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Supporting Online Material for

Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land Use Change

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SUPPORTING MATERIALS FOR
"USE OF U.S. CROPLANDS FOR BIOFUELS INCREASES GREENHOUSE GASSES THROUGH EMISSIONS FROM LAND USE CHANGE"

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Nearly all lifecycle analyses of the greenhouse gas impacts of substituting biofuels for fossil fuels leave out emissions from land use change. See Appendix A. This paper calculates emissions from worldwide land use change resulting from the expansion of corn-based ethanol in the United States, discusses the applicability of these calculations to other biofuels, and provides qualitative and quantitative sensitivity analysis.

I. The Forms of Land Use Change Emissions

This paper uses the term "land use change emissions" to refer to all of the carbon storage and ongoing sequestration that is foregone by devoting land to the production of biofuels. Land, of course, already exists and tends to store and sequester carbon whether devoted to biofuels or not. Using land to produce a biofuel feedstock foregoes some of that storage and ongoing sequestration, which in effect causes offsetting emissions in a variety of ways.

First, a forest or grassland can be directly converted to grow a biofuel such as corn, resulting in the direct loss of the carbon in the standing trees and grasses and a fair chunk of the carbon after plowing up the soils. Soils store major quantities of carbon in forests and grasslands.

Second, the same land, if not devoted to biofuels, could continue to sequester carbon. For example, a young, growing forest will continue to sequester carbon as the forest grows for many years. This ongoing sequestration is lost if the land is converted to a biofuel for ethanol. (Although land converted to grow the biofuel, such as corn, will continue to sequester carbon, the typical biofuel analysis already takes account of that carbon.)

Third, both of these effects can occur indirectly. For example, if corn in the United States is diverted to ethanol production, grasslands or forest could be converted anywhere in the world to replace the corn. Complicating this analysis, these indirect effects can pass through many steps. For example, soybean land in the U.S. can be planted in corn, and forest or grassland plowed up in Brazil to replace the soybeans.

In essence, under typical biofuel calculations, the carbon withdrawn from the atmosphere by growing the feedstock becomes a greenhouse gas credit. Tables 1A and 1B. We call this

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credit a feedstock uptake credit, which we treat as part of the overall land use effect. But the world's land already exists, and that land is for the most part removing carbon from the atmosphere each year and in most cases has stored substantial amounts of carbon for decades that may be lost if used to produce biofuels. The proper focus must be on the net change in carbon removed from the atmosphere that is either stored by land or used to replace fossil fuels. (Replacing fossil fuels is a form of storage because the unneeded fossil fuel remains stored underground.) An accurate accounting must subtract the emissions from land use change from the feedstock uptake credit to produce a proper net estimate of the overall land use effect – the effect of using land to produce biofuels.

II. Relative Greenhouse Gasses from the Production and Use of Corn-Based Ethanol and Gasoline Ignoring Land Conversion

The Greenhouse Gases, Regulated Emissions and Energy Use in Transportation model (GREET) of corn-based ethanol, produced at Argonne Laboratories, provides one of the more commonly accepted analyses of the greenhouse gas benefits from the use of corn-based ethanol. (S*1*-*S3*) It projects, for example, that ethanol as of 2015 will produce a 20% benefit in greenhouse gas emissions per kilometer driven compared to the use of reformulated gasoline. The corn ethanol scenario analyzed by GREET generated primarily through the more efficient "dry milling" process.[5] We have divided the emissions into four categories:

- Making feedstock emissions are those emissions associated with the production and drilling for oil and transportation to a refinery, or in the case of ethanol, with the production of corn through the use of fertilizer, tractor fuel and other inputs.
- Fuel emissions for gasoline are those associated with the refining process, and for ethanol, with the production of ethanol from corn. (In calculating fuel emissions, GREET, like other life-cycle analyses, has assigned a significant chunk of the emissions to the dry distillers grain (DDG) by-product that is used for feed, and our analysis assumes the accuracy of this assignment.)
- Vehicle operations are primarily those emissions connected with the burning of gasoline or ethanol in the vehicle.
- Finally, in the case of ethanol, there is a large emissions credit connected to the removal of carbon from the atmosphere through growing the corn, which we call the feedstock uptake credit, and which we list as part of the land use effect. (GREET incorporates this credit into the overall calculation for feedstock emissions, but we segregate it to highlight the effects of land use change.)

GREET calculates emissions of GHGs as CO_2 equivalents on an emissions per mile driven, which compensates for the differential energy content of gasoline and ethanol, and which we translate into grams per kilometer as shown in Table 1A. (We used GREET's calculations for E-85, a blend of 85% ethanol, and then isolated the impact of the ethanol itself.)

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[5] The default GREET 1.7 corn ethanol production process is 85% dry milled and 15% wet milled. (GREET, EtOH sheet, row 160).

Table 1B presents the same data as grams of GHGs per mega joule of energy in the fuel.[6] The advantage of using emissions per mega joule is that they are independent of the relative fuel efficiency of the vehicle.

