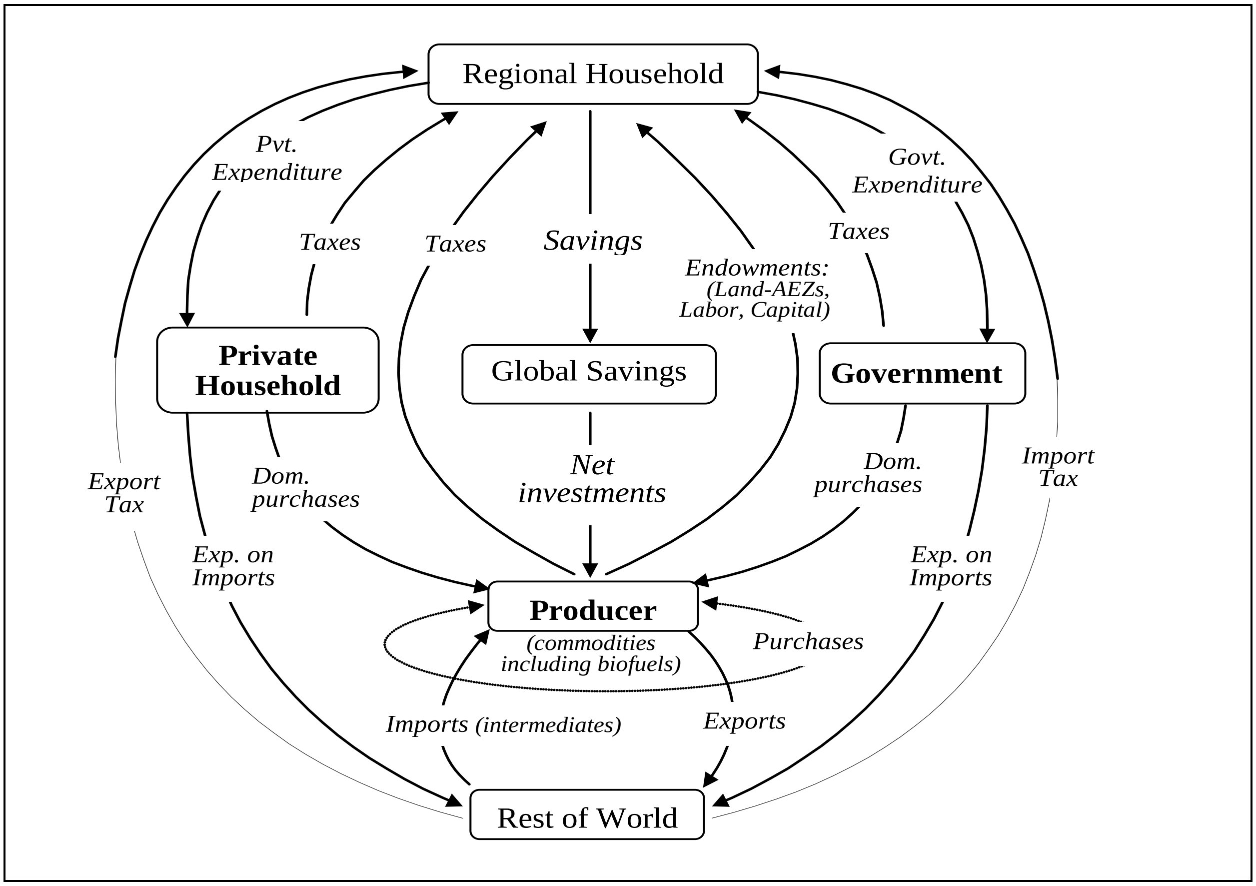
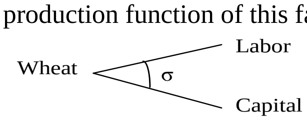


Figure 1. An overview of the GTAP model

In GTAP each country or composite region is represented by a regional household which collects all incomes generated by the economy and allocates them among three components of the final demand: Private Household, Government, and Savings (for details see Brockmeier (1996)). In this model households (consumers) maximize their utilities according to their budget constraints and producers minimize their production costs subject to resource constraints. The model determines demands for and supplies of goods and services according to consumer and producer behaviors. Resources are labor, capital, land, and natural resources, and they owned by consumers. In GTAP, markets are competitive, consumers and producers are price takers, and utility and production functions usually follow the constant elasticity of substitution (CES) functional forms[4]. We will introduce the production and consumption structures of GTAP later in this report.

The GTAP model simulates the world economy using a global database which contains input-output tables for almost all countries. These tables provide detailed information on production and consumption of commodities and services along with investment and bilateral trade among regions. This database also includes payments to labor, capital, and land (for details see Dimaranan (2006)). GTAP data come from a multitude of sources. The country input-output tables are generally provided by contributors in the countries who have access to national statistics data. Trade data come from UN sources and USDA. Protection data come from several sources, but CEPII in France is the major source. Energy data come from the IEA in Paris. There are other sources as well. The GTAP staff at Purdue set the standards for data and assure quality and consistency. The database also includes the most updated global land cover and land uses database by region disaggregated into 18 Agro Ecological Zones (AEZs). These AEZs share common climate, precipitation and moisture conditions. The land cover and land use database is based on the Center for Sustainability and Global Environment (SAGE) database (for more information on the land use database see Lee et al. (2005)). The land use data base provides information on global crop yields as well. Note that the land use database excludes inaccessible forests. The version 6 of the GTAP data base covers 57 groups of commodities and services for

[4] Here, we use a simple graphical example to explain a constant elasticity of substitution functional form. Consider a producer which can use labor (L) and capital (k) to produce wheat (W). The following simple figure depicts the production function of this farmer:



In this graph σ represent the elasticity of substitution between labor and capital. If the farmer can only use labor and capital in a fixed proportion, then σ=0. However, if the farmer can reduce number of work hours and increase the amount of capital (say due to an increase in wage rate) to achieve its production goal, then σ is a number greater than zero. In general, σ can take any number between zero and infinity when we consider substitution among inputs or among consumption of goods and services.

87 countries and regions. Version 6 is based on 2001 data, and was the starting point for the biofuels analysis reported in this paper.

The GTAP model and its data base have been frequently modified and improved in the past three years to develop an improved tool for examining the economic and environmental consequences of the global biofuel production. In this process Taheripour et al. (2007) have explicitly introduced three biofuel commodities (including ethanol from food grains, ethanol from sugarcane, and biodiesel from oilseeds) into the GTAP data base version 6.

Birur, Hertel, and Tyner (2008) have incorporated biofuels into the GTAP-E model[5]. They augment the model by adding the possibility for substitutability between biofuels and petroleum products. We will henceforth refer to this model as GTAP-BIO-ADV (advanced GTAP-BIO model). Figures 2 and 3 represent the structure of consumption and production sides of this model. In these figures CES means constant elasticity of substitution (as explained in footnote 4 above) and CDE stands for constant difference elasticity and is the means of expressing household preferences in GTAP.

[5] GTAP-E was originally developed by Burniaux and Truong (2002) to incorporate energy into the GTAP framework, and recently modified by McDougall and Golub (2007).

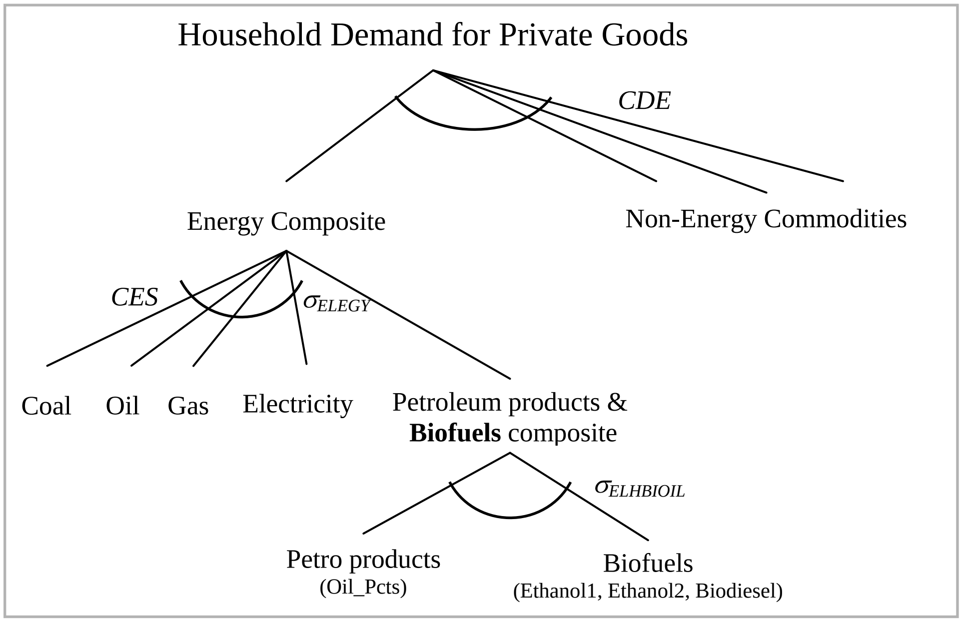


Figure 2. Structure of consumption side of the GTAP-BIO-ADV model

Figure 2 indicates that households could use biofuel as a substitute for petroleum products in GTAP-BIO-ADV. On the other hand, Figure 3 shows that at the bottom-most level of the production side biofuels are a compliment to petroleum products in the production process. It should be noted here that in a general equilibrium model like GTAP, all the equations are solved simultaneously, so it is not a stepwise solution process.

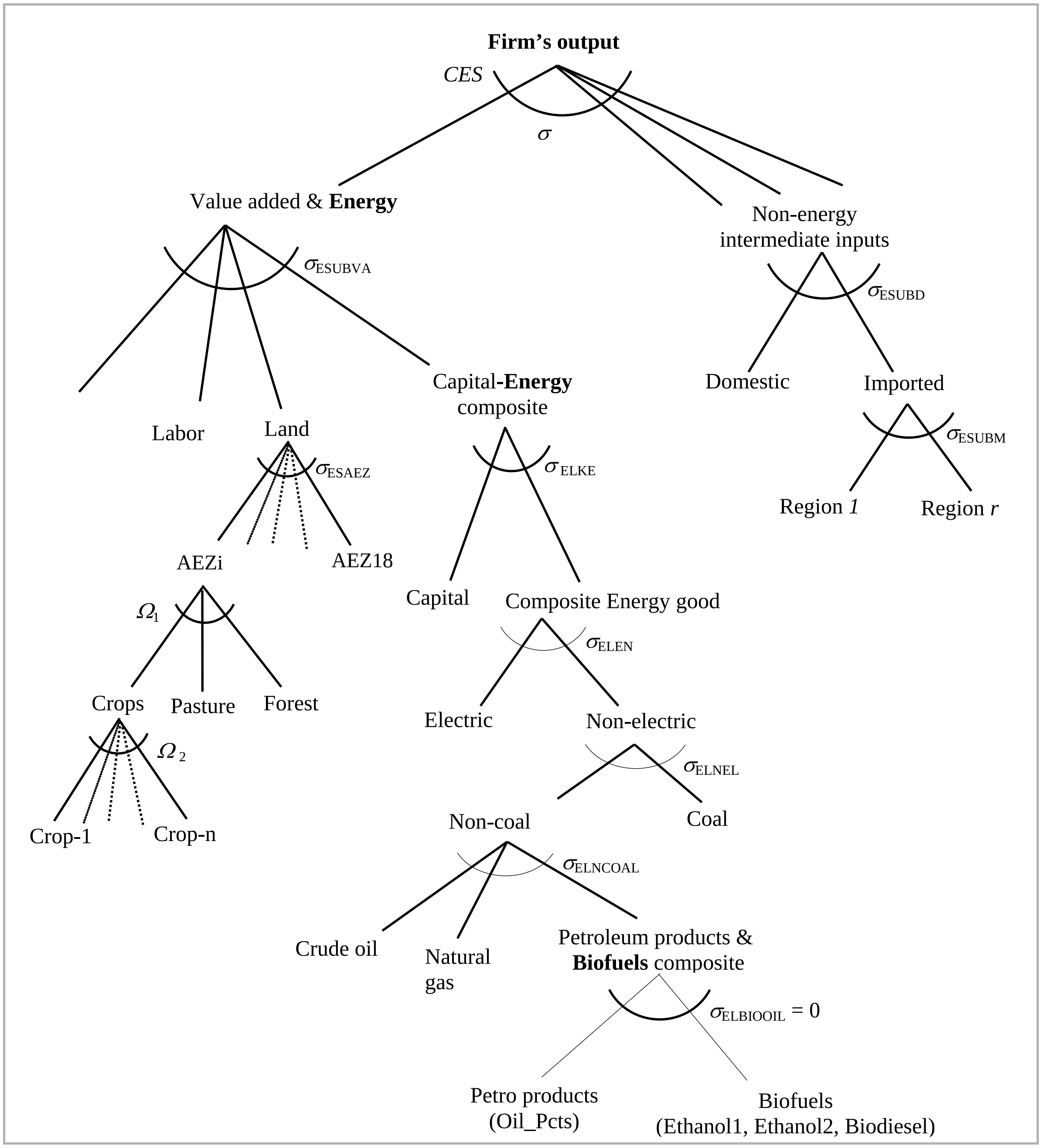
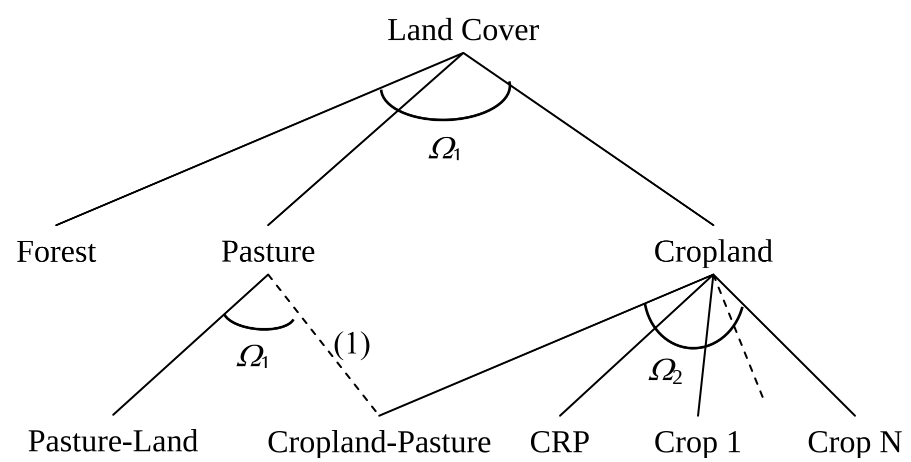


Figure 3. Production structure of GTAP-BIO-ADV

Hertel, Tyner, and Birur (2008) have recently augmented this model with a land use module to better depict the global competition for land among land use sectors. The land use module traces changes in the demand for land across the world at the AEZ level and thereby captures the potential for real competition between alternative land uses. In this module land does not move across AEZs. However, distribution of land across its alternative uses can change within each AEZ. Alternative uses of land are: forest, grassland, and cropland. In this module livestock producers compete to use grassland, and there is competition among agricultural activities to use croplands. Corn is in the coarse grains category along with sorghum, oats, and barley. However, in the US, that grouping is mostly corn. For example, in 2009, corn constituted 95.4% of the coarse grains production (by weight). Most of the rest was sorghum, which also could be used for biofuels. There is no need to separate corn from the other coarse grains.

Recently, Birur (2010) has added two new land categories of cropland-pasture and unused cropland (e.g. retired cropland under the US Conservation Reserve Program (CRP)) into supply of land. Figure 4 represents the new structure of land supply in the modified model.



(1) To create this link we introduced an industry into the GTAP framework which uses only cropland-pasture as an input and sells its output (land) to the livestock industry.

Figure 4. Land cover and land use activities in the GTAP-BIO-ADV

In the new land supply tree cropland pasture and unused cropland (mainly CRP) are explicitly defined as components of cropland. CRP land mainly generates environmental benefits. Hence, this type of land is introduced as an input into the sector which provides these services (i.e. Oth_Ind_Se). Cropland-pasture is an input into livestock industry. To facilitate transition of cropland-pasture from livestock industry to crop production and vice versa, an industry is added to the model which uses cropland-pasture as an input and sells its output (cropland-pasture) to the livestock industry. This industry competes in the land market with crops. Finally, the livestock industry combines cropland-pasture with pasture land in its production function as shown in Figure 5. This figure indicates that the livestock industry combines pasture land with cropland-pasture in the value added nest and uses feed and non-feed inputs in its production function.

