

**Land Use Change Carbon Emissions due to US Ethanol Production\***

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## **Introduction**

US ethanol production has increased sharply from 1.7 billion gallons (BGs) in 2001 to over 9 BGs in 2008. According to the Renewable Fuel Standard (RFS) in the US Energy Independence and Security Act of 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 around the world, and the implications of land use changes are complex and controversial. A sizeable ethanol production program has the potential to increase 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 carbon emissions associated with ethanol production and consumption.

Argonne National Laboratory (ANL) (Wang 1999 and 2005) has developed a life cycle model (GREET) which estimates the carbon emissions of corn ethanol production. The GREET model classifies carbon 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 no calculation of emissions from land use changes due to biofuel production included in the GREET model. The land use emissions due to biofuel production were highlighted in the literature more recently (Searchinger et al. 2008<sup>1</sup> and Fargione et al. 2008). This paper aims to evaluate carbon emissions due to the global land use changes induced by US corn ethanol production. 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

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<sup>1</sup> We will henceforth refer to this paper as SEA

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. 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 (2008) to evaluate impacts of biofuel production for the global livestock industry.

The second component consists of two spreadsheet modules which convert land use changes estimated in GTAP to the associated carbon emissions. These modules generate carbon emissions factors which we use to convert land use changes into carbon emissions. The modules calculate two distinct sets for emissions factors using two independent data sets. These are Woods Hole Research Center and IPCC data sets on the soil and land cover carbon profiles. The Woods Hole data set divides the whole world into 10 regions and provides data on the soil and land cover carbon profiles for each region. The IPCC data set which we use in this paper provides data at a global scale with no geographic distribution.

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. It must be emphasized that the numerical results included here are subject to revisions. We are constantly improving various aspects of the GTAP model and database, so we expect the results to evolve as this work progresses. Rather than

using the terms direct and indirect emissions, as is commonly done, 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.

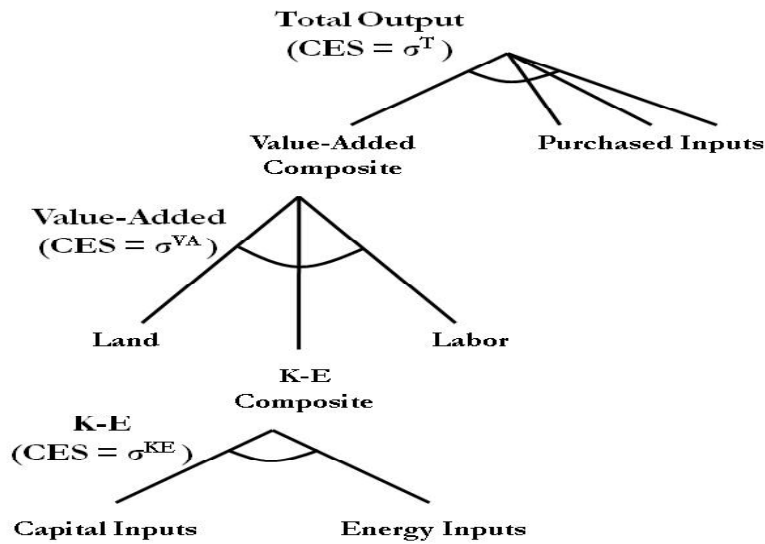
The rest of this paper is organized as follows. We first introduce the GTAP model and its specifications along with the land use results from this model. Then we introduce the land use carbon emission factors which we use to convert land use changes into CO<sub>2</sub> emissions. After that we present CO<sub>2</sub> emissions caused by US ethanol production due to land use changes. We then compare these results with results from other studies.

### **Land Use Changes from the 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 feed stuffs, 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 of the global economy.

GTAP is a CGE model which considers production, consumption, and trade of goods and services by regions and at a global scale. In this model 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

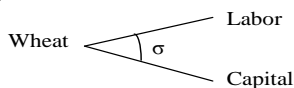
according to consumers and producers behaviors. Resources are labor, capital, land, and natural resources, and they owned by consumers. In GTAP, markets are competitive, consumers and producers are price takers, and utility and production functions usually follow the constant elasticity of substitution (CES) functional forms<sup>2</sup>. As an example, Figure 1 depicts a nested CES production function which is used to model crop output in GTAP.



**Figure 1. Nested CES production function for crop output in GTAP**

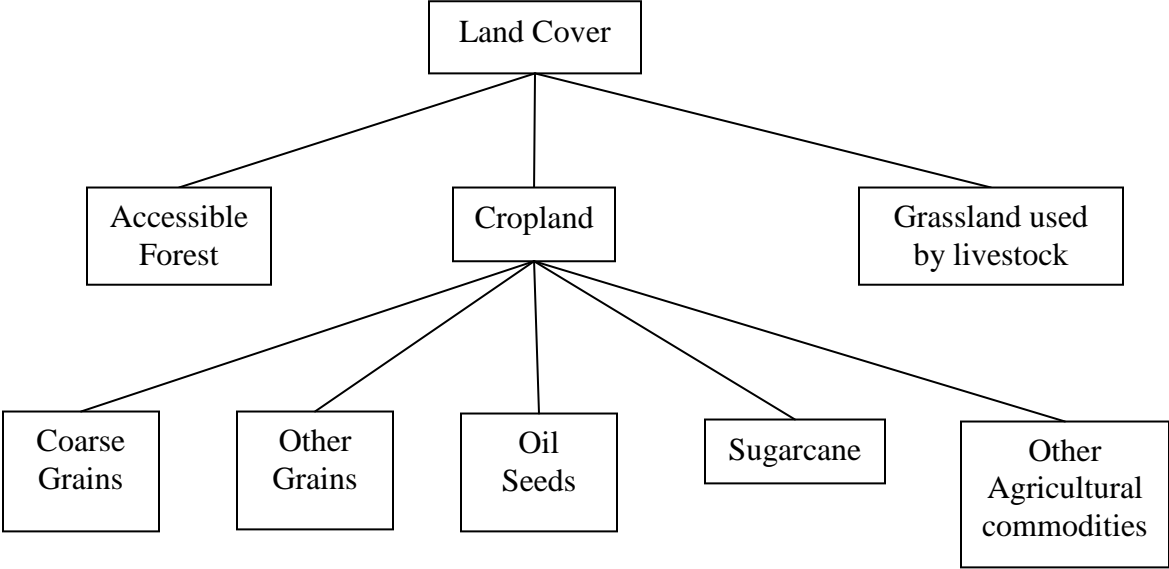
A special version of GTAP, developed by Burniaux and Truong (2002) and modified by McDougall and Golub (2007), incorporates energy into the GTAP framework. Birur, Hertel, and Tyner (2008) have introduced biofuels into this model. They augment the model by adding the possibility for substitutability between biofuels and petroleum products.

<sup>2</sup> 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 of this farmer:



In this graph  $\sigma$  represent the elasticity of substitution between labor and capital. If the farmer can only use labor and capital in a fixed proportion, then  $\sigma=0$ . 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  $\sigma$  is a number greater than zero. In general,  $\sigma$  can take any number between zero and infinity when we consider substitution among inputs or among consumption of goods and services.

In recent work, Birur, Hertel, and Tyner (2008) have augmented this model with a land use module to accurately depict the global competition for land between land use sectors. The land use module disaggregates land use into 18 Agro-Ecological Zones (AEZ). These AEZ's share common climate, precipitation and moisture conditions, and thereby capture 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. Figure 2 represents land use activities in GTAP.



**Figure 2. Land cover and land use activities in GTAP**

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. The ratio of marginal and average productivities measures the implicit costs of transferring one unit of non-cropland to cropland. In our

simulations we assumed that the price elasticity of yield and the ratio of average and marginal productivities are equal to 0.25 and 0.66, respectively. Keeney and Hertel (2008) have provided a detailed discussion on these parameters and other parameters used in the land use module along with econometric evidence behind them.

Taheripour et al. (2008) have extended the GTAP modeling framework to handle production, consumption, and trade of biofuel byproducts. In particular, they introduced distillers dried grains with solubles (DDGS) and oilseed meals as byproducts of ethanol and biodiesel into the model. Taheripour, Hertel, and Tyner (2008) have extended the GTAP model to evaluate implications of the biofuel boom for the global livestock industry. Their model improves earlier work in this field in several ways. Specifically, it further disaggregates economic activity in the economy with an aim of better understanding the linkages among biofuel production, byproducts, feedstuffs, and livestock production. In this model, the corn ethanol industry produces ethanol and distillers dried grains with solubles (DDGS) as a byproduct. The crude vegetable oil industry produces crude vegetable oil and oilseed meals. The edible vegetable oil and biodiesel industry uses crude vegetable oil, and livestock industries use oilseed meals in their production processes. We use this model to determine global land use changes due to US ethanol production.