Calculated in this way, corn-based ethanol produces a greenhouse gas benefit of 57 g/km compared to the use of gasoline (a benefit of 18 g/MJ), and a 373 grams per liter benefit, which represents a 20% improvement. GREET 1.7 includes a small 2.5 g/km land conversion charge in its calculation of feedstock emissions, whose merit we discuss below. We removed this small conversion cost so that we could replace with alternative land conversion costs calculated in this paper. These GHG benefits can also be translated into GHG benefits for each hectare of corn field devoted to ethanol. They translate into 1.8 MT/ha/yr (CO2 equivalents).[7]

If corn-based ethanol could not receive a credit for removing carbon from the atmosphere – deleting the feedstock uptake credit from the GREET model-- it would increase greenhouse gas emissions by 48%. It follows that if the use of land to grow corn for ethanol has the net effect of reducing land-based carbon sequestration, the overall effect will be a bigger release of greenhouse gasses.

III. Calculating the Land Use Change Costs of Corn-Based Ethanol

A. Brief Background Discussion of Corn Markets and Response to Increased Ethanol Demand

In 2004, farmers harvested 30 million hectares of domestic corn.(*S4*) Of this figure 11% was already used for corn-based ethanol, and 15% was exported, primarily for use as an animal feed, with Asia (48%), North America (18%), and the Middle East (18%) the dominant markets.(*S5*) Of the corn used domestically for purposes other than ethanol, 82% went to animal feed, and 18% went to food, high fructose corn syrup, corn oil, corn starch or other processed corn uses.(*S5*) The amount of ethanol produced and hectares of corn production are already rising rapidly in response to Congressional mandates, the use of ethanol as a gasoline oxygenate, high gasoline prices, and tax credits.(*S6*)

As each hectare of corn production is diverted to ethanol production, the price of corn will rise and grain substitutes will rise, and the rise in prices will modestly decrease the consumption of corn and soybeans for non-ethanol purposes. Competing demands for land that can grow either corn, soybeans or wheat will also create pressures for price increases for those crops, although effects on soybean prices are counter-balanced in part through by-products from

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6 To do so, we use GREET's assumption of the energy content of fuel, which allows the conversion of g/km to g/MJ at 3.04 mega joules per kilometer.

7 The calculation is grams/km (57) * kilometers per liter (7.15) (part of the GREET model) * liters per MT (405) (10.28 liters/bushel) * metric tonnes per hectare in the 2015 scenario (10.8) (425 bushels/ha) = 1,782,624 g/ha of GHGs or roughly 1.8 MT. This calculation uses kilometers per liter but is ultimately independent of driving efficiency because any change would be reflected in the emissions of cars running gasoline as well as cars running ethanol and result in comparable changes to both numbers on a proportionate basis

corn-based ethanol such as dry distillers grain (DDG's), corn gluten feed, and corn gluten, which can also be used as high-protein animal feeds that substitute for soybean meal fed to livestock. On balance, the combined production of corn, soybeans and wheat will increase to compensate for the shift of corn to ethanol, and that in turn will result in more hectares of land brought into some form of crop production. Of course, individual farmers around the world do not perform these calculations and assume a responsibility to make-up a certain level of crops. What they react to is an increase in price. As expected, scientists have documented that a rise in the price of soybeans has a significant affect on the rate of clearing of rain forest and grassland in Brazil. (*S7)*

Ultimately each hectare of corn used for ethanol —even at low production levels — results in some fraction of an increase in cropland in production worldwide, but the result is most obvious when one considers large possible increases in ethanol production. For example, the same agricultural modeling analysis used in this study calculates that corn-based ethanol will rise to 56 billion liters at $54/barrel of oil and with existing tax credits by 2016(*S10-S11*). At that level at then-prevalent yields, 12.8 million hectares of corn would be devoted entirely to ethanol—43% of the entire U.S. corn land harvested for grain in 2004(*S4*)—and impacts on world markets and cropland in production become obvious.[8] The same analysis also predicts that corn ethanol could rise to 112 billion gallons at $64/barrel of oil if constraints on automobile use are removed, which would require 25.4 million hectares, roughly 85% of the corn lands in 2004.

B. Brief Summary of Our Method for Calculating Land Use Change Emissions

This section briefly describes our method for calculating land use change emissions.

1. The first step used established models to estimate the change in cropland in production in individual countries around the world as a result of a significant rise in corn-based ethanol in the U.S.

2. The next step required that we calculate the average per hectare emissions of CO_2 that result from the average hectare of cropland expansion in each country. To calculate emissions, we used data compiled at the Woods Hole Research Center to estimate the net conversion of different types of ecosystems (for example, forests or grasslands) to cropland in each major world region over the period of 1990-99. We apportioned the additional cropland in each country to different ecosystem types according to the proportion of ecosystem converted in the 1990's. We then calculated carbon losses in vegetation and soils for each ecosystem type.

3. The above calculations yield a total level of greenhouse gas emissions associated with the increased level of ethanol production in the CARD

[8] Corn production in 2004 was 300 million MT (11.8 billion bushels) using 29.8 million hectares. (*S4*). At 405 liters per MT (10.28 liters/bushel), that would require 138 million MT (5.45 billion bushels) to produce 56 billion liters. At projected average corn yields of 10.8 MT per hectare (425 bushels) by 2015 that would require 12.8 million hectares.

analysis. We then converted that level back to a rate of emissions from land use change per liter of ethanol, which could be translated into per kilometer driven and per mega joule of fuel energy in ethanol. We then factor those land use change emissions into the GREET greenhouse gas estimates of the other emissions associated with ethanol.