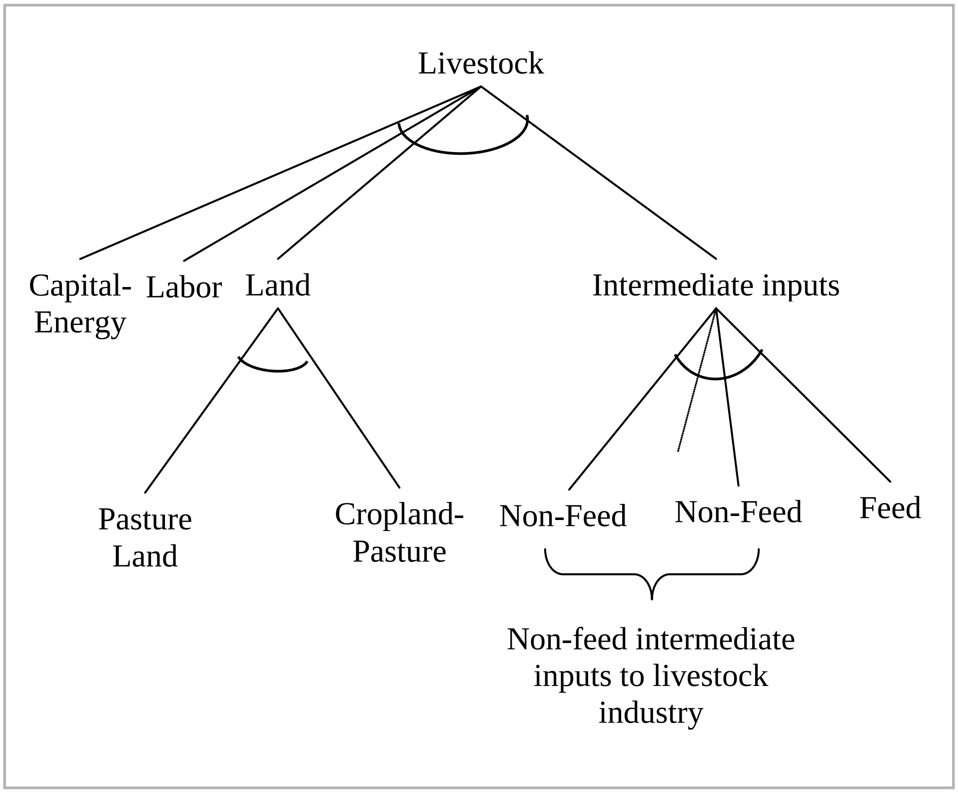


Figure 5. Production structure of the livestock industry

The land use module determines expansion of cropland and its distribution among agricultural activities according to two important parameters: price elasticity of yield and ratio of productivities of marginal and average lands. The price elasticity of yield measures changes in crop yield due to the changes in crop price. In the simulations reported in this report we assumed that the price elasticity of yield is equal to 0.25. Keeney and Hertel (2008) have provided a detailed discussion on this parameter along with econometric evidence behind it.

The ratio of marginal and average productivities measures the productivity of new cropland versus the productivity of existing cropland. We will henceforth refer to this ratio as ETA. In our earlier work we were assumed that ETA=0.66 all across the world. In this report we use a set of regional ETAs at the AEZ level which is obtained from a bio-process-based biogeochemistry model (Terrestrial Ecosystem Model (TEM): Zhuang et al., 2003) along with spatially referenced information on climate, elevation, soils, and vegetation land use data. The new regional ETAs vary across the world and among AEZs. Appendix A represents these ETAs along with more details on their calculation processes. The new estimated ETA values are now included in the model by country and AEZ.

A major attempt has been made to introduce production, consumption, and trade of biofuel byproducts into the GTAP modeling framework. Taheripour et al. (2010) and Taheripour, Hertel, and Tyner (2009) represent the latest modifications in this area. These papers extend the original GTAP-BIO database (Taheripour et al. 2007) in several directions to properly trace the links among biofuel, vegetable oil, food, feed, and livestock industries. Unlike the initial database these papers distinguish between feedstock of the US and EU ethanol industries. In the modified GTAP-BIO database, the US uses corn and EU uses wheat in ethanol production. Following the original work, the ethanol industry also produces distillers dried grains with solubles (DDGS). They also split the “other food products” industry into two distinct industries: processed food and processed feed. In addition, they split the vegetable oil sector into two distinct industries: crude vegetable oil and refined vegetable oil. The crude vegetable oil sector uses oilseeds and produces crude vegetable oil (as the main product) and oilseed meal (as the byproduct). Unlike the original GTAP-BIO database which directly converts oilseeds to biodiesel, they introduce a biodiesel production technology which uses crude vegetable oil and other inputs to produce biodiesel.

In addition, the latter paper uses a three level nesting structure for the demand for animal feedstuffs in the livestock industry which brings more flexibility into this part of the model. Figure 6 depicts this nesting structure. At the lower level of this nesting structure DDGS and coarse grains are combined to create an energy feed. At this level oilseeds and oilseed meals are combined to create a protein feed as well for countries that use oilseeds directly as feed. At a higher level the protein and energy feed ingredients are combined. At this level other crops also are bundled together. The livestock industry receives some inputs from processed livestock industry as well, and these materials are bundled together at the second level too. Finally, all feed ingredients are combined to create the feed composite.

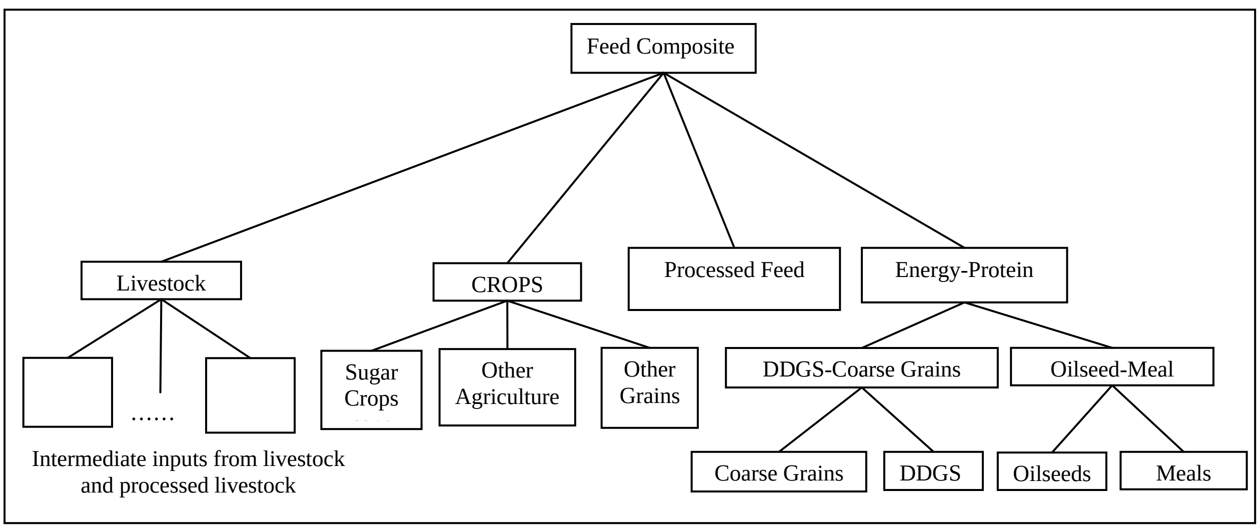


Figure 6. Structure of nested demand for feed in livestock industry

They assigned elasticities of substitution to the different components of the demand for feed to replicate changes in the prices of DDGS and meals in the US and EU during the time period of 2001-2006. In addition, they did several experimental simulations and sensitivity tests to reach displacement ratios between DDGS, grains, oilseeds, and oilseed meals according to the literature in this area. Since oilseeds and oilseed meals are good substitutes in some regions, they applied a relatively high elasticity of substitution, 20, between these two feed materials for all types of animal species. Following the literature, they used values of 25, 30, and 20 for the elasticities of substitution between coarse grains and DDGS in the dairy farms, other ruminant, and non-ruminant feed structure, respectively. They also applied a non zero and small value, 0.3, for the elasticity of substitution between the energy and protein feedstuffs because DDGS could displace a portion of meals in some feed rations, as shown in Arora, Wu, and Wang (2008) and Fabiosa (2009). In the composite of other crops and composite of processed livestock inputs they applied elasticities of substitution of 1.5 for all types of livestock industry. Finally, following Keeney and Hertel (2005) they used 0.9 for the elasticity of substitution at the higher level of the feed demand nest.

Here we use some GTAP simulation results to show how these elasticities shape the cost structure of the livestock industry. To accomplish this task we use the results obtained from the simulations introduced in the next section of this report. In particular, we use the results of the first simulation of the second group of experiments. This particular simulation replicates transition of the global economy from 2001 to 2006. The results of this simulation predict that the cost shares of coarse grain, other crops, and meals in the US livestock industries declined during the time period of 2001-2006, while the cost share of DDGS increased. The largest substitution is DDGS for coarse grains, but there is also substitution for other crops and oilseed meals, depending on the livestock species. Note that we dropped processed feed from the list of animal feeds to highlight the changes in the shares of crops, DDGS, and meals in this time period (Table 1).

Table 1. Cost shares of major feed items in the US livestock industries in 2001 and 2006*

Feed Items	2001			2006		
	Dairy	Meat Ruminant	Non-Ruminant	Dairy	Meat Ruminant	Non-Ruminant
Coarse Grains	67.6	68.4	82.9	61.0	57.5	82.5
Other crops	6.4	10.4	2.9	6.0	9.8	2.7
DDGS	5.6	6.4	1.1	12.9	17.6	2.1
Oilseeds meals	20.3	14.9	13.1	20.1	15.0	12.7

*Processed feed is dropped from this table to highlight shares of items listed in the table.

To evaluate the land use implications of US ethanol production we use a new model which includes all modifications and improvements which have been made in the GTAP-BIO-ADV model and its data base described above and in the associated references. In short this model has the following specifications:

1) It covers production, consumption, and trade of three types of biofuels: ethanol from crops, ethanol from sugarcane, and biodiesel from crude vegetable oil.
2) By products are DDGS and oilseeds meals.
3) The crude vegetable oil industry uses oilseeds and produces crude vegetable oil and oilseed meals.
4) The biodiesel industry uses crude vegetable oil to produce biodiesel.
5) The demand for feedstuffs follows a three level nesting structure.
6) The land module handles two new land categories of unused cropland and cropland pasture. While the model could trace changes in these two groups of land across the world, we have data on cropland pasture for the US and Brazil and data on CRP only for the US.

7) We have calibrated ETA for each AEZ and region instead of using the globally fixed ETA parameter as in the past.
8) Energy demand and supply elasticities have been re-calibrated for this version.
9) In this report we divide the world economy into 19 regions, 34 groups of commodities and services, 32 industries, and 5 groups of endowments. The list of regions, commodities, industries and endowments are shown in Appendix B.
10) In this report when we shock US ethanol, we hold production of other biofuels constant.

3. GTAP simulations and their results

To evaluate the land use implications of US ethanol production we develop three groups of simulations. In the first group we follow the approach that we used in our earlier report (Tyner, Taheripour, and Baldos, 2009). In this approach, we calculate the land use implications of US ethanol production off of the 2001 database. This approach isolates impacts of US ethanol production from other changes which shape the world economy. This method assumes that other factors such as population growth, yield improvement, and economic growth do not affect the land use implications of producing more ethanol from agricultural resources. Hertel et al. (2010) provide more insights on this approach. While this approach uses the 2001 starting point, it is different from our January 2009 draft results in that all the model changes described above have been included in this first set of simulations.

In the second group of simulations, we first construct a baseline which represents changes in the world economy during the time period of 2001-2006. Then we calculate the land use impact of the US ethanol production off of the updated 2006 database, while we follow the principles of the first group of simulations for the time period of 2006-2015. Finally, in the third group of simulations we use the updated 2006 database obtained from the second group of simulations, but we assume that during the time period of 2006-2015 population and crop yields will continue to grow. These are two important factors which could alter the land use impacts of ethanol production in the future. These three groups of simulations and their results are described in the rest of this section.

Group 1: Simulations with no economic and yield growth and 2001 base

We calculate the land use implications of the US ethanol production for the following 6 time segments:

- Ethanol production from 2001 to 2006 level.
- Ethanol production from 2006 level to 7 B gallons,
- Ethanol production from 7 B to 15 B gallons by increments of 2 B gallons.

The global biofuel industry has followed a rapid growth path during the time period of 2001-2006. The historical observations from this time period have been used to calibrate the biofuel-parameters of the model (Hertel, Tyner, and Birur, 2008). Then we consider gradual increases in the production of US ethanol after 2006 to evaluate marginal impacts of ethanol production. For this purpose we first increase the US ethanol production from its 2006 level (4.855 BG) to 7 B gallons. Thereafter we increase ethanol production by increments of 2 B gallons to achieve the goal of 15 B gallons of ethanol in 2015.

The detailed global land use changes obtained from the first group of simulations are shown in Appendix C. Table 2 summarizes these results. These results indicate that producing 13.23 BGs of ethanol (from the 2001 production level to 15 BGs) requires about 2.96 million hectares of additional land, of which 1.01 million hectares (34%) are expected to be in the US, with the reminder (1.95 million hectares) in other regions (66%). This result suggests that the land use changes due to US ethanol production will mainly take place outside the US. Results from this group of simulations also indicate that the size of required land to achieve the 15 BGs ethanol production is much smaller than the land use changes suggested by a simple calculation which ignores important factors that could mitigate land use impacts of ethanol production[6]. Several factors mitigate the land use consequences of ethanol production. Among them are: less corn consumption in the livestock industry due to using more DDGS in the livestock industry, reductions in output of the livestock industry, reallocation of croplands across the world among alternative crops, and higher yields in crop production due to higher prices. Hertel et al. 2010 have decomposed contributions of these factors in mitigating the land use impacts of ethanol production.

Table 2. Global land use changes due to the US ethanol production: Off of 2001 database

Changes in US corn ethanol production	Land use changes (hectares)			Distribution of land use changes (%)			Hectares per 1000 gallons
	Within US	Other Regions	World	Within US	Other Regions	World	
3.085 BG (2001 to 2006)	227982	382394	610376	37.4	62.6	100.0	0.20
2.145 BG (2006 to 7 BG)	162558	297766	460324	35.3	64.7	100.0	0.21
2.000 BG (7 to 9 BG)	152990	295051	448041	34.1	65.9	100.0	0.22
2.000 BG (9 to 11 BG)	154018	310639	464657	33.1	66.9	100.0	0.23
2.000 BG (11 to 13 BG)	154706	325639	480345	32.2	67.8	100.0	0.24
2.000 BG (13 to 15 BG)	155000	340311	495311	31.3	68.7	100.0	0.25
13.23 BG (2001 to 15 BG)	1007253	1951800	2959053	34.0	66.0	100.0	0.22

The magnitude of land requirement to increase US ethanol production from its 2001 level to 15 BG obtained from these simulations is smaller than its corresponding value in our earlier report (Tyner, Taheripour, and Baldos, 2009) by about 16.7% (i.e. 2.96 million hectares versus 3.55 million hectares). Two major modifications in the GTAP model contribute to this reduction.

[6] One can determine land use changes due to the US ethanol production by multiplying corn yield (370 bushels per hectare of land) by a corn to ethanol conversion factor (e.g. 2.7 gallons per bushel of corn). This simple approach leads to 1000 gallons of ethanol per hectare of land. Hence, based on this simple calculation, increasing ethanol production from its 2001 level (1.77 BG) to 15 BG needs about 13 million hectares of land.

A portion of this reduction is associated with the land conversion factors. As noted earlier in this report we apply a set of regional land conversion factors at the AEZ level. These land conversion factors in several AEZs are higher than the single conversion factor of 0.66 which we used in our earlier work (see Appendix A).