Since eventually we combine GTAP and GREET results and both models incorporate impacts of byproducts in their calculations, it is useful to compare key assumptions of these models on byproducts. In a recent paper Arora, Wu, and Wang (2008) have calculated hypothetical corn-DDGS displacement ratios for beef cattle, dairy cattle, and swine (we will henceforth refer to this paper as AWW). According to AWW calculations, 1 kg of DDGS displaces 1.19 kg corn in the feed cattle ration. The corresponding displacement ratios for dairy

cattle and swine are 0.73, and 0.89, respectively. This indicates animals are different in their ability to utilize DDGS. AWW have also shown that in general 1 kg of distillers grains displaces 1.271 kg of conventional feed ingredients.

This AWW result is consistent with assumptions behind the GTAP database and model. The value of marginal product (VMP) of an input (increment in output from using one more unit of input multiplied by the output price) should be equal to the price of that input at equilibrium. Suppose a representative livestock producer is faced with the choice between corn and DDGS. At equilibrium the following condition should hold:

$$(1) \frac{MP_{other\ feeds}}{P_{other\ feeds}} = \frac{MP_{DDGS}}{P_{DDGS}} .$$

Now suppose 1 kg of DDGS displaces 1.271 kg of traditional feeds (e.g. corn, meal, and urea). This leads us to the conclusion that the price of DDGS should be greater than the price of traditional feeds by the displacement ratio. Now let's rewrite equation 1 in the following form:

$$(2) \frac{P_{DDGS}}{P_{other\ feeds}} = \frac{MP_{DDGS}}{MP_{other\ feeds}} .$$

According to the AWW calculations we can say:

$$(3) \frac{MP_{DDGS}}{MP_{other\ feeds}} = 1.271 .$$

Equations 2 and 3 imply:

$$(4) \frac{P_{DDGS}}{P_{other\ feeds}} = 1.271 .$$

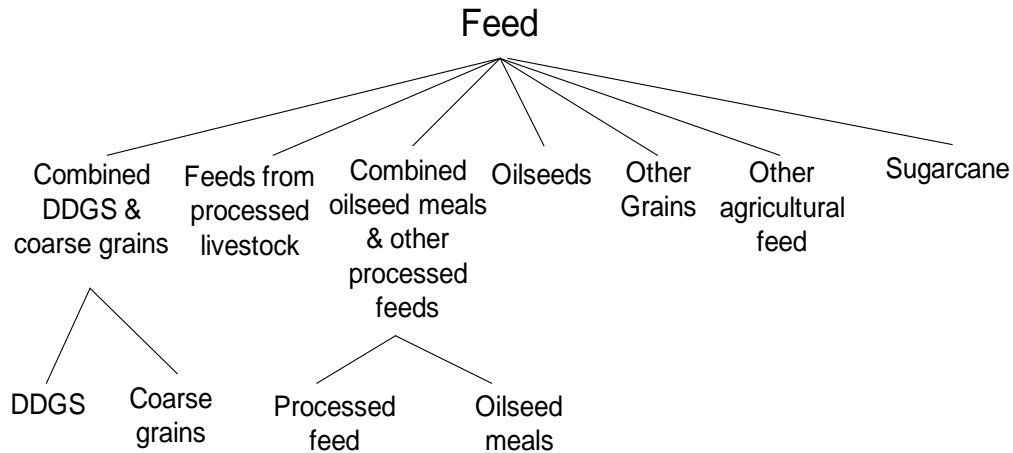
In building the GTAP-BIO database we have evaluated values of biofuels and their byproducts at market prices. The ratio of DDGS price (4.20 cents per pound) over the corn price

(3.40 cents per pound) was about 1.23 on average for 2001<sup>3</sup>. This is very close to the overall displacement ratio calculated by AWW (i.e. 1.271). So we can conclude that the GTAP-BIO database is consistent with the calculations made by AWW.

As mentioned earlier, the GTAP model used in this paper covers three types of livestock activities. The nested demand structure for animal feeds used in the model is shown in Figure 3. To account for differential abilities of animals in digesting DDGS as shown in AWW, we vary the elasticity of substitution between coarse grains and DDGS in the dairy, other ruminant, and non-ruminants feed rations, respectively in the GTAP. The values chosen reflect the relative ease of substitution in the different animal rations: dairy = 20, other ruminant = 30, and non-ruminant = 10. It is important to note that substitution among feeds in GTAP is not restricted to substitution between corn and DDGS. As shown in Figure 3 substitutions are occurred among feedstuffs in different ways. The model determines displacement ratios among feedstuffs based on changes in the relative prices of feeds, magnitudes of the elasticities of substitution, and expansion/extraction for livestock activities. For example, using elasticities mentioned above, GTAP generates a corn-DDGS displacement ratio of 1.16 kg corn for one kg DDGS at a 15 billion gallon ethanol production level, which is roughly consistent with the AWW results described above.

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<sup>3</sup> Note that the displacement ratio may go down as the ethanol industry grows over time due to the massive production of DDGS.



**Figure 3. Nested demand for animal feed**

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 in and bilateral trade among regions. This database also includes payments to labor, capital, and land (for details see Dimaranan (2006)). The database is also augmented with the most updated global land cover and land uses database at the AEZ level by region. 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. Taheripour et al. (2007) have introduced information on biofuels, including corn ethanol, sugarcane ethanol, and biodiesel from soybean and rapeseed into the GTAP database. In this paper we divided the world into 18 regions based on their role in the world economy and their land characteristics. Commodities and services are divided into 30 relatively homogeneous groups. Appendix A presents the regions and commodities.

Following Birur, Hertel, and Tyner (2008) we calibrated the model against actual observations for energy and biofuel markets over the time period: 2001-2006. Then the model is used to evaluate land use changes due to US ethanol production. To calculate land use changes, 6 main simulations were conducted<sup>4</sup>:

- 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.

In addition, 6 more simulations were made to test sensitivity of the results with respect to changes in export demand elasticities for coarse grains. For this test we reduced trade elasticities associated with coarse grains by 40% as a proxy for a falling dollar and the possibility of a more inelastic export demand in the world market of this commodity<sup>5</sup>.

The detailed global land use changes obtained from these simulations are shown in Appendix B<sup>6</sup>. In general, simulation results indicate that producing 13.23 BGs of ethanol (from the 2001 production level to 15 BGs) requires about 3.55 million hectares of additional land, of which 1.24 million hectares are expected to be in the US, with the remainder (2.31 million hectares) in other regions (see Appendix B, Table B1)<sup>7</sup>. Results also indicate that reducing trade elasticities associated with the export demand for coarse grains reduces global land use changes to 3.37 million hectares, while it increases the amount of the US in the global land use changes to

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<sup>4</sup> It is important to note that the only thing changing in these simulations is the added ethanol demand. We have not included growth in corn demand due to income and population growth nor growth in corn yields except the price induced yield increase. In other words, we have isolated the biofuels shock only. Therefore, since the results are not a forecast incorporating all the other changes in the economy, one cannot expect them to replicate what would happen with and without biofuels if all these other factors were included.

<sup>5</sup> In particular we reduced the elasticities of substitution among regional imported coarse grains from 2.6 to 1.04 and among imported and domestic coarse grains from 1.3 to 0.52.

<sup>6</sup> Land conversion costs are not included in these simulations nor in the GTAP database.

<sup>7</sup> In some regions such as Russia, China, and South & Other America forest areas are increased due to US ethanol production. In these regions some low productivity lands are converted to forest due to higher prices of forest.

1.45 million hectares. These changes are due to the fact that average US cropland productivity is higher than average global productivity.

In the rest of this section we discuss the results from the six main simulations in more detail. Table 1 summarizes the land use changes for the main six simulations. As mentioned earlier, producing 13.23 BGs of ethanol requires about 3.55 million hectares of additional land, 34.8% of which is expected to be in the US, with the remainder (65.2%) in other regions (see the last line of Table 1). This indicates two important points: *i*) the land use changes due to US ethanol production will mainly take place outside the US and *ii*) 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<sup>8</sup>. Several factors mitigate the land use consequences of ethanol production. The most important factors 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.