C. Impacts of Ethanol Growth on Lands in Crop Production

Our analysis uses a model developed by the Center for Agriculture and Rural Development (CARD), at Iowa State University based in significant part on models developed by the Food and Agricultural Policy Research Institute (FAPRI) at Iowa State and the University of Missouri.[9] The CARD modeling system includes a set of partial equilibrium, non-spatial, econometric market models. Our analysis permits the direct comparison of two different scenarios in the 2016 crop year: 55.84 billion liters of U.S. ethanol from corn and 111.76 billion liters, a rise of 55.92 liters.[10] These differences reflect projections of ethanol use based on different prices of gasoline and different constraints on automobile use of ethanol, but the accuracy of those projections regarding the absolute use of ethanol are unimportant to this analysis. This analysis focuses on the rate of land use change emissions per unit of ethanol, which GREET expresses as emissions per kilometer using ethanol, and which we also express as emissions per mega joule in fuel. As discussed below, it is possible that these emissions per kilometer could differ for much larger levels of ethanol.

Ethanol produces a feed by-product known as dry distillers grains (DDGs). Our analysis assumes that livestock will be able to use all DDGs—although cows can use far more than other livestock because of nutritional requirements—and therefore assumes the working out of various transportation constraints on DDG use today. Roughly one third of the corn in the diverted cropland therefore remains available for use as animal feed and does not need to be replaced.

The analysis also calculates reductions in livestock and crop demand around the world as a result of higher prices, changes in U.S. crop production, production levels and exports of different crops, livestock and dairy. Most significantly, the analysis estimates increased land in crop production in individual countries around the world in 13 separate crops.

This rise in ethanol production requires the diversion of corn from 12.78 million hectares at 2016 yields.[11] To produce this added corn, American farmers grow corn on significant land that would otherwise produce soybeans and wheat, and to a lesser extent other crops, and the result is declines in a variety of U.S. agricultural exports, and significant rises in prices, as

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9 The specific models used in this analysis are the CARD international ethanol analysis, the FAPRI international sugar model, and modified or reduced-form versions of the FAPRI U.S. and international crop models as described in (*S8-S9*). A general description of the modeling system can be found in (*S10*).

10 Of this 55.92 billion liter increase in ethanol, 2% is attributed to ethanol from sources other than corn. We ignore this distinction in this analysis. Doing so does not attribute land use change emissions to corn ethanol from other forms of ethanol, but it does assume that the emissions from land use change of these other feedstocks for ethanol are the same as those for corn.

11 Based on 10.79 MT/ha and 405.3 liters/MT for a total of 4,375.4 liters/ha.

reflected in Tables 2A and 2B. There are also significant declines in exports of chicken, pork and dairy but a modest increase in the export of beef because the availability of DDG's decreases the cost of beef relative to other meats.

Not all grain is replaced because the rise in prices decreases demand for uses of grains other than for ethanol. The CARD model factors in these reductions in demand, but they are modest. Even with the large price increases for grain, domestic meat prices increase by only 4-5% at the retail level, and out-of-home food prices increase by only 0.9% because the price of grain is only a modest part of the overall retail price of meat.(*S10*) Although the model calculates changes in consumption of all major crops, it is impossible to express these changes as a single decline in overall demand because the decline of each grain represents in part a decline in overall consumption of all grains due to higher prices and in part shift to other crops. It is also difficult to equate all changes in grain in one number because each grain also supplies different quantities of calories, protein, fats and other products. One way to express the shifts in demand is to calculate the diversion of corn for ethanol as a percentage of the world's total livestock feed by weight and responding decline in meat and milk. In our analysis, the diversion is 10% of the baseline animal feed expressed by weight. In response, we calculate a decline of meat from all livestock of 0.9% by weight. Appendix B. There are also declines of 0.56% of fluid milk equivalents. The decline in livestock takes place roughly half in developed countries (1,172,000 metric tones) and half in undeveloped countries (988,000 MT), and declines in dairy are comparably split.

These declines in consumption result in greenhouse gas "benefits" because they reduce the emissions from land use change. (For example, if the rise in prices were so great that none of the diverted grain were replaced, there would be no land use emissions.) The decline in meat consumption in the developed world might arguably be beneficial from a health perspective, but the decline in the undeveloped world in large part occurs because poor people have to reduce their meat consumption. This change in diet reduces greenhouse gasses otherwise associated with production of grain for meat but probably not through a desirable mechanism.

Our analysis assumes that yields in all countries will continue to increase according to present projections through 2015-16 in all crops, including, for example, an average world corn yield increase worldwide by 11.5% from 2007. (*S12*) Faced with higher prices, farmers will also attempt harder to increase yields with expanded irrigation, and increased or improved use of fertilizer, pesticides and advanced seeds.[12] On the other hand, bringing additional croplands into production will also depress yields by requiring use of less productive lands, and increased corn prices will cause many farmers to plant corn after corn, instead of rotating corn and soybeans, which also depresses yields. We assume that these positive and negative effects on yield balance each other out although we test an alternative scenario in our sensitivity analysis.