Introducing the new land categories (cropland pasture and unused land[7]) into the model also contributes to the reduction in land requirement. In particular, in the US and Brazil in the presence of cropland pasture farmers convert a portion of this type of land to crop production. For example, an increase in US ethanol production from its 2001 level to 15 BG brings about 1.2 million hectares of cropland pastures into crop production, but not only to corn production. Indeed, a portion of this land conversion prevents sharp reductions in production of other crops. It is important to note that the competition between crop and livestock industry prevents full conversion of cropland pasture to crop production.

These two modifications not only reduce the land requirement of ethanol production. They also alleviate the adverse impact of ethanol production on the prices and consumption of crops.

Table 2 also indicates that the required land for producing 1000 gallons of ethanol grows as we move to higher levels of ethanol production. For example, for the 2001 to 2006 simulation, an additional 3.085 B gallons of ethanol triggers global land use changes of roughly 610,376 hectares. This is equal to 0.20 hectares per 1000 gallons of ethanol. However, for the 13 BGs to the 15 BGs simulation, an additional 1000 gallons of ethanol requires 0.25 hectares of land. To increase ethanol production from the 2001 level to 15 BGs, we need an average of 0.22 hectares of land per 1000 gallons of ethanol. The marginal level (0.25) is higher than the average (0.22),

[7] In these simulations we hold the area of US CRP land constant.

which would be expected because as more land comes into production, the yields on the incremental area would be lower.

Table 3 depicts another aspect of the land use implications of US ethanol production. This table shows the distribution of land use changes between forest and grassland. About 24.7% of the required croplands which are needed to increase ethanol production from its 2001 level to 15 BGs come from forest, and the rest (75.3%) come from grasslands. Table 3 also indicates that as we move to higher levels of ethanol production the portion of forests in the converted land into crop production increases very slightly (from 23.5 % in 2001 to 25.1% at the 15 BGs ethanol production.

Table 3. Global land use changes due to the US ethanol production: Off of 2001 database

Changes in US corn ethanol output	Land use changes (hectares)			Distribution of land use changes (%)		
	Forest	Grassland	Crop*	Forest	Grassland	Total*
3.085 BG (2001 to 2006)	-143716	-466652	610376	23.5	76.5	100.0
2.145 BG (2006 to 7 BG)	-114409	-345912	460324	24.9	75.1	100.0
2.000 BG (7 BG to 9 BG)	-112330	-335712	448041	25.1	74.9	100.0
2.000 BG (9 BG to 11 BG)	-116795	-347864	464657	25.1	74.9	100.0
2.000 BG (11 BG to 13 BG)	-120688	-359650	480345	25.1	74.9	100.0
2.000 BG (13 BG to 15 BG)	-124151	-371156	495311	25.1	74.9	100.0
13.23 BG (2001 to 15 BG)	-732089	-2226946	2959053	24.7	75.3	100.0

*The difference between the changes in cropland and the sum of forest and grassland is due to rounding. Cropland pasture is included in cropland.

In the absence of crop yield growth, the increasing global land use change given equal increments of US ethanol production is explained by the differences in the productivity of available lands. Productive lands are employed first before marginal lands, which have lower productivity and lower yields. At low levels of production, more productive lands are available; hence, less land is required to produce additional ethanol. However, at high levels of production, most of the productive land is already being used, and only marginal land is available. Given this, more marginal land is required to produce the same increment of US corn ethanol production.

Group 2: Simulations with updated baseline for the time period of 2001-2006

The global economy changed significantly over the 2001-2006 period. Countries followed different economic growth paths, population increased everywhere at different rates, land productivity rapidly increased in many regions (with some exceptions), and technology has improved in many areas. These are important factors which could alter the land use implications of biofuels. In the second group of simulations we take these factors into account.

To accomplish this task we developed a database which includes data on: crop production, harvested area, forest areas, gross capital formation, labor force (skilled and unskilled), gross domestic product, and population for the whole world at the country level. Then we used this data set to generate a baseline which replicates transition of the global economy from 2001 to 2006, while we targeted global biofuel production during this time period in the presence of population, income, and yield growths. In building the baseline we guide the model to replicate the historical paths of changes in harvested area across the world as well. Furthermore, we trace changes in global forest area to match our land use results with the historical changes in forest areas during the time period of 2001-2006. We adjusted rates of technological improvements to trace changes in cropland and forest areas.

Data sources

To construct the baseline the following data items were collected:

1- Population: World population figures by country were obtained from the UN website for 2001-2006. Then the population figures by region were calculated for our GTAP aggregation[8]. Finally, the percentage change in population between 2001 and 2006 was calculated for each region (see table 4).

2- GDP: Real GDP figures by country were obtained from the World Development Index (WDI) database for 2001-2006. Then the GDP figures by region were calculated for our GTAP aggregation. Finally, the percentage change in GDP between 2001 and 2006 was calculated for each region (see table 4).

3- Capital: Real capital formation figures by country were obtained from the WDI database for 2001-2006. Then the capital formation figures by region were calculated for our GTAP aggregation. Finally, the percentage change in capital formation between 2001 and 2006 was calculated for each region (see table 4).

4- Labor: Labor force figures by country were obtained from the WDI database for 2001-2006. Then the labor force figures by region were calculated for our GTAP aggregation. Finally, the percentage change in labor force between 2001 and 2006 was calculated for each region (see table 4). We followed Walmsley, Dimaranan, and McDougall (2000) to split labor force into groups of skilled labor and unskilled labor.

5- Crop production: Crop production figures by crop type and by country were obtained from the FAO website for 2001-2006. Then crop production figures by region were calculated for our GTAP aggregation for 2001-2006.

6- Harvested Area: Harvested areas by crop type and by country were obtained from the FAO website for 2001-2006. Then the harvested areas by region were calculated for our GTAP aggregation for 2001-2006.

[8] The aggregation schedule is shown in Appendix B, Table B-2.

7- Yield: Yields were calculated by region and by crop using items 5 and 6 introduced above. Since yield fluctuates over time, annual percentage changes in yields were calculated. Then we obtained the average of percentage changes in yield over the time period of 2001-2006 for each crop within each region. Table 5 reports the cumulative yield change for each region and crop category over the five years. Thus these percentages are roughly five times the annual growth rates.

8- Global forest export price - Values and quantities of exports of forestry products were obtained from the FAO website for 2001-2006. These figures were used in defining a global price index for forest products to shape technological progress in forest industry.

9- Finally, we used the FAO assessment of changes in global forest areas to track changes in the global forest areas (FAO, 2006). The FAO assessment covers the time period of 2000-2005, while we need changes in 2001-2006. So we assumed that changes in forest areas within the period of 2000-2005 are similar to the changes in the time period of 2001-2006.

Table 4. Percentage changes in macro economic variables (2001-2006)

Regions	Population	GDP	Skilled labor	Unskilled labor	Capital
1 USA	5.2	15.0	5.7	5.2	18.9
2 EU27	1.82	10.2	7.4	-1.1	13.1
3 BRAZIL	6.88	17.2	24.4	8.5	11.1
4 CAN	5.31	14.6	9.1	8.3	34.0
5 JAPAN	0.59	8.8	0.2	-4.1	0.7
6 CHIHKG	3.59	59.0	17.5	4.7	83.6
7 INDIA	8.51	45.9	27.5	8.7	94.8
8 C_C_Amer	6.41	16.8	33.7	6.8	25.4
9 S_o_Amer	7.19	24.4	50.2	10.1	54.4
10 E_Asia	2.75	25.9	15.1	5.3	21.6
11 Mala_Indo	7.18	29.1	56.5	9.0	30.1
12 R_SE_Asia	7.2	33.7	26.6	9.3	43.0
13 R_S_Asia	10.8	32.5	34.4	15.5	39.0
14 Russia	-2.38	37.7	2.2	1.2	69.6
15 Oth_CEE_CIS	2.27	25.5	14.9	-2.2	40.0
16 Oth_Europe	2.27	25.5	14.9	-2.2	40.0
17 MEAS_NAfr	10.18	26.7	30.7	19.1	47.8
18 S_S_AFR	13.47	27.5	17.3	13.6	45.2
19 Oceania	7.79	17.4	11.1	8.5	54.8

Table 5. Percentage change in yield (accumulation of growth rates 2001-2006)

Region\Crop	Wheat and Paddy Rice	Coarse Grains	Oilseeds	Sugarcane	Other Agriculture
1 USA	-2.3	11.0	11.6	1.8	-7.3
2 EU27	4.0	7.3	13.5	7.8	-1.8
3 BRAZIL	12.4	22.8	3.5	8.1	9.3
4 CAN	10.8	10.2	14.4	33.3	18.1
5 JAPAN	-4.1	-18.4	-8.6	5.1	-0.5
6 CHIHKG	6.3	17.0	5.6	42.6	5.2
7 INDIA	5.3	16.4	15.6	-4.1	-2.4
8 C_C_Amer	4.0	13.2	28.6	13.2	5.4
9 S_o_Amer	10.0	9.0	-0.7	6.4	3.5
10 E_Asia	5.6	48.3	3.6	0.0	5.6
11 Mala_Indo	4.3	19.4	27.4	9.3	19.8
12 R_SE_Asia	10.1	18.1	10.8	-4.6	15.6
13 R_S_Asia	6.8	37.8	-5.1	4.4	11.5
14 Russia	20.8	17.2	22.2	48.8	15.0
15 Oth_CEE_CIS	15.1	26.0	16.7	22.6	13.5
16 Oth_Europe	15.1	26.0	16.7	22.6	13.5
17 MEAS_NAfr	20.3	25.3	46.6	4.3	1.7
18 S_S_AFR	6.4	9.8	10.2	-5.7	3.4
19 Oceania	10.9	-9.6	0.7	2.2	17.3

To generate the 2006 baseline, we shock major macroeconomic variables according to the historical observations for the time period of 2001-2006. In particular, we shocked GDP, gross capital formation, labor force, and population at the regional level. We also introduced shocks to increase global biofuels outputs according to actual observations for the same time period. In addition to these shocks, we guide the model to replicate observed improvement in yield over the time period of 2001 to 2006 by crop and by region. Finally, we introduced technological changes in input output ratios to replicate regional changes in harvested area during the time period of 2001-2006. Furthermore we guide the model to trace changes in forest area during the baseline time period. Appendix D shows the list of implemented shocks. This experiment provides us a new database which represents the world economy in 2006 in the presence of changes in the major derivers of the world economy. To separate out the impacts of the US ethanol program from other derivers of the world economy we repeat this experiment without the US ethanol shock. The difference between the land use implications of these two simulations gives us the impact of the US ethanol program for the time period of 2001-2006.

Then we used the updated 2006 database to evaluate the land use impacts of increasing US ethanol from its 2006 level to 15 BG incrementally. The global land use implications obtained from the second group of simulations are shown in Appendix C. Table 6 summarizes these results.

Table 6. Simulated global land use changes due to the US ethanol production: Off of updated baseline

Changes in US corn ethanol production	Land use changes (hectares)			Distribution of Land Use changes (%)			Hectares per 1000 gallons
	Within US	Other Regions	World	Within US	Other Regions	World	
3.085 BG (2001 to 2006)	106870	360397	467268	22.9	77.1	100.0	0.15
2.145 BG (2006 to 7 BG)	77989	246464	324452	24.0	76.0	100.0	0.15
2.000 BG (7 to 9 BG)	73308	233222	306529	23.9	76.1	100.0	0.15
2.000 BG (9 to 11 BG)	73754	233992	307746	24.0	76.0	100.0	0.15
2.000 BG (11 to 13 BG)	74717	238378	313094	23.9	76.1	100.0	0.16
2.000 BG (13 to 15 BG)	75731	242685	318416	23.8	76.2	100.0	0.16
13.23 BG (2001 to 15 BG)	482368	1555137	2037506	23.7	76.3	100.0	0.15

The results obtained from the second group of simulations indicate that we need 2.04 million hectares of cropland to increase ethanol production from the 2001 level to 15 BGs. This figure is smaller than its corresponding figure obtained from the first group of simulations by 31.1%. Two main factors contribute to this reduction. During the time period of 2001-2006 crop yields are growing faster than the demands for crops in many regions. This reduces the size of land use changes in this period. Then when we calculate the land use implications of US ethanol for the time period of 2006-2015 from the updated database of 2006, we get smaller land use changes because crop yields are higher in the updated database.

In the second group of simulations cropland pasture moves to crop production faster than in the first group of the simulations as well. In the presence of economic growth about 5.3 million hectares of cropland pasture will move to crop production.

Table 7 represents distributions of land use changes between forest and pasture for the second group of simulations. In this group of simulations on average about 32.5% of required land for ethanol production comes from forest land. This figure is higher than the corresponding figure of the first group of simulations (i.e. 24.7%).

Table 7. Simulated global land use changes due to the US ethanol production: Off of updated baseline

Changes in US corn ethanol output	Land use changes (hectares)			Distribution of land use changes (%)		
	Forest	Grassland	Crop*	Forest	Grassland	Total*
3.085 BG (2001 to 2006)	-151706	-315487	467268	32.5	67.5	100.0
2.145 BG (2006 to 7 BG)	-105357	-219095	324452	32.5	67.5	100.0
2.000 BG (7 BG to 9 BG)	-99673	-206854	306529	32.5	67.5	100.0
2.000 BG (9 BG to 11 BG)	-100005	-207740	307746	32.5	67.5	100.0
2.000 BG (11 BG to 13 BG)	-101633	-211466	313094	32.5	67.5	100.0
2.000 BG (13 BG to 15 BG)	-103423	-214992	318416	32.5	67.5	100.0
13.23 BG (2001 to 15 BG)	-661797	-1375633	2037506	32.5	67.5	100.0

*The difference between the changes in cropland and the sum of forest and grassland is due to rounding

Group 3: Simulations with crop yield and population growth for the time period of 2006-20015

Some advocates of the US corn ethanol program argue that crop yields will increase in the future such that this increase could eliminate the land use implications of ethanol production. This argument neglects the impacts of the future changes in the demand for crops. Demands for crops could increase in the future due to several factors such as changes in population and income, dietary transition as poorer countries consume more meat, or technological progress. In other words, one cannot examine yield (supply) increases alone; we must also include assumptions about increases in crop demand as well. In the third group of simulations we examine impacts of changes in crop yields and demand as important items which could determine demand and supply for crops and food products.

For our model simulations we use population growth as a proxy for food demand increase. We assume that population will continue to grow globally during the time period of 2006-2015 after 2006 at the annual growth rate of 2001-2006. We also assume that crop yield will increase uniformly at 1% annually after 2006 in all regions and across all types of crops. While 1% might seem small, it is actually a large number as it is applied in all regions and for all crops. We also assume that the regional demands for forest products will increase according to their annual rates of 2001-2006. We made the latter assumption to maintain the long run pattern in forest products outputs. These simulations also include all the changes incorporated in the baseline simulation of the second group of simulations.

To find the land use impacts of US ethanol program under these assumptions we did simulations with and without US ethanol production off of the updated data base for 2006 (obtained in the second group of simulations) for the time period of 2006-2015 in the presence of population and yield shocks. The global land use implications of the US ethanol plan under these assumptions are shown in appendix C. To understand the land use implications of the US ethanol program under these assumptions we first analyze the land use implications with no US ethanol production. Table 8 indicates land use changes due to the yield and population growth for US, EU, Brazil, and other regions.

Table 8 indicates that after 2006 the cropland areas of US, EU, Brazil, and other regions would fall due to the simultaneous shocks in yield and population growth. This means that yield growth would dominant the demand growth for crops, and therefore the demand for cropland decreases everywhere. In addition to that, the yield growth contributes to higher levels of food consumption everywhere.