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<sup>8</sup> 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 gallon ethanol per hectare of land. Hence, based on this simple calculation, raising ethanol production from its 2001 level (1.77 BG) to 15 BG needs about 13 million hectares of land.

**Table 1. Global land use changes due to the US ethanol production**

<b>Changes in US Corn Ethanol Production</b>	<b>Land Use Changes (hectare)</b>			<b>Distribution of Land Use Changes (%)</b>			<b>Hectare per 1000 Gallon</b>
	<b>Within US</b>	<b>Other Regions</b>	<b>World</b>	<b>Within US</b>	<b>Other Regions</b>	<b>World</b>	
3.085 BG (2001 to 2006)	274104	445027	719131	38.1	61.9	100.0	0.23
2.145 BG (2006 to 7 BG)	196307	346442	542749	36.2	63.8	100.0	0.25
2.000 BG (7 to 9 BG)	186086	346361	532446	34.9	65.1	100.0	0.27
2.000 BG (9 to 11 BG)	189134	368658	557792	33.9	66.1	100.0	0.28
2.000 BG (11 to 13 BG)	192674	392080	584754	32.9	67.1	100.0	0.29
2.000 BG (13 to 15 BG)	197028	417505	614533	32.1	67.9	100.0	0.31
13.23 BG (2001 to 15 BG)	1235332	2316073	3551405	34.8	65.2	100.0	0.27

Table 1 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 719,131 hectares. This is equal to 0.23 hectares per 1000 gallons of ethanol. However, for the 13 BGs to the 15 BGs simulation, an additional 1000 gallons of ethanol requires 0.31 hectares of land. To increase ethanol production from the 2001 level to 15 BGs we need an average of 0.27 hectares of land per 1000 gallons of ethanol. The marginal level (0.31) is higher than the average (0.27), which would be expected because as more land comes into production, the yields on the incremental area would be lower.

Table 2 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 23.2% of the required croplands which are needed to increase ethanol production from its 2001 level to 15 BGs come from forest, and the rest (76.8%) come from grasslands. Table 2 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 22.5 % in 2001 to 23.2% at the 15 BGs ethanol production).

Table 2. Global land use changes due to the US ethanol production

Changes in US Corn Ethanol Output	Land Use Changes (hectare)			Distribution of Land Use Changes (%)		
	Forest	Grassland	Crop*	Forest	Grassland	Total*
3.085 BG (2001 to 2006)	-161860	-557265	719131	22.5	77.5	100.0
2.145 BG (2006 to 7 BG)	-125910	-416838	542749	23.2	76.8	100.0
2.000 BG (7 BG to 9 BG)	-124182	-408265	532446	23.3	76.7	100.0
2.000 BG (9 BG to 11 BG)	-130379	-427410	557792	23.4	76.6	100.0
2.000 BG (11 BG to 13 BG)	-136919	-447827	584754	23.4	76.6	100.0
2.000 BG (13 BG to 15 BG)	-144179	-470355	614533	23.5	76.5	100.0
13.23 BG (2001 to 15 BG)	-823430	-2727960	3551405	23.2	76.8	100.0

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

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.

### Land Use Carbon Emission Factors

We use emissions factors to convert land use changes into the land use carbon (LUC) emissions. As mentioned earlier we adopt two sets of emission factors in this paper. The first set of emission factors are calculated based on the Woods Hole Research Center data. This data set, which is taken from the supporting documents of SEA, provides data on the carbon stored in the vegetation and in the soil of forests and grasslands within various global regions. The second set of emissions factors are calculated based on the IPCC land and land cover carbon profiles. The IPCC data set provides data at a global scale with no geographic distribution. In the rest of this section we introduce these data sets and our carbon emissions factors.

Land conversions of forest and grassland into crop production releases carbon emissions from two sources: 1) direct carbon emissions from land conversion and 2) foregone carbon sequestration by forests. The direct carbon 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, if land had remained forested. This is the opportunity costs of cleared land in terms of its potential to store carbon. Our carbon emissions factors cover both direct and indirect emissions.

The Woods Hole 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. The IPCC data set which we use in this paper provides the same information at a global scale with no geographic distribution.

Each 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. For both data sets, 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.<sup>9</sup> 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.

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<sup>9</sup> In essence, we are assuming that 25% of the carbon in wood is stored in buildings, furniture, etc.

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, for the Woods Hole data set, in each area we have two groups of emissions factors: forest and grassland emission factors. However, for the IPCC data set we have only these two groups of emissions factors at the global scale. The Woods Hole and IPCC data sets along with their emissions factors are presented in Appendix C. Figures, in this appendix are calculated based on the assumption that the converted land to crop production will remain under crop production for 30 years.

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 assume corn production does not increase carbon stored in the soil due to the fact ethanol production may encourage farmers to change their rotation plan from corn-soybean to corn-corn and use intensive tillage practices. In addition, we assumed that the GREET model already has taken into account the amount of carbon released from production and consumption of corn and assigned some credits to the carbon captured from atmosphere during corn production.

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 18 regions. Table 3 relates each region of GTAP to one of the regions of the LCU module.

To test the sensitivity of carbon emissions factors with respect to the time period of ethanol production, we also calculated these factors for 50, 80, and 100 years from the Woods Hole data set. Note that the assumed time period only affects the GHG released at the time of conversion – not the annual foregone sequestration. Therefore, the total emissions will not be proportional to the assumed program period. To save space, detailed calculations for these cases are not reported in this report. However, we report the emissions factors obtained for these cases in Table 3. We now present carbon emissions factors for forest and grassland.

Table 3. GTAP and LUC module regions

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

First consider carbon emissions factors for forest areas across the world presented in Table 4. The regional emissions factors, derived from Woods Hole data set decrease with the duration of ethanol production. So the higher the duration of ethanol production, the lower the emissions factors in each region.

Consider now the regional forest emissions factors derived from the Woods Hole data set. Converting forest areas to cropland in South and South East Asia, China, and India generates the highest CO<sub>2</sub> emissions per hectare of land compared to the rest of the world. For example, the forest annual emissions factor in these regions is equal to 23 metric ton CO<sub>2</sub> per hectare forest, if 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 for the 30 years ethanol production is equal to 10.4 metric ton CO<sub>2</sub> per hectare of forest.

Table 4. GTAP regions and their corresponding carbon emissions factors for forest areas (figures are in annual metric ton CO<sub>2</sub> equivalent per hectare)

	Regions	30 Years	50 Years	80 Years	100 Years
		Duration of Ethanol Production	Duration of Ethanol Production	Duration of Ethanol Production	Duration of Ethanol Production
Based on Woods Hole Data Set	United States	19.6	12.3	8.3	6.9
	Canada	15.3	9.3	5.9	4.8
	Sub Saharan Africa	10.4	6.4	4.1	3.3
	European Union 27				
	Rest of European Countries	18.6	13.0	9.8	8.8
	Russia	14.1	8.8	5.9	4.9
	Brazil				
	Central and Caribbean Americas	16.1	9.9	6.4	5.3
	South and Other Americas				
	Middle Eastern and North Africa	12.2	8.4	6.3	5.6
	East Asia				
	Oceania	13.2	8.4	5.7	4.8
	Japan				
	China and Hong Kong				
	India	23.0	15.1	10.6	9.1
	Rest of South East Asia				
	Rest of South Asia	23.0	15.1	10.6	9.1
	Malaysia and Indonesia				
	IPCC for the Whole world	45.8	39.0	35.1	33.9

Table 4 also shows forest emissions factors derived from IPCC data. As shown in this table, IPCC factors are much larger than the corresponding regional factors derived from the

Woods Hole data set<sup>10</sup>. For example, for 30 years ethanol production the IPCC forest emission factor is equal to 45.8 metric tons CO<sub>2</sub> per hectare.

Table 5 shows annual emissions factors for grassland areas derived from the Woods Hole and IPCC data sets. This table illustrates that converting grasslands to crop production releases smaller CO<sub>2</sub> 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<sub>2</sub> per hectare for the 30 years ethanol production), and the lowest is Sub Saharan Africa (with 2.2 metric tons CO<sub>2</sub> per hectare for the 30 years). As shown in Table 5, the IPCC grassland emissions factors are much higher than the Woods Hole factors<sup>11</sup>.