Ultimately, as shown in Appendix C, our analysis predicts an increase in crop production of 10.816 million hectares. These lands occur in a wide variety of countries, including 2.8 million hectares in Brazil, 2.3 million hectares in China and India combined (each is separately estimated) and 2.2 million hectares in the U.S. The total increase in cropland around the world is

[12] Some discussions of hope and challenges with dramatically increasing yields beyond existing trends are at (*S13-S14*).

larger than the increase would need to be if confined to the United States because, with the prominent exception of Brazilian soybeans, foreign yields tend to be significantly lower than those in the U.S.

D. Greenhouse Gas Emissions from Cropland Conversion

The next step in the analysis calculates the greenhouse gas emissions from these increases in cropland in each country. These emissions depend on which countries expand production and what kinds of lands they expand into. For this purpose, we used data compiled at Woods Hole Research Center of the amount and type of land conversion to cultivation in the years 1990-99, based on references set forth in Appendix D. For example, in Canada, 20% of the land conversion to cropland in that period has come from temporal evergreen forest, and 80% has come from temperate grassland. (In other regions, there is a greater variety of types and more balanced conversion.) We assumed that future conversions in each country would come from forest and grassland types in the same proportion as for the years 1990-99. Appendix D presents this data.

In turn, we estimated the amount of carbon in vegetation and soils for each type of forest or grassland and calculated emissions from agricultural conversion for each type. This calculation assumed the loss of 25% of the carbon in the top meter of soils, [13] and the loss of all carbon in vegetation through burning or decomposition because plant material needs to be removed to turn forest or grassland into cropland. We calculated a weighted average of the emissions associated with each ecosystem type in each region to produce an average emission cost per hectare. This calculation primarily consists of up-front conversion costs, in that the costs will occur over a few years as a result of the conversion itself. Because of the way we use these emissions, we only need to assume that all the emissions we calculate will occur within 30 years, and we therefore avoid the uncertainties of the precise rate of loss within this period.

There is also ongoing, foregone carbon sequestration on those forests that are re-growing, and whose conversion sacrifices that carbon sequestration. These re-growing forests have lower amounts of stored carbon, which are reflected in lower up-front carbon loss estimates for vegetation, but they would also continue to add carbon each year if not cultivated, and that foregone carbon sequestration is lost. We separated growing from re-growing forests and estimated the rate of carbon addition on those portions of forests that are re-growing. These rates are modest compared to many estimates of potential reforestation benefits because they are based on changes in carbon content of forests over time of all re-growing forests of a regional type, which implicitly accounts for the fact that some portion of forests are regularly disturbed and lose carbon (e.g., through fire). We counted as a cost of land use change the foregone carbon sequestration that will not occur on otherwise re-growing forests over 30 years.

This analysis does not include greenhouse gas emissions associated with the fertilizer, pesticides, tractor use and other sources of emissions from producing the crops on replacement

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[13] One review article found that studies on average found a 22% reduction in soil organic carbon for conversion of forest to cropland,(*S15*) while a separate meta-analysis, recombining data from other studies, found reductions of 42% for conversion of forest to pasture and 59% for conversion of pasture to cropland.(*S16*)

lands because there should be no increase in the emissions from producing crops for food. The GREET analysis, like other analyses, calculates emissions from fertilizer and other inputs for the production of corn for ethanol. If corn were not being used for ethanol but continued to be used for livestock and direct food, those same emissions would continue, so diverting corn to ethanol by itself does not actually cause any such emissions. In effect, if corn for ethanol only used existing cropland and were not replaced, these emissions counted in GREET would be inappropriate. However, replacing the corn and other crops elsewhere will also produce GHG emissions through fuel, fertilizer, and pesticides. We assume that these emissions in producing replacement grains are equivalent to those in producing the diverted corn. (Generally, foreign farmers use fewer inputs and fuel per hectare but they also have lower yields.) In effect, we assume that emissions *per MT* in producing corn and other replacement crops around the world equal the emissions in the U.S.[14]

The above calculations yield an estimated weighted average level of carbon emissions for each hectare in each region, which we converted from pure carbon to CO_2 equivalents. See Appendix D, Tables D-11 & D-12. We then assigned this level of carbon emissions per hectare to each country in that region. Multiplying the number of additional hectare of cropland in each country by that carbon loss per hectare, we then calculated a level of carbon loss per country. Summing these losses yields a total carbon loss internationally that would occur with 55.92 billion additional liters of corn-based ethanol. See Appendix E, Table E-3. Dividing the amount of carbon loss to land use change by the number of liters yields a land use change emission cost per liter, which can in turn be translated into emissions per kilometer driven for addition into the GREET model results for corn-based ethanol.