Table 8. Simulated global land use changes due to population and yield growth after 2006 (figures are in 1000 hectares)

Period	Land cover	US	EU	Brazil	Others	World
2006-2007	Forestry	132.2	216.6	419.1	2168.9	2936.8
	Cropland	-163.8	-241.7	-106.5	-2428.4	-2940.5
	Pastureland	31.7	25.1	-312.6	259.5	3.7
2007-2009	Forestry	357.0	562.3	910.7	6157.2	7987.1
	Cropland	-369.0	-570.3	-246.9	-6065.2	-7251.4
	Pastureland	12.0	8.0	-663.8	-91.9	-735.7
2009-2011	Forestry	522.9	778.8	1083.4	9211.1	11596.3
	Cropland	-410.9	-693.1	-279.9	-7889.1	-9273.0
	Pastureland	-112.0	-85.8	-803.5	-1322.0	-2323.3
2011-2013	Forestry	712.4	1013.8	1305.5	12550.1	15581.9
	Cropland	-457.8	-820.4	-310.0	-9859.0	-11447.1
	Pastureland	-254.6	-193.5	-995.5	-2691.2	-4134.7
2013-2015	Forestry	979.3	1348.3	1643.3	15831.4	19802.3
	Cropland	-530.6	-983.9	-353.6	-11628.8	-13496.8
	Pastureland	-448.7	-364.4	-1289.7	-4202.6	-6305.5

The simulation results indicate that consumption of crops and food products grow faster than population everywhere across the world. This indicates that the yield effect works through two channels: 1) reduction in crop land area needed to satisfy demand, and 2) higher per capita consumption of food. This means that one percent yield improvement will not end with one percent reduction in cropland, even if there is no population growth.

The released croplands are going to forest to support the long run growth in forest products. Note that as mentioned earlier in this group of simulations we assume the global forest sector will continue to grow according to its 2001-2006 growth rate.

With this discussion we now examine impacts of adding biofuel shocks into this picture. In general, the US ethanol program in this group of simulations generate smaller land use changes compared the results of the second group of simulations. Table 9 shows that under the assumptions of this group of simulations we need 1.7 million hectares of cropland to increase ethanol production from the 2001 level to 15 BGs. This figure is smaller than the corresponding figure obtained from the second group of simulations by 20%. For the earlier time segments after 2006 the size of land requirement is significantly smaller than what we observed in the second group of simulations. For example, in this group of simulations we need only 0.11 hectares of cropland to produce 1000 gallons of ethanol in the time segment of 2006-2007, while the corresponding number obtained from the second group of simulations is about 0.15.

As we move forward towards 2015, the population growth dominants the yield growth in some regions, and the land requirement grows. Table 9 shows that the share of US in land requirement is about 24.4% on average in this group of simulation.

Table 9. Simulated global land use changes due to the US ethanol production: with yield and population growth after 2006

Changes in US corn ethanol production	Land use changes (hectares)			Distribution of Land Use changes (%)			Hectares per 1000 gallons
	Within US	Other Regions	World	Within US	Other Regions	World	
3.085 BG (2001 to 2006)	106870	360397	467268	22.9	77.1	100.0	0.15
2.145 BG (2006 to 7 BG)	58373	175123	233496	25.0	75.0	100.0	0.11
2.000 BG (7 to 9 BG)	57966	177186	235151	24.7	75.3	100.0	0.12
2.000 BG (9 to 11 BG)	60830	184916	245746	24.8	75.2	100.0	0.12
2.000 BG (11 to 13 BG)	65116	199837	264953	24.6	75.4	100.0	0.13
2.000 BG (13 to 15 BG)	70656	206057	276713	25.5	74.5	100.0	0.14
13.23 BG (2001 to 15 BG)	419811	1303516	1723327	24.4	75.6	100.0	0.13

The distribution of land use changes between forest and pasture land are similar to the second group of simulations. Our assumption on the regional demands for forest products derives this result. It is very important to note that adding income growth or changes in other economic factors into this picture may change the geographical distribution of land use changes or the distribution of the land requirement for ethanol production between forest and grassland. (Table 10)

Table 10. Simulated global land use changes due to the US ethanol production: With yield and population growth after 2006

Changes in US corn ethanol output	Land use changes (hectares)			Distribution of land use changes (%)		
	Forest	Grassland	Crop*	Forest	Grassland	Total*
3.085 BG (2001 to 2006)	-151706	-315487	467268	32.5	67.5	100.0
2.145 BG (2006 to 7 BG)	-75942	-157560	233496	32.5	67.5	100.0
2.000 BG (7 BG to 9 BG)	-76424	-158735	235151	32.5	67.5	100.0
2.000 BG (9 BG to 11 BG)	-79870	-165871	245746	32.5	67.5	100.0
2.000 BG (11 BG to 13 BG)	-86227	-178732	264953	32.5	67.5	100.0
2.000 BG (13 BG to 15 BG)	-89932	-186782	276713	32.5	67.5	100.0
13.23 BG (2001 to 15 BG)	-560101	-1163167	1723327	32.5	67.5	100.0

*The difference between the changes in cropland and the sum of forest and grassland is due to rounding

4. Land use CO_2 emission factors

We use emissions factors to convert land use changes into the land use CO_2 emissions (LUCE). Land conversions of forest and grassland into crop production releases CO_2 emissions from two sources: 1) direct CO_2 emissions from land conversion and 2) foregone CO_2 sequestration by forests. The direct CO_2 emissions consist of carbon stored in the vegetation and in the soil, which are released when forests or grasslands are cleared and converted into croplands. The forgone carbon sequestration accounts for the amount of carbon that could have been stored from annual forest growth, if land had remained forested. This is the opportunity costs of cleared land in terms of its potential to store carbon.

As mentioned earlier in this report we use the Woods Hole data set[9]. This data set divides the world into 10 homogenous regions, determines distributions of forests and grasslands within each region across different types of vegetation cover, and provides detailed information on the carbon stored in the vegetation and in the soil of forests and grasslands within each region.

[9] This data set, which is taken from the supporting documents of SEA

The Woods Hole data set provides two key carbon figures for each type of land according to its natural vegetation. These figures are carbon stored in the soil and carbon stored in the vegetation. We assume that when a natural vegetation area (either forest or grassland) is converted to cropland, about 25% of the carbon stored in its soil will be released into the atmosphere. In addition, we assume 75% of carbon stored in the forest type vegetation and 100% percent of carbon stored in the grassland vegetation will be released into the atmosphere at the time of land conversion[10]. If more than one type of vegetation is available in an area we calculate the weighted average emissions for that area, where weights are shares of vegetation areas. We calculate emissions factors for forest areas and grasslands, separately. Sensitivity analysis can be conducted on any of the data and assumptions used in this analysis.

Regarding the forgone carbon sequestration we assumed when a natural vegetation area is converted to cropland, it loses its carbon sequestration capacity as long as it is under crop production. Again, if more than one type of land is available we use weighted average of forgone carbon sequestration. We simply add the direct and forgone sequestration in each region. Hence, in each area we have two groups of emissions factors: forest and grassland emission factors. The Woods Hole data set along with emissions factors obtained from this data set are presented in Appendix E. Data in this appendix are calculated based on the assumption that the converted land to crop production will remain under crop production for 30 years[11]. We recognize that the 30 year period is somewhat arbitrary, and we have not considered what changes might occur after that period. Thirty years is about the life of a biofuels facility, so it seems as reasonable an assumption as any.

[10] In essence, we are assuming that 25% of the carbon in wood is stored in buildings, furniture, etc.
[11] To test the sensitivity of carbon emissions factors with respect to the time period of ethanol production, we calculated the land use emissions factors for 50, 80, and 100 years from the Woods Hole data in our earlier report (Tyner, Taheripour, and Baldos, 2009).

At this point it is important to note that some research indicates that conservation tillage practices and enhanced rotation programs can increase carbon sequestration ability of croplands. This means that using advanced technologies in corn production can increase carbon stored in soil (West and Post, 2002). In this paper we ignore impacts of advanced tillage methods on the carbon sequestration ability of cropland.

As we mentioned earlier the Woods Hole data set divides the world into 10 regions. On the other hand this version of the GTAP model divides the world into 19 regions. Table 11 relates each region of GTAP to one of the regions of the Woods Hole data set.

Table 11. GTAP and Woods Hole regions

GTAP Regions	Woods Hole Regions
United States	United States
Canada	Canada
Sub Saharan Africa	Africa
European Union 27 East Europe and Rest of Former Soviet Union Rest of European Countries	Europe
Russia	Former Soviet Union
Brazil Central and Caribbean Americas South and Other Americas	Latin America
Middle Eastern and North Africa	North Africa and Middle East
East Asia Oceania Japan	Pacific Developed
China and Hong Kong India	China/India/Pakistan
Rest of South East Asia Rest of South Asia Malaysia and Indonesia	South and Southeast Asia

We now present regional forest[12] and grassland emissions factors derived from the Woods Hole data set in Table 12. Converting forest areas to cropland in South and South East

[12] Searchinger et al. 2008 calculated forest forgone emissions from carbon uptake by growing forest. Indeed they divided growing forest uptake by the area of total area forest in each ecosystem to determine forgone carbon emissions. We followed this approach to make our results comparable with Searchinger et al. 2008 results.

Asia, China, and India generates the highest CO_2 emissions per hectare of land compared to the rest of the world in the Wood's Hole data. For example, the forest emissions factor in these regions is equal to 23 metric tons of CO_2 per hectare of forest per year, when the duration of ethanol production is 30 years. The lowest emissions factor among forest areas is in Sub Saharan Africa. In this region the forest annual emissions factor is equal to 10.4 metric tons of CO_2 per hectare of forest.

Table 12. GTAP regions and their corresponding CO_2 emissions factors for forest and grassland areas (figures are in annual metric ton CO_2 equivalent per hectare for 30 years corn production time horizon)

Regions	Forest emissions factors	Grassland emission factors
United States	19.6	3.7
Canada	15.3	5.7
Sub Saharan Africa	10.4	1.5
European Union 27 East Europe and Rest of Former Soviet Union Rest of European Countries	18.6	6.6
Russia	14.1	7.0
Brazil Central and Caribbean Americas South and Other Americas	16.1	2.5
Middle Eastern and North Africa	12.2	2.2
East Asia Oceania Japan	13.2	3.5
China and Hong Kong India	23.0	6.6
Rest of South East Asia Rest of South Asia Malaysia and Indonesia	23.0	6.6

The third column of Table 12 shows annual emissions factors for grassland areas derived from the Woods Hole. Figures of this table illustrate that converting grasslands to crop

However, this approach underestimates the magnitude of forgone forest emissions. Growing forest update should be divided by the area of growing forest - not the total area in forest. In addition, for many ecosystem types the Woods Hole database shows zeros for growing forest.

production releases smaller CO_2 emissions compared to deforestation. The highest regional grassland annual emissions factor, derived from the Woods Hole data set, is Russia (with 7 metric tons CO_2 per hectare per year), and the lowest is Sub Saharan Africa (with 2.2 metric tons CO_2 per hectare per year).

5. Estimated land use CO_2 emissions due to the US ethanol production

We now combine simulated land use changes due to US ethanol production with the CO_2 release emissions factors. This is a straight forward process. Suppose ΔLF_{rj} (see Tables 2, 6, 9) is the size of change in land type j (for j = forest and grassland) in region r due to X gallons of increase in the US ethanol production. In addition, suppose that the annual CO_2 emissions factor for land type j in region r for a 30 year ethanol production is about Frj (see Table 12). Then the global annual CO_2 emissions due to producing x gallons of ethanol per year in the US will be equal to:

$$(1)\quad LUE_W = \sum_r \sum_j \Delta LF_{rj} \cdot F_{rj} \ .$$

Using this approach we calculated CO_2 emissions for all land use simulation scenarios (Three groups of simulations and 6 time segments) and for all emissions factors derived from the Woods Hole data sets. Once we have emissions, we can calculate the marginal and average land use emissions due to production of each gallon of pure ethanol (E100) for all groups of simulations examined in this paper. For example, Table 13 shows how we calculated the marginal land use emissions due to producing each gallon of E100 for the 13 to 15 BGs for the first group of our simulations.

Table 13. Estimated marginal land use emissions per gallon of E100 for 13 to 15 billion gallons simulation (30 year pay off method)

Total 30 year emissions from land use changes (million metric tons)	110.77
Change in ethanol production (million gallons) per year	2000
Emissions (metric tons per gallon-year of ethanol)	0.0554
Emissions (grams per gallon-year of ethanol)	55386
One year marginal emissions (grams per gallon of ethanol)	1846

The value of 110.77 million metric tons of emissions presented in this table is obtained by multiplying regional forest and grassland changes due to an increase in ethanol production from 13 to 15 BGs (see appendix C) by their corresponding Woods Hole annual emissions factors presented in the second and third columns of Table 12 and then summed over regions. The result of this calculation is multiplied by 30 to present the magnitude of total emissions over 30 years. One can follow the rest of example through table 13. We now present land use emissions for all groups of simulations discussed earlier in this report.

Land use emissions for the first group of simulations

Table 14 represents marginal and average land use emissions obtained from simulations off of the 2001 database. This table indicates that marginal emissions are increasing in ethanol production. For example, while an increase in ethanol production from 7 BGs to 9 BGs generates 1687 grams CO_2 emissions per gallon of ethanol, moving from 9 BGs to 11BG causes 1745 grams CO_2 per gallon. When ethanol production reaches 15 BGs, then each additional gallon of ethanol generates 1846 grams of CO_2. Table 14 indicates that average emissions are increasing in ethanol production as well. This table shows that during the time period of 2001-6 on average each gallon of US ethanol was generating 1477 grams CO_2. However, if ethanol production reaches 15 BGs, then on average each gallon of ethanol generates 1676 grams of emissions. It is important to note that in this group of simulations about 61% of emissions come from deforestation and 39% come from converting grasslands into crop production.

Table 14. Annual marginal and average estimated land use emissions due to the US ethanol production: Obtained from the simulations off of the 2001 database

Time Segment	Marginal Emissions (grams CO_2 per gallon of ethanol)				Average emissions (grams CO_2 per gallon of ethanol)			
	Changes in ethanol production	Forest	Grasslands	TOTAL	Total ethanol production	Forests	Grasslands	TOTAL
2001-6	3.085	886	590	1477	3.085	886	590	1477
2006-7	2.145	990	628	1619	5.23	929	606	1535
2007-9	2.000	1033	654	1687	7.23	958	619	1577
2009-11	2.000	1067	677	1745	9.23	982	632	1613
2011-13	2.000	1097	701	1797	11.23	1002	644	1646
2013-15	2.000	1122	724	1846	13.23	1020	656	1676

Note that in this paper we ignored impacts of the first 1.77 billion gallons of ethanol on the average land use changes per gallon of ethanol production. Incorporating land uses changes due to the first 1.77 billion gallons of ethanol will moderately reduce the average emissions per gallon of ethanol.

Land use emissions obtained from this group of simulations are smaller than our earlier estimates for land use emissions. For example, as shown in table 14, on average each gallon of US generates 1676 grams emissions. The corresponding number in our earlier report was about 2210 grams emissions. This shows about 16.5% reduction emissions per gallon of ethanol. This is due to using the new regional ETAs and incorporating cropland pasture into the picture.

Land use emissions for the second group of simulations

Table 15 presents the marginal and average emissions for the second group of simulations, where we calculate land use changes according to the updated baseline for 2001-6.

Emissions obtained from second group of simulations follow the pattern of the first group. However, their magnitudes are smaller than the first group.

Table 15. Annual marginal and average estimated land use emissions due to the US ethanol production: Obtained from the simulations off of the updated 2006 database

Time Segment	Marginal emissions (grams CO_2 per gallon of ethanol)				Average emissions (grams CO_2 per gallon of ethanol)			
	Changes in ethanol production	Forest	Grasslands	TOTAL	Total ethanol production	Forests	Grasslands	TOTAL
2001-6	3.085	925	465	1390	3.085	925	465	1390
2006-7	2.145	1019	399	1418	5.23	963	438	1402
2007-9	2.000	1020	406	1427	7.23	979	429	1409
2009-11	2.000	1017	409	1426	9.23	987	425	1412
2011-13	2.000	1027	419	1446	11.23	994	424	1418
2013-15	2.000	1040	427	1467	13.23	1001	424	1426

As shown in table 15, when the US ethanol production reaches to 15 BGs of ethanol each additional gallon of ethanol generates about 1467 grams of emissions. At this level of ethanol production, on average each gallon of ethanol causes 1426 grams of CO_2 emissions. These figures are smaller than the corresponding figures of the first group of simulations by 21% and 15%. These reductions are due to yield improvement during the time period of 2001-2006. As noted earlier in this time period yield has improved in many regions faster than the demand for crops for food. It is important to note that in this group of simulations about 70% of emissions come from deforestation and the rest comes from converting grasslands into crop production.

Land use emissions for the third group of simulations

Table 16 shows the marginal and average land use emission for the third group of simulations, where we calculate land use changes according to the simulations with the updated 2001-06 database and population, yield, and forest product growth.