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<sup>10</sup> Searchinger et al. 2008 calculated forest forgone emissions from carbon uptake by regrowing forest. Indeed they divided regrowing 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. However, this approach underestimates the magnitude of forgone forest emissions. Regrowing forest uptake should be divided by the area of regrowing forest - not the total area in forest. In addition, for many ecosystem types the Woods Hole database shows zeros for regrowing forest and uptake from regrowing forest. For these reason the forgone carbon emissions calculated from Woods Hole data is below the corresponding numbers presented in the IPCC data.

<sup>11</sup> IPCC includes forgone emissions from grassland, but Woods Hole does not.

Table 5. GTAP regions and their corresponding carbon emissions factors for grassland areas (figures are in annual metric ton CO<sub>2</sub> equivalent per hectare)

	<b>Regions</b>	<b>30 Years Duration of Ethanol Production</b>	<b>50 Years Duration of Ethanol Production</b>	<b>80 Years Duration of Ethanol Production</b>	<b>100 Years Duration of Ethanol Production</b>
Based on Woods Hole Data Set	United States	3.7	2.2	1.4	1.1
	Canada	5.7	3.4	2.1	1.7
	Sub Saharan Africa	1.5	0.9	0.6	0.4
	European Union 27	6.6	4.0	2.5	2.0
	Rest of European Countries	6.6	4.0	2.5	2.0
	Russia	7.0	4.2	2.6	2.1
	Brazil				
	Central and Caribbean Americas	2.5	1.5	0.9	0.8
	South and Other Americas				
	Middle Eastern and North Africa	2.2	1.3	0.8	0.7
	East Asia				
	Oceania	3.5	2.1	1.3	1.0
	Japan				
	China and Hong Kong	6.6	4.0	2.5	2.0
	India				
	Rest of South East Asia				
	Rest of South Asia	6.6	4.0	2.5	2.0
	Malaysia and Indonesia				
	IPCC for the Whole world	16.6	14.8	13.8	13.4

### Land Use Carbon Emissions Due to the US ethanol Production

We now combine land use changes due to US ethanol production with the carbon release emissions factors. This is a straight forward process. Suppose  $\Delta LF_{rj}$  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 carbon emissions factor for land type  $j$  in region  $r$  for a  $t$  year ethanol production is about  $F_{rjt}$ . Then the global annual carbon emissions due to producing  $x$  gallons of ethanol per year for a time period of  $t$  in the US will be equal to:

$$(5) LUE_w^t = \sum_r \sum_j \Delta LF_{rj} \cdot F_{rjt} \cdot x$$

Using this approach we calculated carbon emissions for all land use simulation scenarios (6 main simulations and 6 simulation with low export demand elasticities), all durations of

ethanol production (30, 50, 80, and 100 years), and for all emissions factors derived from the Woods Hole and IPCC data sets. Appendix D presents detailed results for the 2001 to 2006 land use changes with the corresponding emissions factors derived from the Woods Hole data set for 30 years ethanol production as an example.

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 cases examined in this paper. For example, Table 6 shows how we calculated the marginal land use emissions due to producing each gallon of E100 for the 13 to 15 BGs case. The value of 132.578 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 table B1) by their corresponding Woods Hole annual emissions factors presented in the first columns of Tables 4 and 5 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 6.

Table 6. 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)*	132.578
Change in ethanol production (million gallons)	2000.000
Emissions (metric tons per gallon of ethanol)	0.0663
Emissions (grams per gallon of ethanol)	66289
One year marginal emissions (grams per gallon of ethanol)	2210

\*Emissions are calculated based on Woods Hole emissions factors

Tables 7 and 8 summarize land uses emissions results for the main six GTAP simulations for the marginal and average land use changes. These tables are based on the emissions factors derived from Woods Hole data set for 30 years of ethanol production. Table 7 evaluates marginal changes in CO<sub>2</sub> emissions due to additions in ethanol production. CO<sub>2</sub> emissions are increasing in ethanol production at an increasing rate. For example, while an increase in ethanol production

from 7 BGs to 9 BGs generates 3.83 million metric tons CO<sub>2</sub> per year, moving from 9 BGs to 11BG causes 4.01 million metric tons CO<sub>2</sub> per year.

Table 7. Marginal land use emissions due to the US ethanol production  
(30 years duration of ethanol production)

Simulations	Increase in Ethanol Production (BG)	Annual LUC Emissions (million metric ton CO <sub>2</sub> equivalent)			Annual CO <sub>2</sub> Emissions from Land Use Change (grams per gallon of ethanol)		
		Forest	Grasslands	TOTAL	Forests	Grasslands	TOTAL
2001 to 2006 level	3.085	3.06	2.11	5.17	992	682	1675
2006 Level to 7 B gal	2.145	2.34	1.58	3.91	1089	735	1824
7 B to 9 B gal	2.000	2.29	1.55	3.83	1143	773	1916
9 B to 11 B gal	2.000	2.39	1.62	4.01	1194	811	2004
11 B to 13 B gal	2.000	2.50	1.70	4.20	1249	852	2101
13 B to 15 B gal	2.000	2.62	1.80	4.42	1312	898	2210

Table 8. Average land use emissions due to the US ethanol production  
(30 years duration of ethanol production)

Simulations	Increase in Ethanol Production (BG)	Annual LUC Emissions (million metric ton CO <sub>2</sub> equivalent)			Annual CO <sub>2</sub> Emissions from Land Use Change (grams per gallon of ethanol)		
		Forest	Grasslands	TOTAL	Forests	Grasslands	TOTAL
2001 to 2006 level	3.085	3.06	2.11	5.17	992	682	1675
2001 to 7 B gal	5.23	5.40	3.68	9.08	1032	704	1736
2001 to 9 B gal	7.23	7.68	5.23	12.91	1063	723	1786
2001 to 11 B gal	9.23	10.07	6.85	16.92	1091	742	1833
2001 to 13 B gal	11.23	12.57	8.55	21.12	1119	762	1881
2001 to 15 B gal	13.23	15.19	10.35	25.54	1148	782	1931

One can see the increasing rate in CO<sub>2</sub> emissions when we convert these numbers in CO<sub>2</sub> emissions per gallon of ethanol. From Table 7, where the US was producing below 5 BGs ethanol, annual CO<sub>2</sub> emissions were about 1675 grams per gallon of ethanol. However, if ethanol production reaches 15 BG, then each additional gallon of ethanol generates 2210 grams of CO<sub>2</sub>. It is important to note that about 60% of emissions come from deforestation and 40% come from converting grasslands into crop production.

The average CO<sub>2</sub> emissions from land use changes due to different ranges of US ethanol production are shown in Table 8. An increase in US ethanol production from the 2001 level (1.77

BG) to 7 BGs ethanol production is expected to add about 9.08 million metric tons of CO<sub>2</sub> emissions into the atmosphere per year. If US ethanol production reaches 15 BGs, then an additional 16.5 million metric tons of CO<sub>2</sub> emissions will be added to the atmosphere per year. At the 9 BGs level of ethanol production (roughly corresponding to the current situation) every gallon of ethanol production on average adds 1786 grams CO<sub>2</sub> per year into the atmosphere due to land use changes. If we move to 15 BGs then every gallon of ethanol production on average will add 1931 grams CO<sub>2</sub> emissions per year into the atmosphere through land use changes.

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.

We now summarize land use carbon emissions for all cases if the US produces 15 billion gallons of ethanol (see Table 9). In every case the marginal emissions are greater than the average emissions. For example, when the US produces 15 billion gallons of ethanol, producing an additional gallon of ethanol generates 2210 grams of emissions, while at this level of output each gallon of ethanol on average generates 1931 grams of emissions due to land use changes. The average and marginal emissions follow similar patterns across the cases presented in Table 9.