G. Results

The above efforts yield a total amount of carbon loss from land conversion of 3.801 billion MT (CO_2 equivalent) to produce an additional 55.92 billion liters of ethanol. Appendix E, Table E-1. Much of that cost occurs immediately, but some of the soil carbon loss could occur over 30 years. Because we compare these emissions to the cost of 30 years of ethanol consumption, we treat them as up-front costs. That yields a land conversion cost (rate of emissions) of 67,976 grams to produce 1 liter of ethanol per year. That translates (at the GREET estimate of 7.15 kilometers per liter of pure ethanol), into 9,507.1 grams of GHGs per kilometer CO_2 equivalent). (As emphasized above, the driving efficiency does not alter the proportionate relationship between ethanol and gasoline because an increase in mileage efficiency would proportionately reduce both of their emissions per kilometer.) These costs can be amortized over 30 years (i.e., 30 years of ethanol) at 316 grams per kilometer. These emissions can be factored into the GREET analysis of GHG benefits per kilometer using corn-based ethanol. Driving a kilometer using corn-based ethanol under the GREET analysis produces a benefit of 57 grams of GHGs per kilometer after subtracting the modest GREET 2.5 grams per kilometer land use

[14] Our analysis calculates that a small portion of the grain diverted for ethanol is not made up because of a reduction in demand due to higher prices. Technically, therefore, we are assuming that emissions with producing that grain on replacement lands are modestly higher per bushel than producing the grain in the U.S. Relative to the land conversion costs we calculate, the emissions associated with the production of grain are modest, so even some difference either way would not significantly affect our findings, but we would welcome further analysis of this question.

change charge. Factoring in our 316 g/km charge for land use change results in an increase of GHG's when using ethanol instead of gasoline to 536 g/km compared to 221 g/km. (In grams per mega joule, the increase is from 74 g/MJ to 177 g/MJ, an increase of 103 g/MJ). Viewed another way, the GREET numbers we use, not counting land conversion, project a 20% reduction in GHG's using corn-based ethanol compared to using gasoline, but factoring in land conversion costs and amortizing them over 30 years roughly doubles greenhouse gas emissions (from 278 g/km for gasoline to 536 g/km for ethanol, an increase of 93%) (Table 1A & 1 B).

As discussed, most of these land conversion costs occur up-front, within a few years, and by our assumptions, all would occur within 30 years. Eventually, over time, using corn-based ethanol instead of gasoline, as calculated by Argonne, would produce GHG benefits that would recoup these costs. It would take 167 years to pay-back the up-front carbon loss.[15] In other words, ethanol production would cause net greenhouse gas emissions until corn ethanol had been used for 167 years.

IV. Sensitivity Discussion

This section discusses some of the uncertainties in our analysis and provides some qualitative and quantitative analysis of possible alternative assumptions.

A. Scale of Biofuel and Land Use Demand

Our analysis calculates a rate of emissions from land use change per unit of ethanol, but to do that it needs to posit some aggregate level of ethanol increase. According to our model, the size of the increase in corn ethanol does not significantly affect the direction or location of increased biofuels according to the assumptions used, which include no reduction of acreage under the Conservation Reserve Program and no overall reduction in yields due to the use of more marginal lands. In general, the overall effect of increased biofuel use on supplies and reductions in demand for food and feed is roughly linear for increases within a certain range. As an example, we modeled a scenario in which corn-based ethanol increased by 30.6 billion liters instead of 56 billion liters, an aggregate increase only 55% as large. In this scenario, the increase in GHGs was 284 g/km instead of 316 g/km, an emission rate from land use change 10% lower.[16]

[15] This is calculated as 9,507.1 g/km over 30 years, representing the land use change emissions, divided by 57 g/km advantage of ethanol over gasoline ignoring land use change. This calculation assumes that forests and grasslands would cease to sequester any additional carbon after 30 years. Further carbon sequestration after this period would increase the payback period.

[16] This analysis was based on a “bottleneck” scenario, under which the U.S. ethanol consumption is limited by insufficient E-85 vehicles in the fleet, thus keeping the increase in ethanol to only 30.6 billion liters compared to the 55.9 billion liter increase we principally analyzed. According to our analysis, that increased ethanol causes an increase of 5.4 million hectares of cropland, which causes the emission of 1.868 billion MT of GHGs, which results in emissions from land use change of 284 g/km versus 316 g/km in the scenario with a larger ethanol increase.

Much larger increases in biofuels (outside the range analyzed) could change these calculations with unpredictable results for the magnitude of emissions from land use change. These increases could occur not just through larger increases in the U.S. but also through large biofuel increases in demand in other countries reflected by their biofuel goals. (*S17-S18)*. In general, as demand increases dramatically, producers will find it harder to fully meet this demand with new cropland, and they will have to use more and more marginal land. That implies larger price increases, meaning that increased biofuels may come more at the expense of demand for food and feed, which would decrease land use change emissions (at the expense of more reduced diets). Much higher prices, and reduced availability of good lands, may also spur more investments in yield increases to supply some of the needed grain, which would also reduce land use change emissions. However, reliance on more marginal lands with lower yields implies more land needed per unit of new supply and possibly expansion into more remote lands, both of which would increase land use change emissions.

The size of the biofuel increase causes price increases for crops that are somewhat outside of historical range until the last few years. The CARD model was adjusted, however, to reflect the higher price regime of recent years and to estimate long-term equilibrium behavior. In addition, the baseline price predicted for 2016 of $3.15 per bushel, which already reflects heavy biofuel demand, is within historical ranges reached five times out of the last twenty-seven years. The 40% increase in corn price under the higher biofuel use scenario compared to the baseline, although high, is also within historical year-to-year price changes observed in the last two decades of 20 to 52 percent. The main difference is that the high prices in the projection period are more permanent than historical shocks that elevated prices.