Table 16. Annual marginal and average estimated land use emissions due to the US ethanol production: Obtained from the simulations off of the updated 2006 database and with population and yield growth after 2006

Time Segment	Marginal emissions (grams CO_2 per gallon of ethanol)				Average emissions (grams CO_2 per gallon of ethanol)			
	Changes in ethanol production	**Forest**	**Grasslands**	**TOTAL**	**Total ethanol production**	**Forests**	**Grasslands**	**TOTAL**
2001-6	3.085	925	465	1390	3.085	925	465	1390
2006-7	2.145	716	317	1032	5.23	839	404	1244
2007-9	2.000	721	351	1072	7.23	806	390	1196
2009-11	2.000	698	391	1089	9.23	783	390	1173
2011-13	2.000	697	452	1149	11.23	768	401	1169
2013-15	2.000	659	501	1159	13.23	751	416	1167

As shown in table 16, in this case during the time period of 2006-2015 the marginal emissions grow when the population growth dominates the yield growth. For example, an additional gallon of ethanol produces about 1032 grams emissions in the time segment of 2006-7, while each gallon of additional ethanol causes 1159 grams emissions in the time segment of 2013-15. In this group of simulations on average each gallon of ethanol generates about 1167 grams of emissions. This figure is smaller than the corresponding figure obtained from the second group of simulations by about 18 percent.

6. Final analysis

We now compare the land use emissions obtained from the three groups of simulations with the results of SEA. Table 17 shows lower emissions due to indirect land use change when we incorporate all economic and demographic and yield growth into account in the third group of simulations. The average value of the third group of simulations is about 13.6% of the original SEA result. The results of the first and the second groups of simulations are about 20% and 16.6% of SEA.

Table 17. Estimated land use change emissions due to U.S. ethanol production (Comparing GTAP and Searchinger et al. (2008) results)

Searchinger et al. (2008)	Total Emissions for 30 years (million metric tons)	3801
	Change in ethanol production (billion liters of ethanol)	55.92
	Total emissions for 30 years (grams per liter)	67972
	Liters per gallon	3.785
	Total emissions for 30 years (grams per gallon of ethanol)	257302
	One year emissions (grams per gallon of ethanol)	8577
GTAP results off of 2001 database	One year average emissions (gram per gallon of ethanol)	1676
	One year marginal emissions (gram per gallon of ethanol)	1846
GTAP results off of 2006 database	One year average emissions (gram per gallon of ethanol)	1426
	One year marginal emissions (gram per gallon of ethanol)	1467
GTAP results off of 2006 plus population & yield growth	One year average emissions (gram per gallon of ethanol)	1167
	One year marginal emissions (gram per gallon of ethanol)	1159

Total emissions from production and consumption of ethanol

Table 18 contains the estimated well-to-wheel ethanol emissions for the marginal and average land use changes for the three groups of simulations[13]. For the first group of simulations production and consumption of each gallon of ethanol (E100) on average generates about 6800 grams of GHGs emissions. In this case about 24.6% of released emissions are related to land use changes. When we incorporate changes in population and other factors, each gallon of ethanol (E100) on average causes about 6550 grams of GHGs emissions. In this case about 21.7% of released emissions are related to land use changes. Finally, in the third group, when we take into account the population and yield growth after 2006, then production and consumption of each

[13] In this report the direct marginal GHG emissions (i.e. non-land emissions) of ethanol for the post 2006 are taken from 100% dry mill.

gallon of ethanol (E100) generates about 6291 grams of emissions. In the third case, about 18.5% of released emissions are related to land use change.

Table 18 indicates well to wheel ethanol emissions expressed as grams/gal of ethanol and in grams per Megajoule (MJ). For the first, second, and third groups of simulations, production and consumption of each gallon of ethanol (E100) on average generates about 84.4 g/MJ, 81.3 g/MJ, 78.1 g/MJ emissions, respectively. Land use emissions for the third group of simulations are 14.5 grams/MJ.

Table 18. Estimated annual well-to wheel ethanol emissions for marginal and average land use changes

Description		Land use emissions (grams/gal)	Land use emissions (grams/MJ)	Well-to-wheel emissions without land use[a] (grams/gal)	Well-to-wheel emissions plus land use (grams/gal)	Well-to-wheel emissions plus land use (grams/MJ)[b]
Simulations Off of 2001	Marginal	1846	22.9	5100	6946	86.3
	Average	1676	20.8	5124	6800	84.4
Simulations Off of 2006	Marginal	1467	18.2	5100	6567	81.5
	Average	1426	17.7	5124	6550	81.3
Simulations Off of 2006 Plus population & yield growth	Marginal	1159	14.4	5100	6259	77.7
	Average	1167	14.5	5124	6291	78.1

[a]From GREET simulations. We used the default values in GREET version 1.3c for 2015 for the simulations. The marginal and average differ for ethanol direct emissions because the fraction that is wet versus dry milling decreases over time yielding slightly lower direct emissions for the marginal case.
[b]Low heating values of gasoline and ethanol are: 116090 BTU/gal and 76330 BTU/gal.

Finally, Table 19 compares total emissions of E100 obtained from the three groups of simulations with the emissions of conventional gasoline. This table indicates that ethanol production induces lower emissions compared to conventional gasoline for all groups of simulations. For example, total GHGs emissions due to production and consumption of E100 (including land use emissions) obtained from the first group of simulations are about 10342 grams per gallon of gasoline equivalent for the average land use changes. This figure is about

90.5% of the emissions due to production and consumption of conventional gasoline. When we use the updated 2006 database, total estimated GHGs emissions due to production and consumption of E100 are about 9961 grams per gallon of gasoline equivalent for the average land use changes. This figure is 87.2% of the emissions due to production and consumption of conventional gasoline. Finally, when we use the updated data base, and we assume population and yield increase after 2006, then total estimated emissions for E100 are 9568 grams per gallon of gasoline equivalent for the average land use changes. In this case the E100 emission estimate is about 83.7% of emissions associated with conventional gasoline. Table 19 presents emissions of ethanol and gasoline in grams per gallon of gasoline equivalent and per MJ.

Table 19. Estimated well-to-wheel ethanol and gasoline emissions

Description		Emissions in grams per gallon of gasoline equivalent			Emissions in grams/MJ		
		Ethanol	**Gasoline**	**Ethanol vs gasoline (percent)**	**Ethanol**	**Gasoline**	**Ethanol vs gasoline (percent)**
Simulations Off of 2001	Marginal	10564	11428	92.4	86.3	93.3	92.2
	Average	10342	11428	90.5	84.4	93.3	90.5
Simulations Off of 2006	Marginal	9988	11428	87.4	81.5	93.3	87.4
	Average	9961	11428	87.2	81.3	93.3	87.2
Simulations Off of 2006	Marginal	9520	11428	83.3	77.7	93.3	83.3
	Average	9568	11428	83.7	78.1	93.3	83.7

Since the third group simulations takes into account changes in population, crop yields, economic growth, and growth in primary inputs during the time period of 2001-2006 and after that assumes that population and yield growth will continue, the emissions obtained from this group of simulations are lower than the other cases. However, the results are derived from our assumptions, in particular for the time period of 2006-2015. Any change in these assumptions could alter the results. In other words, we have assumed 1 percent global growth in yields for all crops and 2001-06 population growth through 2015. Changes in these assumptions would alter the numerical results.

7. Conclusions

The overarching objective of this research has been to estimate the global land use changes induced by US corn ethanol programs and in doing so to closely examine some of the critical issues that have been overlooked in some prior studies. It is a very controversial topic. Some argue it is impossible to measure such changes. Others argue that failure to measure the land use changes and the consequent GHG emissions would lead us to incorrect policy conclusions. After working on this topic for over two years, we come out between these extremes. First, with almost a third of the US corn crop today going to ethanol, it is simply not credible to argue that there are no land use change implications of corn ethanol. The valid question to ask is to what extent land use changes would occur. Second, our experience with modeling, data, and parameter estimation and assumptions leads us to conclude that one cannot escape the conclusion that modeling land use change is quite uncertain. Of course, all economic modeling is uncertain, but it is important to point out that we are dealing with a relatively wide range of estimation differences. The estimation range depends on what is being simulated, as will be seen below.

Over the two plus years we have working on this topic, we have made numerous improvements in the models used for the analysis. These improvements are spelled out in the text above and in the appendices. We have better data on land productivity and on cropland pasture and CRP lands, and these data and associated parameters are now in the model. We have improved the treatment of the livestock and livestock feed sectors. Similarly, these changes are reflected in the current version of the model. We have amassed data on crop yields and many other variables for every region of the world and used much of that data in our analysis and model calibration. These data and model improvements have significantly improved the analysis and model results.

Table 20 provides a convenient summary of the evolution of some of our results over the different versions of the model and data. The third column replicates the summary results from our January 2009 draft paper before all the model changes described were implemented. The January 2009 results are provided only for reference, so our comparisons will be based on the three simulations reported in this paper. The fourth column is with all the model improvements and the 2001 data base. The fifth column is with the baseline updated to 2006 as described above. The last column is both with the updated baseline to 2006 and the assumed growth in demand and supply as described above.

Table 20. Summary of the different modeling results

Result	Units	Original Jan. 09 estimates	Model improvements with 2001 data base	Baseline updated to 2006	Updated baseline and growth in demand and yield
Land needed for ethanol	Ha./1000 gal.	0.27	0.22	0.15	0.13
Distribution of land use change between forest and pasture	%forest/%pasture	23/77	25/75	33/67	33/67
Distribution of land use change between U.S. and rest of world	%US/%Others	35/65	34/66	24/76	24/76
Average emissions of 15 bil. gal. program	Grams CO_2/gal. of ethanol	1931	1676	1426	1167
% of Searchinger, et al.	%	22.5	19.5	16.6	13.6
Emissions per gallon gasoline eq.	Grams CO_2/gal.	10564	10342	9961	9568
Emissions per MJ	Grams $C0_2$/MJ	86.3	84.4	81.3	78.1
Total ethanol emissions as % of gasoline	%	92.4	90.5	87.2	83.7

In some cases, the results are fairly stable regardless of the simulation. For example, the percentage of land that comes from forest ranges between 25 and 33 percent depending on the model and assumptions being used. Similarly, the fraction of land use change that occurs in the U.S. ranges between 24 and 34 percent. However, the land needed to meet the ethanol mandate ranges between 0.13 and 0.22 hectares/1000 gallons, which is a fairly wide range. The ethanol CO_2 emissions per gallon range between 1167 and 1676, also a fairly large range. However, the total emissions per MJ range between 78.1 g/MJ and 84.4 g/MJ, a small range. The reason for the small range in this case is that the direct ethanol emissions are assumed to be constant, so the land use emissions are being added to a constant level of direct emissions making the variability in total emissions per mile smaller.

Ethanol emissions as a fraction of gasoline emissions range between 83.7 and 90.5 percent. We cannot conclude whether or not corn ethanol would meet a 20 percent standard given the inherent uncertainty in the analysis, and potential improvement in direct emissions associated with corn farming and ethanol production. In a recent analysis including uncertainty in GHG estimation using an earlier version of GTAP-BIO, Hertel et al. (2010) concluded that the corn ethanol induced emissions from land use change range between 2 and 51 g/MJ. Our estimate for the last case is 14.5 g/MJ. This large range taken from another study using similar approaches clearly illustrates the uncertainty inherent in this analysis. It also concludes that zero is not within the error bounds. In other words, we know land use change induced emissions are not zero, but measuring them with high precision is not yet possible.

8. Limitations and future research

As indicated above, analysis such as that undertaken here is very complex and is limited by data availability, validity of parameters, and other modeling constraints. Economic models, like other models, are abstractions from reality. They can never perfectly depict all the forces and drivers of changes in an economy. However, the basic model used for this analysis, GTAP, has withstood the test of time and peer review. Hundreds of peer reviewed articles have been published using the GTAP data base and analytical framework. In this project, we have made many changes in the model and data base to improve its usefulness for evaluating the land use change impacts of large scale biofuels programs. Yet, uncertainties remain. In this paper, we have described the evolution of the modeling and analysis and present openly the evolution of the results. Like other GTAP model versions, once it has been subjected to peer review, this model version will be available to others in the GTAP community to use in their analyses. We believe quite strongly that analysis of this type must be done with models and data bases that are available to others. Replicability and innovation are critical factors for progress in science. They also are important for credibility in policy analysis.

Some of the important topics for future research are as follows:

- More sensitivity on prospective growth in crop demand and supply by region and AEZ. The future growth in demand and supply of agricultural commodities, particularly coarse grains, are critical determinants of the impacts of biofuel programs. If global income and population growth and dietary transition lead to greater growth in demand for coarse grains than in supply, the impacts of biofuels mandates would be greater. On the other hand, if new technologies and broader adoption of these technologies lead to greater growth in supply, then the impacts of biofuels mandates would be reduced.
- Research is needed on the impacts on food and feed systems induced by biofuels under real world conditions of weather variability. Under binding mandates such as the

Renewable Fuel Standard, demand is quite inelastic, which would lead to greater commodity price variability in the event of weather shocks such as drought.

- Improved data and information on land use and land cover change could be used in the future to improve model parameters and perhaps the model structure. We are certainly open to considering new information in this domain in the future.
- In this version of the model, substantial improvements in modeling and parameters for livestock production and use of feedstuffs including DDGS have been made. Nonetheless, as the markets evolve we will learn more about the functioning of these markets as feed users adapt to the new animal feeding realities.
- In general, we will need to update the model in many ways as new versions of the GTAP data base are released. This is an on-going process for GTAP. The new version of the GTAP data base is version 7, so constant quality improvement has been part of business as usual since the launch of GTAP in 1994.
- In this research we relied on Woods Hole data set to derive land use carbon emissions. This data set provides limited information on forgone carbon sequestration due to deforestation. This is a major deficiency. We have developed a set of land use emissions using the TEM model at the AEZ for all GTAP regions. However, they have not yet been verified and subjected to peer review, so they are not used in this analysis.

Our primary focus now is to incorporate cellulosic feedstocks into GTAP and to find better ways of getting greater sub-regional specificity in our analysis. We are now working with partners, including Argonne, to accomplish these objectives.

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Appendix A

Regional Land Conversion Factors (ETA parameters)
Productivity of new cropland versus productivity of existing cropland

Appendix A: Land Conversion Factors

In the GTAP-BIO-ADV model the parameter ETA, which shows productivity of new cropland versus productivity of exiting cropland, plays an important role in determining the land use impacts of biofuel production. In our past simulations for biofuel analyses we usually assumed that ETA=0.66 for all regions across the world. Indeed, with this setup we assumed that productivity of one unit (let say one acre) of new croplands is equal to 2/3 of the productivity of one acre of existing croplands, all across the world. In this report we leave this assumption and we apply regional ETAs at the AEZ level. The regional ETAs are obtained from a process-based biogeochemistry model (Terrestrial Ecosystem Model (TEM)) along with spatially referenced information on climate, elevation, soils, and vegetation land use data. The new regional ETAs are varying across the world and among AEZs. In this appendix, we first explain the role of ETA in the GTAP-BIO-ADV model. Then we briefly introduce the TEM model and its data sources. Finally we explain derivations of the regional ETA parameters along with the results.

Role of ETA in the land use module

As we mentioned above ETA measures the productivity of the new cropland versus the productivity of existing cropland. To avoid confusion we define these two types of land:

Existing cropland: Is defined as a land which has been cultivated and used for crop production in the past. GTAP classifies these lands under the title of crop cover.

New cropland: Is defined as natural land (could be either forest or pasture land) that will be converted to cropland due to the need for expansion in the demand for crops.

We now use an example to explain the role of ETA in the GTAP-BIO-ADV model. Suppose that we want to expand production of corn in region *A* by 600 bushels and also suppose that this region only produces corn. In addition, suppose that the corn yield of the existing cropland is about 150 bushels/acre. So the question is how much land we need to produce 600 more bushels of corn? The answer is that it depends on the productivity of land that we want to bring into crop production. Suppose that region *A* has a piece of forest which can be converted to crop production and that ETA=2/3=0.66. With these assumptions the GTAP-BIO-ADV model will calculate that in region *A* we need 6 acres of land to meet the target. Because it assumes that the yield of the new cropland is about 100 bushels per acre. Now if we assume that ETA=1, (i.e. the productivity of the new and existing cropland are equal) then we need only 4 acres to satisfy the target for corn production. This example highlights the role of ETA in GATP-BIO-ADV model.