Table 9. Annual marginal and average GHGs emissions due to US ethanol production

<b>Carbon Profile</b>	<b>Duration of Ethanol Production (year)</b>	<b>Trade Elasticities of Coarse Grains</b>	<b>Annual Marginal Emissions (grams per gallon of ethanol)*</b>	<b>Annual Average Emissions (grams per gallon of ethanol)**</b>
Woods Hole	30	Original values	2210	1931
	50	Original values	1381	1206
	80	Original values	915	799
	100	Original values	759	663
	30	Reduced by 40%	2207	1862
IPCC	30	Original values	7204	6272

\*Based on the 13 to 15 BGs simulations

\*\*Based on the 2001 to 15 BGs simulations

Annual CO<sub>2</sub> land use emissions due to ethanol production decrease with the assumed duration of ethanol production as would be expected. For example, if cleared land is used to support ethanol production for 30 years, then the annual marginal emissions for each gallon of ethanol would be equal to 2210 grams when we use Woods Hole emissions factors. This figure is reduced to 759 grams if the cleared land is used to support ethanol production for 100 years.

For the 30 year ethanol production case when trade elasticities associated with coarse grains are reduced by 40%, producing an additional gallon of ethanol generates 2207 grams of emissions. Therefore the marginal emissions remain relatively unchanged with reduction in trade elasticities of coarse grains. In this case the average emissions due to production of one gallon of ethanol are about 1862 grams. This number is 3.5% smaller than the corresponding number with original values of trade elasticities.

When we reduce trade elasticities associated with coarse grains, the US increases its croplands by 212 thousand hectares to produce more outputs compared to the case with original elasticities, but other regions reduce their croplands by 391 thousand hectares (see Tables B1 and B2 in Appendix B). Hence, the global land use change goes down by 179 thousand hectares (or 5%). As mentioned earlier, reducing trade elasticities associated with coarse grains only reduces

emissions by 3.5% compared with the case with original trade elasticities. When we reduce trade elasticities of coarse grains, some countries which have low carbon emissions factors give up some corn production, and therefore emissions go down at a lower rate compared with the overall rate of reduction in land use change. Finally, as shown in Table 9, the average and marginal carbon emissions derived from IPCC carbon profile are about 3 times of the corresponding emissions derived from the Woods Hole data set<sup>12</sup>.

In the last part of this section we compare our results for the marginal and average land use emissions with the SEA results (see Table 10). In this comparison we focus on the 30 year ethanol case with no restriction on US exports to be consistent with the SEA assumption on the duration of ethanol production.

Table 10. Land use emissions due to US ethanol production  
(Comparing GTAP and Searchinger et al. (2008) results)

	Total Emissions for 30 years (million metric tons)	3801
	Change in ethanol production (billion liters of ethanol)	55.92
Searchinger et al. (2008)	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	One year average emissions (gram per gallon of ethanol)	1931
	One year marginal emissions (gram per gallon of ethanol)	2210

Table 10 Shows that SEA predicts each gallon of ethanol generates 8577 grams GHGs emissions through land use changes. This figure is roughly four times the results from our analysis, regardless of the difference between the marginal and average cases. The difference is due to three factors. The first factor is related to the SEA assumption on the land requirement for ethanol production. The SEA assumptions lead to a land requirement factor of 0.73 hectares of land per 1000 gallons of ethanol, while we estimate 0.27 hectares per 1000 gallons of ethanol.

<sup>12</sup> Footnotes 10 and 11 explain this huge difference.

The SEA estimation for land use changes due to ethanol production is 2.7 times of the GTAP estimation. The second factor is related to the distribution of land across the world. SEA predicts that land use changes will occur mainly in areas where carbon emissions factors are high (such as India and China), while our predictions indicate that land use changes in these areas are minor (compare appendix B of this report with Appendix C of SEA). Finally, in our analysis we assume that 75% of carbon stored in the forest type vegetations will be released into the atmosphere at the time of land conversion, while SEA assumes that 100% of the carbon will be released. Our sense is that it is reasonable to assume that some of the forest will be converted to long term carbon storage as in furniture and houses.

### **Total Emissions from Production and Consumption of Ethanol**

So far we have analyzed emissions from land use changes due to corn ethanol production. To evaluate non-land use emissions due to production and consumption of ethanol we rely on the GREET model. To separate land use and non-land use emissions, we put zero in the land use cell in GREET and converted the calculations to 100% ethanol.<sup>13</sup> This was done by modifying the assumptions in the GREET model namely the share of alternative fuel (100%) and the share of gasoline by volume added in ethanol (0%) for the E-85 case ('Input' worksheet, Cells D407 and E407, respectively). Appendix E, shows our key assumptions used in the Well-to-Well analysis. Then we added figures in Table 9 to the well-to-wheel ethanol emissions without land use emissions to determine total emissions from production and consumption of one gallon of pure ethanol for both cases of marginal and average emissions (see Tables 11 and 12).

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<sup>13</sup> The GREET model places additional emission credits for ethanol co-products when we incorporate the land use change emissions in the model and this results in confusion when separating land use change emissions. Therefore, rather than plugging in the land use change emissions in the GREET model, the direct calculation was used to explicitly show the contribution of land use changes in the well-to-wheel analysis for corn ethanol fuel.

Table 11. Well-to-Wheel ethanol and gasoline emissions for marginal land use changes  
(Emissions are in grams per gallon)

<b>Carbon Profile</b>	<b>Duration of Ethanol Production (year)</b>	<b>Trade Elasticities of Coarse Grains</b>	<b>Annual Marginal Land Use Emissions</b>	<b>Ethanol Well-to-Wheel Emissions with no Land Use</b>	<b>Ethanol Well-to-Wheel Emissions Plus Marginal Land Use Emissions</b>
Woods Hole	30	Original values	2209.6	5299.9	7509.5
	50	Original values	1381.0	5299.9	6680.9
	80	Original values	914.8	5299.9	6214.7
	100	Original values	759.5	5299.9	6059.4
	30	Reduced by 40%	2206.6	5299.9	7506.5
IPCC	30	Original values	7203.8	5299.9	12503.7

Table 12. Well-to-Wheel ethanol and gasoline emissions for average land use changes  
(Emissions are in grams per gallon)

<b>Carbon Profile</b>	<b>Duration of Ethanol Production (year)</b>	<b>Trade Elasticities of Coarse Grains</b>	<b>Annual Average Land Use Emissions</b>	<b>Ethanol Well-to-Wheel Emissions with no Land Use</b>	<b>Ethanol Well-to-Wheel Emissions Plus Average Land Use Emissions</b>
Woods Hole	30	Original values	1930.6	5299.9	7230.5
	50	Original values	1206.2	5299.9	6506.1
	80	Original values	798.8	5299.9	6098.7
	100	Original values	662.9	5299.9	5962.8
	30	Reduced by 40%	1861.8	5299.9	7161.7
IPCC	30	Original values	6271.8	5299.9	11571.7

Table 11 represents total emissions due to production and consumption of one gallon of E100 for all marginal cases discussed earlier. This table indicates that for the 30 year case, with original trade elasticities and with Woods Hole data, production and consumption of an additional gallon of E100 generate 7509.5 grams of GHGs. In this case, about 29.4% of released emissions are related to land use changes. As shown in Table 11, total emissions of an additional gallon of E100 decreases when duration of ethanol production increases. For example, with 100 year duration, an additional gallon of E100 causes about 6059.4 grams of emissions. About 12.5% of this figure is due to land use emissions.

When we reduce trade elasticities of coarse grains, total emissions due to an additional gallon of E100 mainly remains about the same as original case. According to the IPCC carbon profile, production and consumption of an additional gallon of E100 generate 12503.7 grams

emissions. This figure is 66.5% more than the corresponding number obtained from using the Woods Hole carbon profile. The IPCC data misses the very important distributional implications of land use changes.

Table 12 presents total emissions from production and consumption of one gallon of E100 for all average cases. In general, the average emissions are lower than the marginal emissions in all cases. However, they follow the same pattern of marginal emissions across alternative cases presented in Table 11.

### Well-to-Wheel Ethanol GHGs vs. Gasoline

In this section we compare total emissions of E100 and conventional gasoline. To do so, we convert total emissions per gallon of E100 for all cases presented in Tables 11 and 12 to emissions per mile. Results are shown in Tables 13 and 14 along with emissions per mile for conventional gasoline.