Ultimately, the driving force behind the estimates of increased cropland use is the simple requirement that supply must meet demand. The model permits a calculation of how much of the adjustment to biofuels will be met by reductions in demand for non-biofuel uses of crops, and how much will be met by increased cropland. It also permits estimates of the locations of these increased crops. With larger demand shocks, consumers and producers could respond somewhat differently, but the basic prediction that most of the diverted grain will be replaced is consistent with prior experience. The predictions of the major sources of new production are also consistent with the authors' general knowledge of production opportunities and constraints in the major producing countries.

B. Alternative Greenhouse Gas Policies

Our analysis assumes that land converted to cropland because of biofuels would otherwise continue in its present use. It therefore does not analyze the true carbon opportunity cost of devoting land for biofuels, which includes foregoing opportunities to enhance their carbon content through management. If government policies create an incentive for carbon sequestration, more of these lands might revert to forest or otherwise receive enhanced sequestration efforts, increasing the amount of carbon they sequester. In that event, biofuel production would sacrifice more alternative carbon sequestration, and those alternative rates of carbon sequestration could exceed the benefit of devoting the same land to biofuels (*S19*).

C. Greater Increases in Yields Due to Price Increases

Our analysis assumes that the increase in ethanol will not alter yields, which will continue to increase according to the same worldwide trend lines. It is possible that higher prices will trigger yield increases on top of projected yield increases built into the 2016 baseline that more than offset use of more marginal lands. A rise in price due to ethanol will spur both some further increase in productivity as some farmers invest in irrigation, drainage, improved seeds and more inputs. It will also cause land conversion because experience has shown that farmers respond to price in this way. The question is how much of each. Ultimately, the question turns on the relative cost and technical capacity to increase yields versus the relative cost and capacity to convert more land. USDA has estimated that there is enormous land conversion potential in Brazil at 40 to 170 million hectares (*S20-S21*), and conversion there is proceeding at current prices already.

If we assume that price increases would cause further yield increases adequate to provide 20% of the replacement grain and feed, the payback period would decline to 133 years. (In other words, new cropland would only produce 80% of the replacement grain and feed.) If average yields modestly decline because of the use of more marginal land in a manner that requires a 10% increase in land devoted to replacement crops, the payback period would rise to 183 years.

D. Impacts of Diverted Pasture

Much of additional cropland, in our analyses, is converted from grasslands. Because nearly all world grasslands that could be used for crops are grazed, (*S22*) the conversion of cropland sacrifices forage from grazing land that now provides food for domestic animals. Replacing this forage should in turn lead to more land conversion either for grazing, which is a major source of deforestation in the Amazon (*S23*) or possibly to additional cropland. Our analysis ignores these effects because we wished to limit the analysis of land use change from agriculture to that which could be estimated with established models. As in the case of cropland, some forage could be replaced by intensification, in this case improvements of existing pasture, and some forage might never be replaced because of decreasing demand. In light of the role expansion of pasture is playing in deforestation, the additional land use change to replace forage is probably highly significant.

E. Alternative Carbon Estimates by Land Use Type

Our estimates of carbon in grasslands are based on the carbon of the natural ecosystem. Many of these grasslands are more heavily grazed than under natural conditions and therefore may have less carbon content, as over-grazing can possibly diminish root carbon. The actual carbon content could therefore be lower. However, as discussed above, our analysis fails to account for land use change needed to replace the annual forage no longer available from converted grasslands. As a whole, therefore, we probably undercount the effect of eliminating grassland vegetation.

The only wetlands counted in our analysis are those for Southeast Asian forest types. Wetlands can store large quantities of carbon in organic soils, and carbon losses associated with drainage for agricultural conversion can be much greater than 25%, and may continue indefinitely. If more wetlands are converted than we assume, emissions would be higher.

In general, the estimates of carbon in plants and soils used for this analysis by ecosystem type are more specific but generally comparable to those cited by the IPCC (*S24*). Table 3 compares the carbon emissions per converted hectare using the carbon content of ecosystems summarized in the IPCC analysis and our analysis, assuming 25% loss of carbon in soil and all carbon in vegetation.

Reducing estimates of carbon loss per hectare of conversion translates into proportionate reductions in GHG emissions from land use conversion per unit of ethanol. For example, if our estimates per hectare were cut in half, the pay-back period for corn-based ethanol would decline to 83 years. If emissions were double our analysis per hectare, payback periods would rise to 334 years.

F. Improvements in Pay-Back Time Due to Increases in Ethanol Production Emissions Efficiency

There are a number of factors that do not affect the land use conversion calculations but that could reduce the greenhouse gas emissions associated with other parts of ethanol, increase the relative benefit of corn-based ethanol compared to gasoline and decrease the payback time associated with the land conversion cost. For example, there could be improvements in the efficiency of the conversion of corn to ethanol (although improvements that reduce the level of DDGs per bushel would also increase the land use change emissions), reductions in the amount of energy needed to produce the ethanol, or improvements in the use of ethanol by-products. In addition to effects described above, improvements in yield could also increase the GHG production efficiency of corn by reducing the GHGs per bushel associated with fertilizer, pesticide and tractor use. Yet our land conversion cost is much higher than potential improvements in efficiency gains in the ethanol production process for the simple reason that our land conversion estimates are significantly higher than all the other emissions associated with the production and use of ethanol.