In fact, in GTAP we have a solid and reliable database which provides productivity measures for existing croplands for all regions across the world by AEZ. However, we do not have information on the productivity of new cropland, and there are large uncertainties in predicting future productivity of existing cropland in different parts of the world. So far we used parameter ETA=0.66, based on empirical evidence from US land use and consulting experts on the productivity of the new cropland. In this report we use the TEM model along with spatially referenced information on climate, elevation, soils, and vegetation land use data to determine productivity of new cropland versus the existing cropland at the AEZ level in each region. To accomplish this task using the TEM model we calculate the Net Primary Production, as a proxy for productivity, at 0.5^{o} x 0.5^{o} (latitude by longitude) spatial resolution for all grid cells across the world. In this calculation we assume that all grid cells are producing a generic C4 crop. Then we use this information to derive the land conversion factors at the AEZ level for each region of

GTAP. The next section introduces the TEM model and its calculation steps along with the data used in calculating NPPs. Then we discuss the conversion of NPPs to the land conversion factor.

TEM model

We use a process-based biogeochemistry model, the TEM (Zhuang et al., 2003) to estimate NPP for each 0.5^o x 0.5^o (longitude and latitude) of the global terrestrial ecosystems. TEM uses spatially referenced information on climate, elevation, soils, and vegetation to make monthly estimates of C and N fluxes and pool sizes of the terrestrial biosphere. In TEM, the net ecosystem exchange of CO_2 between the land ecosystems and atmosphere is calculated as the difference between the uptake of atmospheric CO_2 associated with photosynthesis (i.e., gross primary production or GPP) and the release of CO_2 through autotrophic respiration (R_A), heterotrophic respiration (R_H) associated with decomposition of organic matter. The fluxes GPP, R_A and R_H are influenced by changes in atmospheric CO_2, climate variability and change, and the freeze-thaw status of the soil. The following figure represents this model and its major components.

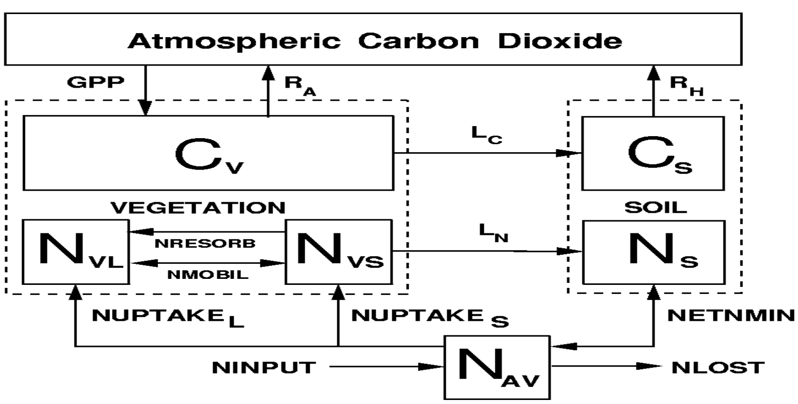

Figure A1. The Terrestrial Ecosystem Model

The model has been extensively used to evaluate C dynamics in northern high latitudes and the globe (e.g., Euskirchen *et al* 2006, Balshi *et al* 2007; Zhuang et al., 2003; Melillo et al., 1993; McGuire et al., 2001). Its structure, algorithm, parameterization, calibration and performance have been well documented.

Parameters in TEM may be specific to different vegetation types, specific to different soil textures, or constant for all vegetation types and soil textures. Most of the parameters in TEM are assigned values derived from the literature, but some parameters are calibrated to the carbon and nitrogen pools and fluxes of intensively studied sites (see Raich et al., 1991 and McGuire et al., 1992 for details). In this paper the model is calibrated for generic C4 crops. The pools and fluxes of ecosystem carbon and nitrogen of these crop ecosystems are shown in table A1.

Table A1. Carbon and nitrogen pools and fluxes used for a generic parameterization

Variable	**Values* for C4**	**Source and Comments**
C_v	649	Evrendilek[2004]
N_v	9.9	Evrendilek[2004]
C_s	3071.5	Evrendilek[2004]
N_s	307.1	Evrendilek[2004]
N_{av}	2.64	Based on 0.86%, the mean N_{av}:N_s ratio
GPP	649	Evrendilek[2004]
NPP	296.6	Evrendilek[2004]
NPPSAT	296.6	Evrendilek[2004]
NUPTAKE	3.98	Calculated from NPP_n, 75%NPP_n=NUPTAKE.

*Units for annual gross primary production (GPP), net primary production (NPP), and NPPSAT are g C $m^{-2}yr^{-1}$. Units for vegetation C (C_v) and soil C (C_s) are g C m^{-2}. Units for vegetation N (N_v), soil N (N_s), and inorganic N (N_{av}) are g N m^{-2}. Units for annual N uptake by vegetation (NUPTAKE) are g N m^{-2} yr^{-1}.

Input data sets

To apply TEM to make spatially and temporally explicit estimates of ecosystem carbon storage and net primary production in this study, we use the same input data sets as were used in Zhuang et al., (2003). These input data sets are important for directly affecting processes in the model (e.g., the effects of soil temperature on heterotrophic respiration) and for defining the parameters that are specific to vegetation types and soil textures. We use a potential vegetation data set similar to that described in Melillo et al. (1993) to run the model to equilibrium prior to driving the model with transient changes in atmospheric CO_2 and climate. Soil texture and elevation do not vary in our simulations. The transient historical atmospheric CO_2 concentrations are used. The data sets describing historical changes in monthly air temperature and precipitation are gridded at 0.5^o x 0.5^o spatial resolution for our simulations (Zhuang et al., 2003).

Global simulations

To run TEM for the globe, we use the data of atmosphere, vegetation, soil texture, and elevation at 0.5° latitude x 0.5° longitude resolution from 1900 to 2000. For the simulations of C4 crops, we assume that each grid cell was replaced with the generic C4 crop and keep the information of soils, elevation and climate as the same as the simulation for natural ecosystems. For each grid cell, we first run TEM to equilibrium for an undisturbed ecosystem using the long-term averaged monthly climate and CO_2 concentrations from 1900 to 2000. We then run the model for 150 years with the climate from 1900 to 1949 to account for the influence of inter-annual climate variability on the initial conditions of the undisturbed ecosystem. We then run the model with transient monthly climate data from 1900 to 2000. The simulated NPP for C4 crop simulations of the year 2000 are used for this analysis.

Using NPP data to obtain ETA

We use the NPP data as a proxy for yield to calculate the regional land conversion factors by AEZ. In this process first we matched the results from TEM with our land database to assign AEZs to all grid cells across the world. Then we imposed several restrictions to drop lands which are not good for crop production. In particular, we dropped the grid cells with the following types of land cover:

- ALPINE_TUNDRA_&_POLAR_DESERT
- FORESTED_BOREAL_WETLANDS
- NON-FORESTED_BOREAL_WETLANDS
- TEMPERATE_FORESTED_WETLANDS
- XERIC_SHRUBLANDS
- TROPICAL_FORESTED_WETLANDS
- DESERTS
- TROPICAL_NON-FORESTED_WETLANDS
- TROPICAL_NON-FORESTED_FLOODPL
- TEMPERATE_NON-FORESTED_WETLAND
- TEMPERATE_FORESTED_FLOODPLAINS
- TEMPERATE_NON-FORESTED_FLOODPL

In addition we dropped all grid cells with cells with median of terrain slopes greater than or equal 5%. We dropped these because they are not appropriate for crop production. Then we used the cleaned database to derive the land conversion factors.

To explain the derivation process first we analyze our data for two sample regions: US AEZ10 and Brazil AEZ4. The following two graphs (figures A2 and A3) represent the shares of available and converted natural grasslands in these two sample areas. In each graph we classified the land into 6 groups of productivities (NPPs). Figure A2 indicates that in this AEZ a big portion of the natural grass land is already converted to crop production. A small amount of grassland is available to be converted to crop production in this AEZ. However, the available land is distributed across all productivity groups. Note that the AEZ10 of the US covers a large area with relatively different land qualities, weather conditions and length of growing periods between 180 to 240 days.

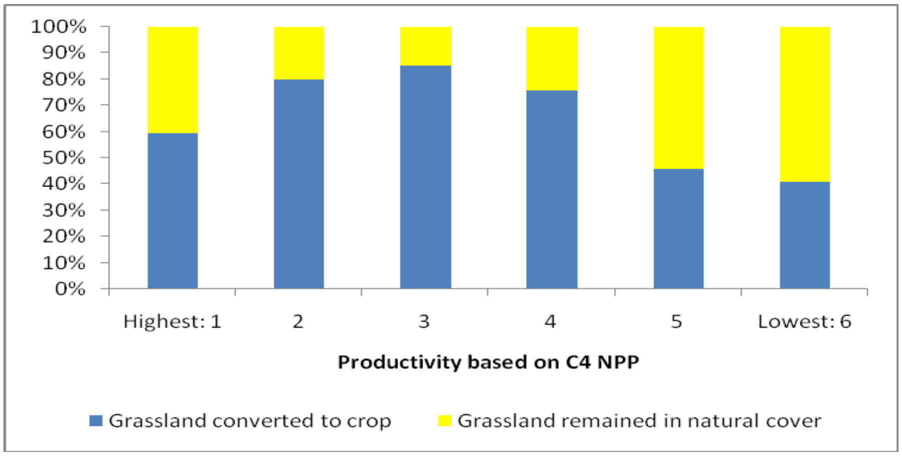

Figure A2. Availability of grassland suitable for crop production in US-AEZ10

Now consider figure A3 which indicates that in the Brazil AEZ4 there are lots of grassland remained in natural cover and only a small portion of grassland in this AEZ has been converted to crop production. In this AEZ available land is distributed across all productivity groups as well.

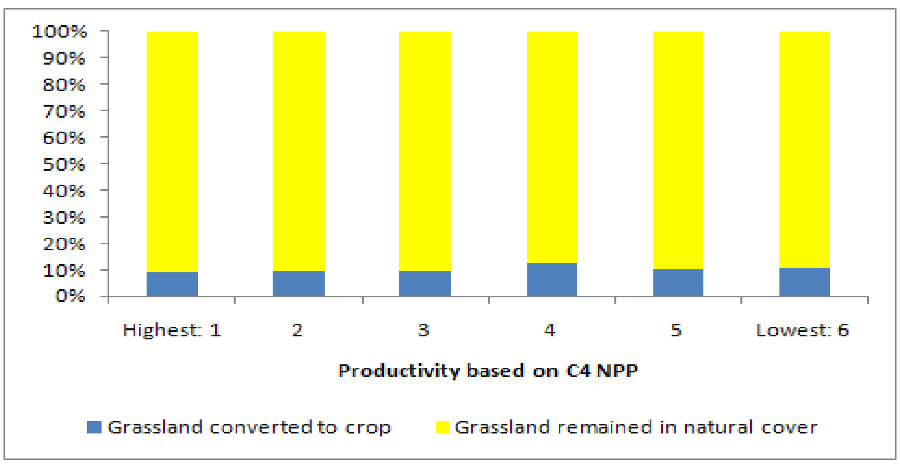

Figure A3. Availability of grassland suitable for crop production in Brazil-AEZ4

Now consider another aspect of the NPP data in these two AEZs. Figure A4 compares the average productivity of grassland converted to crop production in the past with the productivities of all grassland parcels that remained in natural cover in US AEZ10. In this figure grid cells are sorted according to their productivity. So when we move from left side to the right side of the horizontal axis, we move from grid cells with higher productivities to the grid cells with lower productivities.

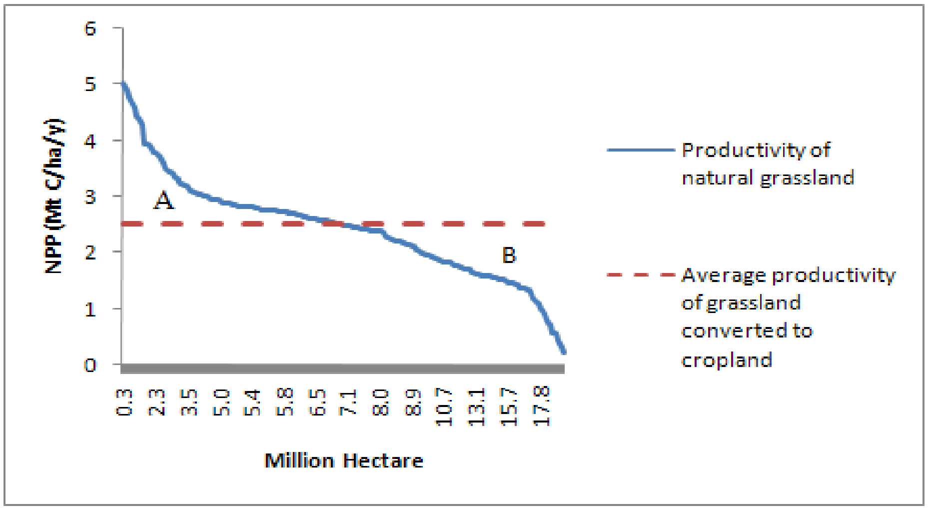

Figure A4. Average and marginal productivities in US AEZ10 for grassland

The ratio of the area A in this graph (area below the productivity of grassland curve and above the average productivity of grassland converted to cropland horizontal line) over the area B (area above the blue curve and below the red line) provides us a land conversion factor for this type of land in this AEZ. All of the land pixels in area A represent pixels with productivity (for C4) higher than the average productivity of existing cropland (the straight line). All of the pixels in B have productivity less than the average cropland. So area A over area B shows average productivity of new land versus average productivity of existing cropland. The assumption then is that the marginal unit of land has this productivity. Figure A5 provides the same information for Brazil AEZ4.

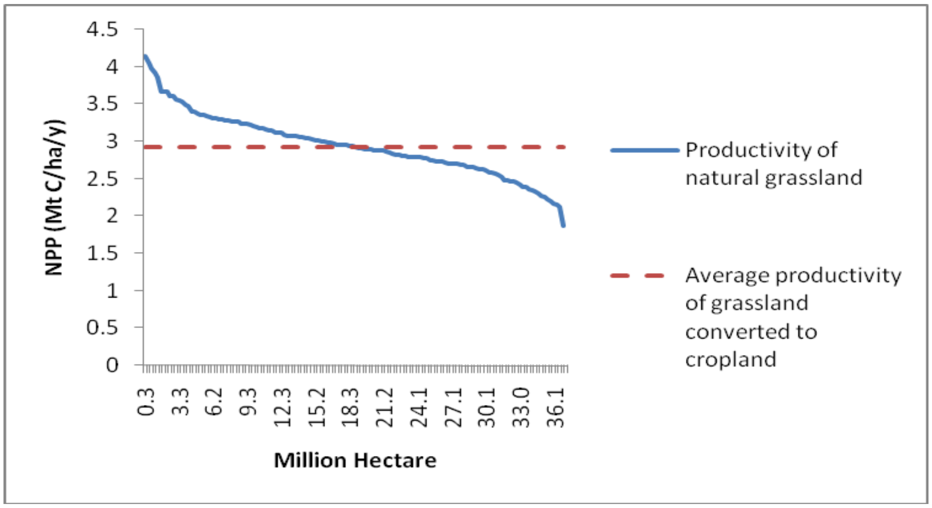

Figure A5. Average and marginal productivities in Brazil AEZ4 for grassland

While we are able to derive the conversion factors for all types of land cover we pooled all land types in each AEZ in each region and we defined the geographical land conversion factors at the AEZ level. It is important to point out that the model does not take into account irrigation. However, in real world in some areas lands are under crop production with irrigation. For this reason we dropped the productivity of all natural land by 10% and we assumed no land conversion factor greater than 1. The results of these calculations are shown in table A2. In this table zero means no land is available and 1 shows that the marginal and average productivities are equal. Table A2 indicates that the US land conversion factors range from 0.51 to 1, depending on the AEZ. Our earlier value for the land conversion factor (i.e. ETA=0.66) falls within this range. However, Table A2 shows that the Brazil land conversion factors range from 0.89 to 1, and most of them are around 0.9. This means that our earlier land conversion factor was underestimating the marginal productivity of land in Brazil. While we apply these land conversion factors in this report we will continue to improve our results in the future.