Table 13. Well-to-Wheel ethanol and gasoline emissions for marginal land use changes  
(Emissions are in grams per mile)

Carbon Profile	Duration of Ethanol Production (year)	Trade Elasticities of Coarse Grains	Ethanol Emissions (grams per mile)	Gasoline Emissions (grams per mile)	Ethanol GHGs vs Gasoline (percent)
Woods Hole	30	Original values	486.0	486.9	99.8
	50	Original values	432.4	486.9	88.8
	80	Original values	402.2	486.9	82.6
	100	Original values	392.2	486.9	80.5
	30	Reduced by 40%	485.8	486.9	99.8
IPCC	30	Original values	809.2	486.9	166.2

Table 14. Well-to-Wheel ethanol and gasoline emissions for average land use changes  
(Emissions are in grams per mile)

Carbon Profile	Duration of Ethanol Production (year)	Trade Elasticities of Coarse Grains	Ethanol Emissions (grams per mile)	Gasoline Emissions (grams per mile)	Ethanol GHGs vs Gasoline (percent)
Woods Hole	30	Original values	467.9	486.9	96.1
	50	Original values	421.1	486.9	86.5
	80	Original values	394.7	486.9	81.1
	100	Original values	385.9	486.9	79.3
	30	Reduced by 40%	463.5	486.9	95.2
IPCC	30	Original values	748.9	486.9	153.8

Table 13 compares total GHGs emissions from ethanol and gasoline while we consider ethanol marginal emissions. According to this table for 30 year ethanol production with original values of trade elasticities and with Woods Hole emission factors, total GHGs emissions due to production and consumption of E100 (including land use emissions) are about 486.0 grams per mile. This figure is approximately identical to the emissions due to production and consumption of conventional gasoline. When the duration of ethanol production goes up, ethanol emissions go down, and therefore its emissions go down compared with gasoline. For example, with 100 year duration, emissions costs of E100 per mile are about 80.5% of conventional gasoline emissions per mile.

If we consider the IPCC carbon profile, then emissions released due to production and consumption of E100 per mile are 66.2% more than the conventional gasoline emissions per mile. When we reduce trade elasticities of coarse grains, emissions costs of E100 is the same as of those for gasoline.

Finally, since average emissions are smaller than the marginal emissions, when we compare ethanol average emissions with gasoline emissions, we can see reduction in E100 emissions compare to gasoline in all cases (compare entries of Tables 13 and 14).<sup>14</sup>

### **Conceptual Issues in Applying Land Use Change Values for Biofuels**

As is clear from the above results, the GHG emissions associated with corn ethanol production are an increasing function of the level of production. That is, emissions due to land

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<sup>14</sup> With respect to the data problems explained in footnotes 10 and 11, we did preliminary calculations with modified data. Two types of modifications were made: 1)For Woods Hole forest emissions we changed the divisor to converted forest instead of total forest, and we selected the closest forest type for cases with missing data; 2)For the IPCC data we excluded foregone emissions from grassland to be consistent with Woods Hole and with our assessment of reality. Making these changes, average annual emissions for the 30 year case change from 96.1% to 97.5% of gasoline. The IPCC case changes from 153.8% of gasoline to 120.7%.

use changes are greater for the 13 to 15 billion gallon increment than for the 9 to 11 billion gallon increment. This makes sense because the further one goes out the land supply curve, the more marginal land is needed to achieve the stipulated production levels. But more importantly, this conclusion raises the conceptual issue on the basis for comparison between corn ethanol and gasoline. The current GREET configuration is done for an average gasoline supply chain. In reality, there is a “supply curve” for GHG for gasoline just as there is for corn ethanol. Tar sands sourced gasoline (probably the marginal source), certainly would have higher GHG than the average refinery crude oil. Theoretically, we should be comparing the marginal corn GHG (13-15 in this paper) with tar sands based gasoline. Otherwise, if we want to continue to use averages for gasoline, we should use the average value for corn ethanol as well. This issue merits further exploration.

### **Future work**

The research reported in this paper represents a tremendous amount of work adapting GTAP to the biofuels induced land use changes and estimating potential changes in land use. While the progress has been significant, we still have additional work on our agenda. Some of the important issues for corn based ethanol are the following:

- **Yield growth** – the current work has price induced yield changes included, but no exogenous yield shocks have been used. We have done all the analysis with and without biofuels attempting to isolate the effects of the biofuels programs. However, we intend to explore alternative ways of examining the impacts of exogenous yield growth on the with and without biofuels cases.
- **Land data base improvements** – Right now the handling of productivity of additional land coming into crops is handled through a model parameter expressing the ratio of the

productivity of the marginal land compared with average land. In the future, we expect to include more explicit data on area and yield of cropland pasture and CRP land in the US and available land in Brazil. Work on this topic has been ongoing but has proved difficult to implement in GTAP. However, we are optimistic the modeling difficulties can be overcome.

- **Additional data sources on land use change induced carbon emissions** – We are exploring other data sources for land use change based carbon emissions. Winrock has produced a data set, and we are considering producing a set at Purdue using data from the Terrestrial Ecosystem Model (Melillo et al., 1993; Zhuang et al., 2003; TEM).
- **Additional sensitivity analysis** – We will continue to perform sensitivity analyses on different parameters and data assumptions.

In addition to the above tasks on corn ethanol, we are now working on cellulose based ethanol. For cellulose, we are exploring different ways of incorporating cellulose into GTAP. It will be preferable to have the new land data on the US and Brazil included so that this land area can compete for cellulosic crops. For crop residues, we are considering including them in GTAP or alternatively handling them with spreadsheet calculations outside GTAP based on area in each of the major crops producing residues. We do not anticipate supply side land use implications from use of residues for biofuels, but there could be demand side implications for land use depending on the policy set in place. We will be meeting with partners to design cellulose scenarios for our future analysis.

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**Appendix A**  
Lists of Commodities, Industries, and Regions

Table A 1. List of industries and commodities in the new model

Industry name	Commodity name	Description	Corresponding Name in the GTAP_BIOB
CrGrains	CrGrains	Cereal grains	Gro
OthGrains	OthGrains	Other Grains	pdr, wht
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
CattleRum	CattleRum	Cattle & ruminant meat production	Ctl
NonRum	Non-Rum	Non-ruminant meat production	oap, wol
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
Bev_Sug_Pri	Bev_Sug_Pri	Beverages, tobacco, sugar, and processed rice	b_t, pcr, 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
Oth_Ind_Se	Oth_Ind_Se	Other industry and services	crpn, i_s, nfm, atp, cmn, cns, dwe, ele, fmp, isr, lea, lum, mvh, nmm, obs, ofi, ome, omf, osg, otn, otp, ppp, ros, tex, trd, wap, wtp, wtr
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 A 2. Regions and their members

<b>Region</b>	<b>Description</b>	<b>Corresponding Countries in GTAP</b>
USA	United States	Usa
CAN	Canada	Can
BRAZIL	Brazil	Bra
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, twm, 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
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
Russia	Russia	Rus
R_Europe	Rest of European Countries	che, xef, xer, alb, hrv, xsu, tur
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 B**  
**Land Use Changes Due to Ethanol Production**

Table B 1. Land use changes due to the US ethanol production - results from the six main simulations (thousand hectares)

Description		USA	Canada	Brazil	Japan	China & Hong Kong	India	Central & Caribbean America	South & Other America	East Asia
2001 to 2006	Forest	-124.9	-38.0	-11.6	-1.0	9.7	-4.1	-2.5	13.9	1.3
	Cropland	274.1	68.6	50.7	1.3	8.7	8.4	14.3	26.0	0.1
	Grassland	-149.2	-30.6	-39.1	-0.3	-18.3	-4.3	-11.7	-39.9	-1.4
2006 to 7 B gal	Forest	-89.3	-27.8	-8.9	-0.8	8.4	-3.7	-1.8	10.4	1.0
	Cropland	196.3	50.8	39.0	1.0	6.3	7.7	11.6	19.5	0.1
	Grassland	-107.0	-23.0	-30.1	-0.2	-14.7	-4.0	-9.7	-29.9	-1.0
7 B to 9 B gal	Forest	-85.1	-27.5	-8.7	-0.8	8.7	-3.9	-1.7	10.2	1.0
	Cropland	186.1	50.7	38.7	1.0	6.2	8.2	11.7	19.3	0.1
	Grassland	-100.9	-23.2	-30.0	-0.2	-15.0	-4.3	-10.0	-29.4	-1.1
9 B to 11 B gal	Forest	-87.6	-29.2	-9.1	-0.8	9.6	-4.4	-1.6	10.7	1.0
	Cropland	189.1	54.5	40.9	1.1	6.6	9.1	12.4	20.3	0.1
	Grassland	-101.6	-25.3	-31.9	-0.3	-16.2	-4.8	-10.8	-31.1	-1.1
11 B to 13 B gal	Forest	-90.8	-31.2	-9.4	-0.9	10.5	-4.8	-1.5	11.4	1.1
	Cropland	192.7	59.0	43.4	1.1	7.0	10.1	13.0	21.4	0.1
	Grassland	-101.9	-27.7	-33.9	-0.3	-17.5	-5.3	-11.5	-32.8	-1.2
13 B to 15 B gal	Forest	-94.9	-33.7	-9.8	-0.9	11.5	-5.3	-1.3	12.3	1.2
	Cropland	197.0	64.4	46.1	1.2	7.5	11.1	13.4	22.5	0.1
	Grassland	-102.2	-30.7	-36.3	-0.3	-19.1	-5.8	-12.0	-34.8	-1.3