For example, if ethanol produced roughly a 40% reduction in GHG emissions compared to gasoline, not counting land conversion costs, the payback period we calculate would be reduced, to 85 years.[17] Even if a producer could eliminate all GHG emissions associated with producing the corn and converting that corn to ethanol – if ethanol emerged in gas stations at no GHG production costs at all and the feedstock uptake credit continued to offset nearly the entire emissions from burning ethanol in the vehicle-- it would still take 38 years to pay back the initial GHG losses.[18]

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17 In such a scenario, the GHG's associated with pure ethanol otherwise shown in table 1 would be only 166.8 per kilometer, which would require a reduction in the emissions involved in producing corn and refining it into ethanol from 197 g/km to 139 g/km and generate a reduction of 111 gm/km. But it would still take 85 years to pay back the initial emission of 9,507 g/km.

18 In such a scenario, apart from land use change, the GHG's associated with pure ethanol would only be those involved in burning it, generating a net emission of 28 g/km counting in GREET's feedstock removal credit, and providing for a greenhouse gas savings per kilometer

Of course, it is also possible that oil companies could reduce the emissions associated with the production of gasoline, which would reduce the GHG benefit of ethanol even ignoring land use change. There is also new analysis indicating that previous estimates of nitrous oxide emissions from cropland are low, and if corrected, may be enough by themselves to eliminate the greenhouse gas benefits of many biofuels even without regard to land use change. (*S25*)

G. Composite Low Emissions Hypothetical

As a further sensitivity exercise, we calculated the emissions associated with a range of more optimistic assumptions. These scenarios include the same demand reduction due to higher prices. (The alternative would mainly imply a larger reduction in meat consumption by poorer people in the developing world, and it is difficult to imagine a policy of deliberately pursuing greenhouse gas benefits by reducing their meat consumption.) However, we altered other assumptions as follows:

- Twenty per cent of all replacement grain would come from price-induced yield increases and therefore would not involve bringing any additional land into cultivation
- Corn-based ethanol would be produced in a manner that, absent land use change, produced a 40% reduction in the greenhouse gasses otherwise generated by gasoline. (This figure compares to the 2015 GREET estimate of 20% reduction and would necessitate a large increase in corn production and ethanol conversion efficiency compared to present production methods.)
- Emissions of GHG's per hectare of land conversion would be half of what we otherwise estimated.

Under this optimistic scenario, we calculate a payback period of 34 years, which means a net increase in greenhouse gas emissions until the end of that period.

V. What About Surplus Cropland?

Some favorable analyses of biofuels state or imply that by using their own reserve or surplus cropland, Europe or the U.S. would avoid land conversion and its emissions. For example, a staff working paper for the European Union estimates that European agricultural reserve lands could meet much of the potentially required new biofuel demands and does not describe impacts on these reserve lands as sources of potential emissions from land use change.(*S18*) Another European lifecycle analysis notes that importation of biofuels from abroad can increase "pressure on rainforest areas," making the whole carbon balance much worse, but assumes that using European lands to produce biofuels would not cause these emissions.(*S26*) More generally, this view is implied by the frequently expressed view that agriculture can produce both feed and fuel through rising yields.(*S13*) In fact, the potential

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compared to gasoline of 251 g/km. But it would till take 38 years to pay back 9,507 g/km of land use change emissions.

availability of unused croplands in some locations does not avert emissions from land use change.

First, to the extent there were true excess croplands, they would revert to grassland or forest and therefore gain carbon. Estimates of carbon gain from reforestation have been estimated at an average of 6.5 MT/yr (CO_2 equivalent) in the U.S (ignoring some emissions costs such as plantings). (*S27*) That compares to 1.8 MT/ha GHG reductions for corn ethanol using GREET data and yield assumptions in the CARD model. A recent paper also estimated the gains from reforestation and reversion to grassland as higher than those per hectare from most biofuels. (*S19*) Our analysis assumes that absent biofuels, Europe and the former Soviet Union would continue to lose cropland, but biofuel demands mean that more land would remain cropland, sacrificing the carbon gains that would accompany reversion to forest or grassland.

Second, continental shifts in crop production are occurring regardless of biofuels, with Latin America gaining cropland and Europe and the former Soviet Union losing cropland prior to recent biofuel expansion (Appendix C and (*S23*)). Declines in cropland in some regions do not prevent expansion in others, and the higher demand from biofuels would trigger greater expansion in Latin America and elsewhere.

Third, there are likely to be significant pressures on the world's land for crop production regardless of biofuels because of a growing population, expected to reach 9.5 billion in 2050, and rising incomes in China and India. Assuming existing rates of yield improvements, analyses project the need for hundreds of millions of hectares of new agricultural land. (*S22, S28-S29*)

Finally, much of what is considered surplus cropland consists of land brought into crop production in a minority of years when prices are high. This land comes in and out of production because of fluctuations in price. Although biofuel expansion will increase the average price of crops, prices will continue to fluctuate around a new average equilibrium price. For example, the CARD analysis predicted that a drought would cause the corn price in an expanded ethanol scenario to rise by $1.35 per bushel. (*S10*) That would trigger temporary increased production. There will remain an "extant margin" of cropland that will come in and out of crop production with price surpluses even as the amount of cropland in production on average rises.

In short, from a carbon perspective, there is no surplus cropland that can produce additional biofuels without some carbon cost.