Table A2. Regional land conversion factors obtained from NPP data for a generic C4 crop[1]

AEZ[2]\Region[3]	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19
1	0.00	0.00	0.91	0.00	0.00	0.00	0.93	1.00	0.95	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.68	0.61	1.00
2	0.00	0.00	0.92	0.00	0.00	0.00	0.89	1.00	0.81	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.59	1.00	1.00
3	0.00	0.00	0.93	0.00	0.00	0.00	0.86	1.00	0.90	0.00	0.00	0.00	1.00	0.00	0.00	0.00	1.00	0.89	0.74
4	0.00	1.00	0.89	0.00	0.00	1.00	0.93	1.00	0.88	0.00	0.88	0.89	1.00	0.00	0.00	0.00	0.86	0.92	0.92
5	0.00	0.00	0.93	0.00	0.00	0.90	0.98	0.88	0.90	0.00	0.90	0.91	0.98	0.00	0.00	0.00	0.00	1.00	0.96
6	0.00	0.00	0.91	0.00	0.00	0.88	0.98	0.97	0.85	0.00	0.88	0.95	0.78	0.00	0.00	0.00	0.00	1.00	0.88
7	0.73	0.00	0.00	0.89	0.00	0.80	0.90	0.59	1.00	1.00	0.00	0.00	0.43	1.00	0.98	0.00	0.46	0.80	0.65
8	0.71	0.90	0.00	0.91	0.00	1.00	0.71	0.72	0.90	1.00	0.00	0.00	0.60	0.84	0.84	0.00	0.71	0.79	0.86
9	1.00	1.00	0.00	0.85	1.00	0.98	0.88	1.00	0.91	1.00	0.00	0.00	1.00	0.94	0.82	0.00	0.77	0.84	0.93
10	0.93	0.96	0.88	0.88	0.96	0.84	1.00	0.89	1.00	0.93	0.00	1.00	0.92	0.89	0.89	0.87	0.98	0.88	0.92
11	0.96	0.83	1.00	1.00	0.94	0.95	0.90	1.00	0.87	0.84	0.00	1.00	0.79	0.89	1.00	0.00	0.00	0.77	0.96
12	0.89	0.86	0.91	0.00	0.95	0.92	0.90	1.00	0.84	0.00	0.00	1.00	1.00	0.00	0.89	0.00	0.00	1.00	0.98
13	0.92	1.00	0.00	0.55	0.00	1.00	1.00	0.00	1.00	1.00	0.00	0.00	1.00	0.63	0.97	0.00	0.00	0.00	0.00
14	0.51	0.89	0.00	0.80	0.00	0.92	1.00	0.00	1.00	1.00	0.00	0.00	1.00	0.90	1.00	0.95	0.00	0.00	0.00
15	0.71	0.90	0.00	0.83	1.00	1.00	1.00	0.00	0.64	1.00	0.00	1.00	1.00	0.90	1.00	0.87	0.00	0.00	1.00
16	1.00	0.89	0.00	1.00	0.00	1.00	1.00	0.00	0.92	0.00	0.00	1.00	1.00	0.85	1.00	1.00	0.00	0.00	1.00
17	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

1 In this table zero means no land is available and 1 means that the marginal and average productivities are equal.
2 Rows are AEZs from AEZ1 to AEZ18.
3 Columns are regions and regions are listed in Appendix B.

Appendix B
Lists of Commodities, Industries, and Regions

Table B 1. 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
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
EthanolC	Ethanol1	Ethanol produced from grains	
	DDGS	Dried Distillers Grains with Solubles	
Ethanol2	Ethanol2	Ethanol produced from sugarcane	
Biodiesel	Biodiesel	Biodiesel produced from vegetable oil	

Table B 2. 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

Appendix C
Land Use Changes Due to Ethanol Production

Table C1. Global land use changes due to US ethanol production: Off of 2001 database (1000 hectares)

Region	2001-2006			2006-2007			2007-2009			2009-2011			2011-2013			2013-2015		
	F	C	P	F	C	P	F	C	P	F	C	P	F	C	P	F	C	P
USA	-111	228	-117	-79	163	-84	-74	153	-79	-74	154	-80	-75	155	-80	-75	155	-80
EU27	-33	52	-19	-28	43	-15	-28	43	-15	-30	45	-15	-31	47	-16	-33	49	-17
BRAZIL	-24	35	-11	-20	28	-9	-19	28	-8	-20	29	-9	-21	30	-9	-21	31	-10
CAN	-38	64	-26	-28	47	-19	-27	46	-19	-28	48	-20	-30	51	-21	-31	53	-22
JAPAN	-1	1	0	-1	1	0	-1	1	0	-1	1	0	-1	1	0	-1	1	0
CHIHKG	11	7	-18	9	5	-14	9	5	-14	10	5	-15	10	6	-16	11	6	-17
INDIA	-4	9	-5	-4	8	-4	-4	8	-5	-4	9	-5	-4	10	-5	-5	10	-6
C_C_Amer	-4	12	-8	-3	10	-7	-2	10	-7	-2	10	-8	-2	11	-9	-2	12	-9
S_o_Amer	18	21	-39	13	16	-29	12	16	-28	12	17	-29	13	17	-30	13	18	-31
E_Asia	2	0	-2	1	0	-2	1	0	-1	1	0	-2	1	0	-2	2	0	-2
Mala_Indo	2	-1	-1	1	0	-1	1	0	-1	1	0	-1	1	0	-1	1	0	-1
R_SE_Asia	1	0	-1	1	0	-1	1	0	-1	1	0	-1	1	0	-1	1	0	-1
R_S_Asia	-1	4	-3	-1	4	-3	-1	4	-3	-1	4	-3	-1	4	-3	-1	4	-3
Russia	51	-3	-49	35	-2	-34	33	-1	-32	34	-1	-33	35	-1	-33	35	-1	-34
Oth_CEE_CIS	-2	26	-25	-1	20	-19	-1	20	-19	-1	21	-20	-1	21	-20	-1	22	-21
Oth_Europe	0	1	0	0	1	0	0	1	0	0	1	0	0	1	0	0	1	0
MEAS_NAfr	0	18	-18	0	15	-15	0	15	-15	0	15	-15	0	16	-16	0	17	-17
S_S_AFR	-11	115	-104	-12	89	-77	-13	88	-75	-14	92	-78	-16	97	-81	-17	101	-84
Oceania	0	19	-18	0	14	-14	0	14	-13	0	14	-14	0	15	-14	0	15	-15
TOTAL	-144	610	-467	-114	460	-346	-112	448	-336	-117	465	-348	-121	480	-360	-124	495	-371

F, C, and P are stand for Forest, Cropland, and Pastureland, respectively

Table C2. Global land use changes due to US ethanol production: Off of 2006 updated database (1000 hectares)

Region	2001-2006			2006-2007			2007-2009			2009-2011			2011-2013			2013-2015		
	F	C	P	F	C	P	F	C	P	F	C	P	F	C	P	F	C	P
USA	-68	107	-39	-41	78	-37	-37	73	-36	-37	74	-37	-37	75	-37	-38	76	-38
EU27	-38	45	-7	-19	25	-6	-18	24	-6	-19	24	-6	-19	25	-6	-20	25	-6
BRAZIL	-36	24	12	-20	15	5	-18	14	3	-17	15	3	-17	15	2	-17	15	2
CAN	-7	20	-13	-9	12	-3	-8	11	-3	-8	11	-3	-8	12	-4	-8	12	-4
JAPAN	-1	1	0	0	1	0	0	1	0	0	1	0	0	1	0	0	1	0
CHIHKG	12	3	-16	-6	17	-11	-4	15	-11	-4	15	-11	-3	15	-12	-3	15	-12
INDIA	-9	21	-12	-9	14	-5	-8	14	-6	-8	14	-6	-9	15	-6	-9	15	-6
C_C_Amer	-11	21	-10	-3	10	-8	-2	10	-7	-2	10	-8	-2	10	-8	-2	10	-8
S_o_Amer	14	21	-35	4	16	-20	3	15	-18	3	15	-18	2	16	-18	2	16	-18
E_Asia	2	1	-4	1	1	-2	1	1	-2	1	1	-2	1	1	-2	1	1	-2
Mala_Indo	-4	6	-2	-7	7	-1	-6	7	-1	-6	7	-1	-6	7	-1	-6	7	-1
R_SE_Asia	-3	4	-1	-5	5	0	-5	4	0	-4	4	0	-4	4	0	-4	4	0
R_S_Asia	-3	15	-11	-3	10	-7	-2	9	-7	-2	9	-7	-2	9	-7	-3	10	-7
Russia	17	18	-35	14	14	-28	11	13	-25	11	13	-24	10	13	-23	10	13	-23
Oth_CEE_CIS	-13	70	-57	-11	26	-15	-10	25	-15	-10	25	-15	-10	26	-16	-10	27	-17
Oth_Europe	-1	1	0	0	1	0	0	1	0	0	1	0	0	1	0	0	1	0
MEAS_NAfr	0	16	-16	0	8	-8	0	7	-8	0	7	-8	0	8	-8	0	8	-8
S_S_AFR	-4	58	-54	9	54	-63	7	51	-58	5	51	-56	5	52	-56	4	52	-56
Oceania	0	15	-15	-1	11	-10	-1	10	-10	-1	10	-10	-1	10	-10	-1	10	-10
TOTAL	-152	467	-315	-105	324	-219	-100	307	-207	-100	308	-208	-102	313	-211	-103	318	-215

F, C, and P are stand for Forest, Cropland, and Pastureland, respectively

Table C3. Global land use changes due to US ethanol production: Off of 2006 updated database with yield and population growth after 2006 (1000 hectares)

Region	2001-2006			2006-2007			2007-2009			2009-2011			2011-2013			2013-2015		
	F	C	P	F	C	P	F	C	P	F	C	P	F	C	P	F	C	P
USA	-68	107	-39	-37	58	-22	-34	58	-24	-34	61	-27	-35	65	-30	-38	71	-32
EU27	-38	45	-7	-43	35	7	-50	44	7	-62	57	5	-74	72	2	-87	90	-3
BRAZIL	-36	24	12	-32	15	17	-26	17	9	-25	20	6	-24	22	2	-25	24	1
CAN	-7	20	-13	-1	10	-9	-1	10	-9	0	10	-10	2	10	-12	4	10	-14
JAPAN	-1	1	0	-1	1	0	-1	1	0	-1	1	0	-2	2	0	-2	2	0
CHIHKG	12	3	-16	-5	-6	11	-6	-9	15	-5	-15	20	-2	-20	21	4	-25	21
INDIA	-9	21	-12	25	-23	-2	35	-37	2	48	-54	6	56	-65	10	65	-77	12
C_C_Amer	-11	21	-10	-10	14	-4	-10	15	-5	-12	17	-5	-15	20	-5	-18	22	-4
S_o_Amer	14	21	-35	3	13	-16	3	12	-16	5	12	-17	8	11	-19	11	10	-22
E_Asia	2	1	-4	1	1	-2	1	1	-2	1	0	-2	1	0	-2	1	0	-2
Mala_Indo	-4	6	-2	0	1	0	2	-2	0	6	-5	-1	10	-9	-1	13	-12	-1
R_SE_Asia	-3	4	-1	-2	1	1	0	0	0	3	-3	-1	6	-5	-1	9	-7	-1
R_S_Asia	-3	15	-11	0	2	-1	0	-1	0	2	-4	2	4	-8	4	8	-14	5
Russia	17	18	-35	37	6	-43	35	4	-39	38	1	-39	41	-1	-40	44	-4	-40
Oth_CEE_CIS	-13	70	-57	-21	58	-37	-31	81	-50	-46	115	-70	-59	147	-88	-70	169	-100
Oth_Europe	-1	1	0	-1	1	0	-1	1	0	-1	1	0	0	1	0	0	1	0
MEAS_NAfr	0	16	-16	1	3	-4	1	3	-3	1	1	-2	1	0	-1	1	-2	1
S_S_AFR	-4	58	-54	11	39	-50	7	34	-41	3	27	-30	-4	22	-18	-11	19	-7
Oceania	0	15	-15	-1	6	-4	-1	4	-3	-1	3	-2	0	2	-2	0	0	-1
TOTAL	-152	467	-315	-76	233	-158	-76	235	-159	-80	246	-166	-86	265	-179	-90	277	-187

F, C, and P are stand for Forest, Cropland, and Pastureland, respectively

Appendix D
Experiments Used in Simulations

Introduction

In this appendix first we briefly explain few basic concepts that we use in defining an experiment in GTAP for non professional readers. Then we introduce experiments which we defined for the simulations we introduced in this paper. As we mentioned earlier, GTAP is a computable general equilibrium (CGE) model. This model consists of equations, identities, a database, a set of parameters or elasticities, and several types of variables. Variables in this model are either endogenous (determined within the model) or exogenous (determined outside the model). For example, in GTAP population and tax rates are exogenous variables, but the household demands for goods and services are endogenous variables. The values of the exogenous variables are given to the model but the system determines the values of the endogenous variables using the equations defined in the model.

In GTAP, an experiment consists of a set of commands that guide the system to move the world economy from an existing equilibrium condition to a new equilibrium. The experiment could be simple or complicated. For example, here we introduce two simple experiments.

Suppose that you would like to examine consequences of a 2% increase in the US population for the world economy, assuming no changes in other exogenous variables. For this simple experiment since population is an exogenous variable, we can directly increase (or shock) it by 2% and ask the system to determine consequences of this increase for the world economy. This experiment is simply can be defined by the following command:

Shock pop(“US”) = 2;

The system starts with the initial equilibrium condition for the world economy (base data), numerically calculates impacts of this shock on the endogenous variables through the equations of the model, and determines a new equilibrium for the world economy.

Now look at another simple experiment. In this experiment we would like to examine impacts of 2% increase in the US demand for meat, while we assume no changes in other exogenous variables. In this case, since the demand for meat is an endogenous variable we cannot directly shock it. Instead, we should shock an exogenous variable which could affect the demand for meat. In this case subsidy is an appropriate exogenous variable. The subsidy on meat consumption could encourage consumers to buy more meat. Now the question is: How much subsidy should be paid to induce the desired increase in the demand for meat? We do not need to answer this question. The system can answer the question through the following swap and shock:

Swap qpd(“meat”, “US”) = tpd(“meat”, “US”);

Shock qpd(“meat”, “US”) = 2;

Here *qpd* and *tpd* represent percentage changes in the demand for meat and its subsidy/tax rate for the US economy. The first command endogenizes the rate of subsidy on meat for the US economy and exogenizes the US demand for this commodity. The second command shocks the US demand for meat, which is now an exogenous variable. The system starts with the initial equilibrium, uses the equations of the system, increases the US subsidy rate on meat to reach 2% increase in the US private demand for meat, and determines a new equilibrium for the world economy through the simulation process. With this introduction we now present the experiments that we used in our simulations. In what follows we present only the main swaps and shocks that derive the results, and we do not present those which we used to fix data problems or avoid minor technical issues.

Experiments of Group 1: Simulations with no economic and yield growth and 2001 base

The experiments used for this group of simulations contain simple shocks and swaps. For the first time period (i.e. 2001-2006) we used the following experiment:

To fix the CRP land of the US

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") = 174.29379;*

Here the swap endogenizes subsidy on ethanol consumption and exogenizes ethanol production and then the shock boosts ethanol production according to its expansion for the time period of 2001-2006 (i.e. 174.3%).

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");*

Then we repeated the same experiment for other time slices with appropriate percentage changes in ethanol production.

Experiments of Group 2: Simulations with updated baseline for the time period of 2001-2006

For the first time period of this group of simulations we used more complicated shocks and swaps.

To control CRP land of the USA

Swap tf(AEZ_COMM,"Oth_Ind_Se","USA")=qoes(AEZ_COMM,"Oth_Ind_Se","USA");

This swap controls changes in the US CRP land.