Table B1. Continued

Description		Malaysia & Indonesia	Rest of South East Asia	Rest of South Asia	EU27	Russia	Rest of Europe	Middle East & North Africa	Sub Saharan Africa	Oceania	Total
2001 to 2006	Forest	2.1	0.5	-1.0	-35.9	51.8	-4.3	0.3	-18.3	0.4	-161.9
	Cropland	-1.1	0.8	3.5	58.8	-3.4	33.5	15.5	140.0	19.4	719.1
	Grassland	-1.1	-1.3	-2.4	-22.9	-48.4	-29.2	-15.8	-121.7	-19.8	-557.3
2006 to 7 B gal	Forest	1.4	0.4	-0.9	-30.6	35.8	-2.9	0.2	-17.0	0.3	-125.9
	Cropland	-0.6	0.6	2.9	49.1	-2.3	25.7	12.4	107.7	14.9	542.7
	Grassland	-0.8	-1.0	-2.0	-18.6	-33.5	-22.8	-12.5	-90.7	-15.2	-416.8
7 B to 9 B gal	Forest	1.3	0.4	-0.9	-31.0	34.1	-2.7	0.2	-18.0	0.3	-124.2
	Cropland	-0.5	0.6	2.9	49.7	-2.1	25.5	12.5	107.1	14.8	532.4
	Grassland	-0.8	-1.0	-2.0	-18.7	-32.0	-22.8	-12.6	-89.1	-15.1	-408.3
9 B to 11 B gal	Forest	1.3	0.4	-1.0	-33.0	35.1	-2.8	0.2	-19.8	0.3	-130.4
	Cropland	-0.5	0.6	3.2	53.0	-2.1	27.0	13.3	113.3	15.8	557.8
	Grassland	-0.8	-1.1	-2.2	-20.0	-33.0	-24.3	-13.5	-93.5	-16.1	-427.4
11 B to 13 B gal	Forest	1.3	0.5	-1.1	-34.9	36.4	-2.8	0.2	-21.4	0.4	-136.9
	Cropland	-0.4	0.7	3.4	56.2	-2.2	28.7	14.2	119.5	16.9	584.8
	Grassland	-0.9	-1.2	-2.3	-21.2	-34.3	-25.9	-14.4	-98.2	-17.3	-447.8
13 B to 15 B gal	Forest	1.4	0.5	-1.2	-36.9	38.1	-2.9	0.2	-22.9	0.5	-144.2
	Cropland	-0.4	0.7	3.7	59.5	-2.2	30.6	15.2	126.0	18.1	614.5
	Grassland	-1.0	-1.2	-2.5	-22.7	-35.8	-27.6	-15.4	-103.1	-18.6	-470.4

Table B 2. Land use changes due to the US ethanol production - results from the six simulations where export demand elasticities for coarse grains are reduced by 40% (thousand hectares)

Description		USA	Canada	Brazil	Japan	China & Hong Kong	India	Central & Caribbean America	South & Other America	East Asia
2001 to 2006	Forest	-135.5	-32.3	-12.5	-1.0	9.8	-4.2	-2.6	14.6	1.3
	Cropland	296.1	60.4	47.4	1.3	7.7	8.6	11.2	23.1	0.1
	Grassland	-160.6	-28.1	-34.9	-0.3	-17.4	-4.4	-8.6	-37.8	-1.4
2006 to 7 B gal	Forest	-159.4	-2.7	3.1	0.6	10.5	-0.6	-3.2	11.4	0.6
	Cropland	321.3	13.3	12.9	-0.4	-1.2	2.3	6.5	9.5	-0.2
	Grassland	-161.9	-10.6	-16.0	-0.2	-9.2	-1.7	-3.3	-20.8	-0.4
7 B to 9 B gal	Forest	-92.4	-24.2	-9.5	-0.7	8.9	-4.1	-1.8	10.7	1.0
	Cropland	201.6	46.2	36.8	1.0	5.5	8.5	9.8	17.7	0.1
	Grassland	-109.2	-22.0	-27.2	-0.3	-14.4	-4.4	-8.1	-28.4	-1.1
9 B to 11 B gal	Forest	-95.0	-26.2	-10.0	-0.8	9.8	-4.6	-1.7	11.3	1.1
	Cropland	205.0	50.4	39.1	1.0	5.9	9.5	10.6	18.8	0.1
	Grassland	-110.1	-24.3	-29.1	-0.3	-15.7	-4.9	-8.9	-30.2	-1.2
11 B to 13 B gal	Forest	-98.5	-28.3	-10.5	-0.8	10.8	-5.1	-1.6	12.1	1.2
	Cropland	209.0	55.3	41.6	1.1	6.3	10.5	11.2	20.0	0.1
	Grassland	-110.5	-26.9	-31.1	-0.3	-17.1	-5.5	-9.6	-32.1	-1.3
13 B to 15 B gal	Forest	-103.0	-30.9	-11.0	-0.8	11.9	-5.6	-1.4	13.0	1.4
	Cropland	213.7	61.0	44.4	1.2	6.7	11.6	11.6	21.2	0.1
	Grassland	-110.7	-30.1	-33.4	-0.3	-18.6	-6.0	-10.2	-34.2	-1.4

Table B2. Continued

Description		Malaysia & Indonesia	Rest of South East Asia	Rest of South Asia	EU27	Russia	Rest of Europe	Middle East & North Africa	Sub Saharan Africa	Oceania	Total
2001 to 2006	Forest	2.2	0.4	-1.0	-29.7	53.3	-3.8	0.3	-15.6	0.5	-155.7
	Cropland	-1.1	0.8	3.5	50.6	-5.0	31.4	13.0	130.8	17.6	697.6
	Grassland	-1.1	-1.2	-2.4	-20.9	-48.3	-27.6	-13.3	-115.2	-18.1	-541.8
2006 to 7 B gal	Forest	4.3	1.8	-0.1	-0.2	41.5	2.5	0.2	5.2	1.9	-82.6
	Cropland	-3.5	-0.8	0.6	9.3	-8.5	9.6	2.6	45.4	0.0	418.6
	Grassland	-0.8	-1.0	-0.6	-9.1	-33.0	-12.1	-2.9	-50.7	-1.9	-336.0
7 B to 9 B gal	Forest	1.3	0.4	-0.9	-27.3	35.5	-2.3	0.2	-16.3	0.4	-121.0
	Cropland	-0.5	0.6	3.0	44.8	-3.3	24.3	10.9	101.8	13.5	522.3
	Grassland	-0.8	-1.0	-2.0	-17.6	-32.3	-22.0	-11.1	-85.5	-13.9	-401.2
9 B to 11 B gal	Forest	1.4	0.4	-1.0	-29.3	36.7	-2.3	0.2	-18.1	0.4	-127.5
	Cropland	-0.5	0.7	3.2	48.2	-3.4	25.9	11.8	108.2	14.4	548.8
	Grassland	-0.9	-1.1	-2.2	-18.9	-33.4	-23.5	-12.0	-90.1	-14.9	-421.3
11 B to 13 B gal	Forest	1.4	0.4	-1.1	-31.3	38.3	-2.4	0.2	-19.7	0.5	-134.3
	Cropland	-0.5	0.7	3.5	51.5	-3.5	27.6	12.7	114.5	15.4	577.0
	Grassland	-0.9	-1.2	-2.4	-20.2	-34.8	-25.2	-12.9	-94.9	-16.0	-442.7
13 B to 15 B gal	Forest	1.4	0.5	-1.2	-33.2	40.1	-2.5	0.2	-21.2	0.6	-141.8
	Cropland	-0.4	0.8	3.8	54.9	-3.6	29.5	13.6	121.2	16.6	608.0
	Grassland	-1.0	-1.3	-2.6	-21.7	-36.5	-27.1	-13.8	-100.0	-17.2	-466.2