To simulate biofuel economy

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

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;

Swap qo("ethanol1","USA") = tpd("ethanol1","USA");

Swap tms("ethanol2","Brazil","USA") = qxs("ethanol2","Brazil","USA");

Swap qo("biodiesel","USA") = tpd("biodiesel","USA");

Swap qo("ethanol1","EU27") = tpd("ethanol1","EU27");

Swap qo("biodiesel","EU27") = tpd("biodiesel","EU27");

Swap qo("ethanol2","Brazil") = tpd("ethanol2" ,"Brazil");

Shock qo("ethanol1","USA") = 174.29;

Shock qxs("ethanol2","Brazil","USA") = 591.8636;

Shock qo("biodiesel","USA") = 2823.3992;

Shock qo("ethanol1","EU27") = 223.308;

Shock qo("biodiesel","EU27") = 409.5644;

Shock qo("ethanol2","Brazil") = 25.616;

These swaps and shocks jointly introduce changes in the crude oil price and define the US, EU, and Brazil biofuel performances and their supporting policies in this area for the time period of 2001-2006.

To shock population

Shock POP(REG) = file default.prm header "PO16";

This shock reads the regional population growth rates for the time period of 2001-2006 from the parameter file of the system and introduces them to the model.

To shock GDP

Swap afereg(REG) = qgdp(REG);

Shock qgdp(REG) = file default.prm header "IN16";

This shock and swap read percentage changes in the regional GDPs for the time period of 2001-2006 from the parameter file of the system and introduces them to the model.

To shock skilled and unskilled labor

Shock qo("sklab",REG)= file default.prm header "LS16";

Shock qo("Unsklab",REG)=file default.prm header "LU16";

Supplies of skilled and unskilled labor are two important endowments in GTAP. These shocks read percentage changes in labor force for the time period of 2001-2006 from the parameter file of the system and introduce them to the labor market of each region. The GTAP-BIO does not consider labor movement across regions, meaning that there is no migration.

To shock capital stock

Shock qo("Capital",REG)=file default.prm header "CA16";

Capital stock is a major deriver of economic growth. Unlike the GTAP dynamic, capital stock is an exogenous endowment in the GTAP static model. The above shock introduces changes in the regional capital stocks during the time period of 2001-2006 to the system.

To introduce technological progress

Shock aoall(ALL_INDS,REG) = file default.prm header "PRNE";

Technological progress is another source for economic growth. The above shock introduces technological progress in all industries except for crop industries. Note that the header PRNE contains zero values for crop sectors. The next commands define the technological progress for crop industries. Note that values for technological progress are obtained based on Hertel, Ludena, and Golub (2009) for non-agricultural industries and service.

To shock crop yields

Swap p_YIELD(CROP_INDS,REG) = afall("land",CROP_INDS,REG);

Shock p_YIELD(CROP_INDS,REG) = file default.prm header "YD16";

In GTAP-BIO-ADV crop yields are endogenous variables and they respond to the prices of crops. In this simulation, we use the above swap to make them exogenous. Then we shock them to simulate the historical observation on yield growth for the time period of 2001-2006.

To control forest and pasture land prices

Swap aosec("forestry") = pxwcom("forestry");

Shock pxwcom("forestry") = 21;

Shock aosec("Dairy_Farms")=1;

Shock aosec("Ruminant")=1;

These commands define technological progress for forestry, ruminant, and non ruminant industries according to the observed changes in the world price index of forestry product (21%) during the time period of 2001-2006. It is also necessary to introduce the technology shocks for the dairy and ruminant industries in order to reproduce changes in forest areas.

Finally, for the time slices after 2006 we followed the simple experiments that we introduced for the first group of simulations.

Experiments of Group 3: Simulations with crop yield and population growth for the time period of 2006-20015

The experiment used for the first time slice of this group is similar to the first experiment of the second group of simulations. For the rest of time slices we just shocked population and yield according the assumptions we explained in the text along with shocks for ethanol production.

Appendix E

Woods Hole land use CO_2 emission data set

Definitions:

We used the same Woods Hole emissions data that was used in the Searchinger, et al. paper (2008). The specific source for that data is not given in the paper, but Richard Haughton, one of the authors, is affiliated with Woods Hole.

In this appendix we used the following abbreviations:

FAE_MH: Forest area by ecosystem in million hectares

FAE%: Forest area by ecosystem in percent

CINV_MT/H: Carbon in vegetation in metric ton per hectare

CINS_MT/H: Carbon in soil in metric ton per hectare

DCEFLC_MT/H: Direct carbon emissions from land conversion in metric tons per ha

RGFA_MH: Re-growing forest area in million hectares

GCUBRGF_MMTC/yr: Gross carbon uptake by re-growing forests in million metric tons carbon per year

CUBF_MTC/H/yr: Carbon uptake by forest area in metric ton carbon per hectare per year

FCS30 _MTC/H: Foregone Carbon Sequestration in 30 years in metric ton per hectare

WACE_MT/H: Weighted average carbon emissions in metric ton per hectare

WACO2E_MT/H: Weighted average CO2 emissions in metric ton per hectare

Table C 1. Woods Hole Land use CO_2 emission data-United States

Description	Broad leaf forest	Mixed forest	Wood land	Coniferous / Mountain Forest	Coniferous Pacific Forest	Chaparral	Total Forest	Grassland	Total Grassland
FAE_MH	54.60	88.20	38.50	24.10	29.20	6.20	240.80	0.00	
FAE%	22.67	36.63	15.99	10.01	12.13	2.57	100.00	0.00	0.00
CINV_MT/H	150.00	170.00	90.00	150.00	200.00	40.00		10.00	
CINS_MT/H	150.00	160.00	90.00	100.00	160.00	80.00		80.00	
25% of CINS_MT/H	37.50	40.00	22.50	25.00	40.00	20.00		20.00	
DCEFLC_MTH	150.00	167.50	90.00	137.50	190.00	50.00		30.00	
RGFA_MH	38.00	47.00	47.00	1.00	15.00	0.00		0.00	
GCUBRGF_MMTC/yr	-34.70	-36.40	-2.10	0.00	-23.60	0.00		0.00	
CUBF_MTC/H/yr	-0.64	-0.41	-0.05	0.00	-0.81	0.00			
FCS30 _MTC/H	19.07	12.38	1.64	0.00	24.25	0.00		0.00	
WACE_MT/H	38.33	65.89	14.65	13.76	25.98	1.29	159.90	30.00	30.00
WACO2E_MT/H	140.69	241.80	53.77	50.50	95.35	4.72	586.84	110.10	110.10

Table C 2. Woods Hole Land use CO_2 emission data- North Africa and Middle East

Description	Temperate Evergreen Forest	Tropical Moist Forest	Tropical Woodland	Total Forest	Tropical Grassland	Desert Scrub	Total Grassland
FAE_MH	6.80	2.10	18.50	27.40	44.20	793.10	837.30
FAE%	24.82	7.66	67.52	100.00	5.28	94.72	100.00
CINV_MT/H	160.00	200.00	27.00		18.00	3.00	
CINS_MT/H	134.00	117.00	69.00		42.00	58.00	
25% of CINS_MT/H	33.50	29.25	17.25		10.50	14.50	
DCEFLC_MTH	153.50	179.25	37.50		28.50	17.50	
RGFA_MH	5.00	1.40	0.00		0.00	0.00	
GCUBRGF_MMTC/yr	-14.50	-6.10	0.00		0.00	0.00	
CUBF_MTC/H/yr	-2.13	-2.90	0.00		0.00	0.00	
FCS30 _MTC/H	63.97	87.14	0.00		0.00	0.00	
WACE_MT/H	53.97	20.42	25.32	99.71	1.50	16.58	18.08
WACO2E_MT/H	198.07	74.93	92.92	365.93	5.52	60.83	66.36

Table C 3. Woods Hole Land use CO_2 emission data- Canada

Description	Temperate Evergreen Forest	Temperate Deciduous Forest	Boreal Forest	Total Forest	Temperate Grassland	Tundra	Total Grassland
FAE_MH	37.30	46.10	461.00	544.40	10.90	322.70	333.60
FAE%	6.85	8.47	84.68	100.00	3.27	96.73	100.00
CINV_MT/H	160.00	135.00	90.00		7.00	5.00	0.00
CINS_MT/H	134.00	134.00	206.00		189.00	165.00	0.00
25% of CINS_MT/H	33.50	33.50	51.50		47.25	41.25	0.00
DCEFLC_MTH	153.50	134.75	119.00		54.25	46.25	0.00
RGFA_MH	7.80	1.70	13.00		0.00	0.00	0.00
GCUBRGF_MMTC/yr	-18.50	-3.00	-17.70		0.00	0.00	0.00
CUBF_MTC/H/yr	-0.50	-0.07	-0.04		0.00	0.00	0.00
FCS30 _MTC/H	14.88	1.95	1.15		0.00	0.00	0.00
WACE_MT/H	11.54	11.58	101.75	124.86	1.77	44.74	46.51
WACO2E_MT/H	42.34	42.48	373.40	458.23	6.51	164.19	170.70

Table C 4. Woods Hole Land use CO_2 emission data-Latin America

Description	Tropical Evergreen Forest	Tropical Seasonal Forest	Tropical Open Forest	Temperate Evergreen Forest	Temperate Seasonal Forest	Total Forest	Grassland	Desert	Total Grassland
FAE_MH	296.30	537.30	252.50	53.60	55.40	1195.10	6.90	30.70	
FAE%	24.79	44.96	21.13	4.48	4.64	100.00	18.35	81.65	0.00
CINV_MT/H	200.00	140.00	55.00	168.00	100.00		10.00	6.00	
CINS_MT/H	98.00	98.00	69.00	134.00	134.00		42.00	58.00	
25% of CINS_MT/H	24.50	24.50	17.25	33.50	33.50		10.50	14.50	
DCEFLC_MTH	174.50	129.50	58.50	159.50	108.50		20.50	20.50	
RGFA_MH	0.00	45.60	0.00	14.68	0.00		0.00	0.00	
GCUBRGF_MMTC/yr	0.00	-164.20	0.00	-48.90	0.00		0.00	0.00	
CUBF_MTC/H/yr	0.00	-0.31	0.00	-0.91	0.00		0.00	0.00	
FCS30 _MTC/H	0.00	9.17	0.00	27.37	0.00		0.00	0.00	
WACE_MT/H	43.26	62.34	12.36	8.38	5.03	131.38	3.76	16.74	20.50
WACO2E_MT/H	158.78	228.80	45.36	30.76	18.46	482.15	13.81	61.43	75.24

Table C 5. Woods Hole Land use CO_2 emission data-Pacific Developed

Description	Temperate Evergreen Forest	Temperate Deciduous Forest	Tropical Moist Forest	Tropical Woodland	Total Forest	Tropical Grassland
FAE_MH	14.00	14.00	63.60	106.10	197.70	70.50
FAE%	7.08	7.08	32.17	53.67	100.00	0.00
CINV_MT/H	160.00	135.00	200.00	27.00		18.00
CINS_MT/H	134.00	134.00	117.00	69.00		42.00
25% of CINS_MT/H	33.50	33.50	29.25	17.25		10.50
DCEFLC_MTH	153.50	134.75	179.25	37.50		28.50
RGFA_MH	13.90	13.30	1.90	0.00		0.00
GCUBRGF_MMTC/yr	-33.30	-26.50	-6.00	0.00		0.00
CUBF_MTC/H/yr	-2.38	-1.89	-0.09	0.00		0.00
FCS30 _MTC/H	71.36	56.79	2.83	0.00		0.00
WACE_MT/H	15.92	13.56	58.58	20.13	108.19	28.50
WACO2E_MT/H	58.44	49.78	214.97	73.86	397.05	104.60

Table C 6. Woods Hole Land use CO_2 emission data- South and Southeast Asia

Description	Tropical Moist forest	Tropical Seasonal Forest	Open forest	Total Forest	Temperate Grassland*	Total Grassland
FAE_MH	159.40	137.60	44.90	341.90		
FAE%	46.62	40.25	13.13	100.00		
CINV_MT/H	250.00	150.00	60.00	0.00	7.00	
CINS_MT/H	120.00	80.00	50.00	0.00	189.00	
25% of CINS_MT/H	30.00	20.00	12.50	0.00	47.25	
DCEFLC_MTH	217.50	132.50	57.50	0.00	54.25	
RGFA_MH	70.88	52.39	18.43	0.00		
GCUBRGF_MMTC/yr	-171.10	-108.00	-16.00	0.00		
CUBF_MTC/H/yr	-1.07	-0.78	-0.36	0.00		
FCS30 _MTC/H	32.20	23.55	10.69	0.00		
WACE_MT/H	116.42	62.80	8.96	188.17	54.25	54.25
WACO2E_MT/H	427.25	230.48	32.87	690.59	199.10	199.10

***** Figures are belong to China, India, and Pakistan

Table C 7. Woods Hole Land use CO_2 emission data-Africa

Description	Tropical Rain Forest	Tropical Moist Forest	Tropical Dry Forest	Montane Forest	Total Forest	Shrub Land	Total Grassland
FAE_MH	222.00	190.20	200.10	27.70	640.00	47.10	
FAE%	34.69	29.72	31.27	4.33	100.00	100.00	0.00
CINV_MT/H	126.70	60.20	12.60	79.90		4.60	
CINS_MT/H	190.00	115.00	70.00	100.00		30.00	
25% of CINS_MT/H	47.50	28.75	17.50	25.00		7.50	
DCEFLC_MTH	142.53	73.90	26.95	84.93		12.10	
RGFA_MH	21.29	23.73	6.44	0.86		0.67	
GCUBRGF_MMTC/yr	-20.20	-19.90	0.00	0.00		0.00	
CUBF_MTC/H/yr	-0.09	-0.10	0.00	0.00		0.00	
FCS30 _MTC/H	2.73	3.14	0.00	0.00		0.00	
WACE_MT/H	50.39	22.89	8.43	3.68	85.38	12.10	12.10
WACO2E_MT/H	184.91	84.02	30.92	13.49	313.35	44.41	44.41

Table C 8. Woods Hole Land use CO_2 emission data-Europe

Description	Temperate Evergreen Forest	Temperate Deciduous Forest	Boreal Forest	Temperate Woodland	Total Forest	Temperate Grassland	Total Grassland
FAE_MH	71.90	55.50	27.50	45.00	199.90	26.70	
FAE%	35.97	27.76	13.76	22.51	100.00	100.00	0.00
CINV_MT/H	160.00	120.00	90.00	27.00		7.00	
CINS_MT/H	134.00	134.00	206.00	69.00		189.00	
25% of CINS_MT/H	33.50	33.50	51.50	17.25		47.25	
DCEFLC_MTH	153.50	123.50	119.00	37.50		54.25	
RGFA_MH	66.00	43.20	27.20	0.00		0.00	
GCUBRGF_MMTC/yr	-137.50	-80.00	-33.10	0.00		0.00	
CUBF_MTC/H/yr	-1.91	-1.44	-1.20	0.00		0.00	
FCS30 _MTC/H	57.37	43.24	36.11	0.00		0.00	
WACE_MT/H	75.85	46.29	21.34	8.44	151.92	54.25	54.25
WACO2E_MT/H	278.36	169.90	78.31	30.98	557.55	199.10	199.10

Table C 9. Woods Hole Land use CO_2 emission data- Former Soviet Union

Description	Temperate Evergreen Forest	Temperate Deciduous Forest	Boreal Forest	Temperate Woodland	Total Forest	Temperate Grassland	Total Grassland
FAE_MH	88.30	53.60	612.90	186.00	940.80	31.20	
FAE%	9.39	5.70	65.15	19.77	100.00	100.00	0.00
CINV_MT/H	160.00	135.00	90.00	27.00		10.00	
CINS_MT/H	134.00	134.00	206.00	69.00		189.00	
25% of CINS_MT/H	33.50	33.50	51.50	17.25		47.25	
DCEFLC_MTH	153.50	134.75	119.00	37.50		57.25	
RGFA_MH	0.00	0.00	0.00	0.00		0.00	
GCUBRGF_MMTC/yr	-137.50	-80.00	-33.10	0.00		0.00	
CUBF_MTC/H/yr	-1.56	-1.49	-0.05	0.00		0.00	
FCS30 _MTC/H	46.72	44.78	1.62	0.00		0.00	
WACE_MT/H	18.79	10.23	78.58	7.41	115.01	57.25	57.25
WACO2E_MT/H	68.96	37.54	288.39	27.21	422.10	210.11	210.11