## **Appendix C**

### **Land use carbon emission spreadsheets**

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\_MTH: Direct carbon emissions from land conversion in metric tons

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 CO<sub>2</sub> emissions in metric ton per hectare

**Table C 1. Woods Hole Land use carbon 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 carbon 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 carbon 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 carbon 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 carbon 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 carbon 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 carbon 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 carbon 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 carbon 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

**Table C 10. World land use carbon emission data- IPCC 2001 Data**

Description	Tropical forests	Temperate forests	Boreal forests	Total Forest	Tropical savannas & grasslands	Temperate grasslands & shrub lands	Deserts and semi deserts	Tundra	Total Grassland
FAE_MH	1.75	1.04	1.37	4.16	2.76	1.78	2.77	0.56	7.87
FAE%	42.07	25	32.93	100.00	35.07	22.62	35.2	7.12	100.00
CINV_MT/H	194	134	42		29	13	4	4	
CINS_MT/H	122	147	247		90	99	57	206	
25% of									
CINS_MT/H	30.50	36.75	61.75		22.50	24.75	14.25	51.50	
DCEFLC_MT/H	176	137.25	93.25		51.5	37.75	18.25	55.5	
*NPP_TC/yr	22	8.1	2.6		14.9	7.0	3.5	0.5	
*CU_MTC/H/yr	12.51	7.79	1.9		5.4	3.93	1.26	0.89	
FCS30_MTC/H	375.43	233.65	56.93		161.96	117.98	37.91	26.79	
WACE_MT/H	231.97	92.73	49.46	374.16	74.86	35.22	19.77	5.86	135.7
WACO2E_MT/H	851.33	340.3	181.52	1373.16	274.73	129.26	72.54	21.49	498.02

\*Note: NPP\_BTC/yr - Net Primary Production in billion metric ton carbon per year  
CU\_MTC/H/yr - Carbon uptake in metric ton carbon per hectare per year

## Appendix D

Table D 1. Global Land Use Changes and Emissions for simulation 2001 to 2006 level (30 years with Woods Hole)

Region	Cropland Area Cover Change (hectares)	Forest Area Cover Change (hectares)	Grassland Area Cover Change (hectares)	Annualized Metric Ton CO2 Equivalent per hectare of Forest	Annualized Metric Ton CO2 Equivalent per hectare of Grassland	Annualized Forest Emissions (Metric Ton CO2 Equivalent)	Annualized Grassland Emissions (Metric Ton CO2 Equivalent)	Annualized Total Emissions (Metric Ton CO2 Equivalent)
United States	274104	-124942	-149163	19.56	3.67	2,444,027	547,429	2,991,456
Canada	68592	-37982	-30610	15.27	5.69	580,145	174,170	754,315
Brazil	50651	-11586	-39065	16.07	2.51	186,213	97,968	284,181
Japan	1340	-1038	-302	13.23	3.49	13,737	1,053	14,790
China and Hong Kong	8653	9675	-18329	23.02	6.64	-222,728	121,641	-101,087
India	8414	-4094	-4320	23.02	6.64	94,242	28,673	122,915
Central and Caribbean Americas	14260	-2512	-11747	16.07	2.51	40,375	29,461	69,835
South and Other Americas	25978	13935	-39913	16.07	2.51	-223,957	100,095	-123,862
East Asia	111	1257	-1368	13.23	3.49	-16,632	4,770	-11,863
Malaysia and Indonesia	-1080	2133	-1054	23.02	6.64	-49,110	6,993	-42,116
Rest of South East Asia	809	457	-1266	23.02	6.64	-10,522	8,403	-2,119
Rest of South Asia	3458	-1025	-2433	23.02	6.64	23,588	16,149	39,737
European Union 27	58828	-35901	-22927	18.58	6.64	667,215	152,158	819,373
Russia	-3410	51777	-48367	14.07	7.00	-728,499	338,743	-389,755
Rest of European Countries	33492	-4342	-29150	18.58	6.64	80,694	193,457	274,151
Middle Eastern and North Africa	15491	273	-15764	12.20	2.21	-3,329	34,868	31,539
Sub Saharan Africa	139998	-18317	-121673	10.45	1.48	191,327	180,104	371,431
Oceania	19440	372	-19813	13.23	3.49	-4,927	69,077	64,150
<b>Total</b>	<b>719131</b>	<b>-161860</b>	<b>-557265</b>			<b>3,061,860</b>	<b>2,105,212</b>	<b>5,167,072</b>
						Forests	Grasslands	TOTAL
Increase in Ethanol Production in gallons					3,085,000,000			
Emissions per Land Type (Metric Ton CO2 Equivalent)						3,061,860	2,105,212	5,167,072
Grams CO2 Equivalent per gallon of Ethanol						992	682	1,675
Grams of CO2 Emissions from Land Use Changes per Bushel of Corn (assumes 2.72 gallons ethanol/bushel)						2,700	1,856	4,556

## **Appendix E**

### **Key Assumptions of the Well-to-Wheel Analysis**

In general, the GREET well-to-wheel analysis of corn ethanol fuel was simulated using the default assumptions for year 2015. Key assumptions for corn production include the use of fertilizers (namely N, P<sub>2</sub>O<sub>5</sub>, K<sub>2</sub>O and CaCO<sub>3</sub>) and pesticides. Also, it is assumed that corn yield is around 158 bushels per acre harvested and that the ratio of harvested to planted acre is around 90%.

For corn ethanol production, ethanol fuel is produced in both dry and wet milling plants. Each plant type contributes to the overall ethanol production based on market shares (87.5% and 12.5%, respectively). Ethanol yield per bushel of corn is assumed at 2.72 and 2.62 gallons for dry milling and wet milling plants, respectively. Assumptions on the share of process fuels for each plant type are also different. For dry milling plants, the share of process fuels from natural gas, coal and biomass is at 89.7% while the rest is from electricity. For wet milling plants, process fuel solely comes from natural gas, coal and biomass sources. Concerning ethanol co-products, dry distiller grain co-products are produced from dry milling plants while corn gluten meal and feed as well as corn oil co-products are produced from wet milling plants. In estimating co-product emission credits, the displacement method is used. For the well-to-wheel analysis, key assumptions include fuel usage for passenger vehicles, fuel heating values and gasoline volume shares. The fuel use of passenger vehicles is assumed at 23.5 miles per gallon. Low heating values for ethanol, conventional gasoline (CG) and reformulated gasoline fuels (RFG) are assumed at 76,330, 116,090 and 113,602 Btu per gallon, respectively. In addition, assumptions on the shares of CG and RFG by volume are at 35% and 65%, respectively.

User-inputted assumptions are also adapted to generate the well-to-wheel emissions for pure gasoline and pure ethanol fuel. In generating emissions for pure gasoline, the O<sub>2</sub> content of RFG is assumed to be zero (Cell C47, Inputs worksheet). Emissions for pure ethanol fuel are estimated by changing the share of alternative fuel in ethanol fuel blend to 100% (Cell D407, Inputs worksheet). The share of gasoline by volume added in ethanol as denaturant is also changed to zero (Cell E407, Inputs worksheet). The CO<sub>2</sub> emission factor from land use change in corn production is also changed to zero (Cell C25, EtOH worksheet). This was done to generate emissions for pure ethanol fuel without land use change emissions.

In the report, some conversions are used to incorporate the land use change emissions in the emissions of pure ethanol and to compare these values to pure gasoline emissions. The results of the well-to-wheel analysis for the pure ethanol (grams per mile) were converted into grams per gallon of ethanol. Using the total fuel use for ethanol in Btu per mile (Cell K52, Vehicles worksheet) and the low heating value of ethanol in Btu per gallon (Cell B20, Fuel\_Specs worksheet) miles per gallon for pure ethanol was computed. This is then multiplied with the emissions per mile from the well-to-wheel analysis to estimate the emissions per gallon of pure ethanol with and without the land use change emissions (Table 11 and 12 of the report). To compare these emissions with those from pure gasoline, the total emissions per gallon of pure ethanol were converted back into emissions per mile using the miles per gallon for pure ethanol (Table 13 and 14 in the report).