VI. GREET Analysis of Land Conversion Costs

As described in Appendix A, most of the quantitative GHG estimates for corn-based ethanol have left out emissions from land-use change. The GREET analysis is one of the few that have not. Its estimate of the emission cost from indirect land use change for corn-based ethanol was 2.5 grams of GHGs per kilometer driven, only 1% of the emissions. GREET authors have been open in calling for further analysis of this issue, and there are four basic reasons the GREET analysis was so small.

First and most importantly, GREET was based on an estimate that extremely little land would be brought into production, using a combination of some informal USDA domestic analysis of market impacts, and a variety of other assumptions. Ultimately, when the numbers are analyzed, they imply that only 24% of the corn hectares diverted to ethanol would result in increased production on additional cropland. In our view, this is not a plausible result. One of the flaws was the assumption that only half of the decline in U.S. exports would be made up by other countries. That assumption would require a high elasticity of demand abroad for all feed grain, and the model's description attributed this reduction in demand to simple assumption. The GREET analysis also assumed that production abroad would occur at high yields for corn that approached those in the U.S. at the time, while yields abroad are much lower. (*S30*)

Second, the GREET analysis assumed that any conversions would occur exclusively on pasturelands or idle cropland. We see no basis for this assumption.

Third, GREET used small emissions numbers for emissions associated with these pasturelands of roughly 0.5 MT/ha/yr. Our estimated emissions for U.S. grasslands converted to cropland, amortized over 30 years, amount to 3.7 MT/ha/yr, which are low compared to IPCC estimates for temperate grassland generally (and foreign temperate grasslands are the same or higher). The GREET estimate was attributed to personal communication with Mark Deluchi. As discussed below, Deluchi also uses a special kind of discounting that we do not consider appropriate.

Finally, the analysis of land use conversion is somewhat scale-dependent. The 1998 agricultural projection used by GREET analyzed an increase in ethanol production only to 11.4 billion liters by 2010. With that increase, it was more plausible that much of the increase in demand could be satisfied by growing yields on existing cropland, or by replanting recently idled cropland. Both cause emissions, as we have argued above, but they are probably lower than the conversion of relatively undisturbed forests and grasslands. At higher production levels the likelihood that each incremental diversion of corn for ethanol will result in conversion of mature forest or grassland increases. As discussed above, in a world of growing demands for meat and grain, and where both the U.S. and foreign countries are considering large renewable fuel mandates on their own of one kind of another, the scenarios used in this paper are more realistic.

VII. The Potential Significance of the Time Horizon

Deluchi (*S31*) provided perhaps the most sophisticated prior analysis of land conversion costs from corn ethanol, and these costs are included as part a thorough analysis of a broad range of fuels through a model he calls the Lifecycle Emissions Model (LEM) [19] Deluchi's comparison of corn-based ethanol to gasoline yielded somewhat similar results to those of Argonne excluding the land conversion charge, but in his 2005 publication (*S31*) he assigns a 123 g/km land conversion cost for E-90, which transforms corn ethanol into a small net source of emissions compared to gasoline under the 2010 scenario. Deluchi's calculations followed

[19] Deluchi's report (*30*) cross-references earlier technical reports and appendices, all of which are available at http://www.its.ucdavis.edu/people/faculty/delucchi/. The description of the Deluchi analysis here is based on the 2005 report, the cross-referenced earlier reports, and communications with Deluchi.

similar logic to that followed here but without the benefit of a formal partial-equilibrium model for agricultural change. The analysis also incorrectly assumed that yields abroad would be the same as those in the United States and failed to account for the loss of foregone annual sequestration on converted forest. Another major distinction between the two analyses is how Deluchi handles time. Deluchi assumed that corn would be used to grow ethanol for only 30 years and the converted land would then be allowed to regenerate, which would restore carbon over time. Viewed this way alone, land use conversion would have no cost. But Deluchi then used a discount rate so that increased emissions in the short term are valued more highly than carbon re-sequestration that takes place over the long-term, resulting in a net increase in emissions. Deluchi took this number and amortized it over 30 years.

This form of analysis highlights that land use changes are not permanent. Its methodology would also go both ways. For example, by this rationale, carbon sequestration through reforestation would not create any net carbon sequestration over the long-term because it would subsequently be lost with land conversion again, but it would produce value because short terms gains are more valuable than long-term losses. We believe our analysis handles time in a more useful manner.

- First, it is not at all clear that land conversion for agriculture will be temporary. It may last indefinitely, and in any event, there is no way of predicting today how long ethanol will be used and the attributed land conversion will remain. Taking credit for future revision of converted lands essentially "books" as a carbon benefit today a stream of future carbon gains that is at best highly contingent.

- Second, we believe the decision to produce biofuels should be separated from any later decisions to reforest. By our approach, the conversion to agriculture is a cost, and if the lands are eventually reforested, that eventual change would be counted as a benefit. Our analysis does not ignore time, but treats it through the payback analysis that determines at what point the carbon balance is at least equal. From a policy perspective, we believe it is appropriate to segregate two distinct decisions.

- Third, the choice of a discount rate, and even the decision whether to select a constant discount rate, a varying but continuous discount rate, or a discontinuous discount rate, reflects an enormous range of technical and policy judgments. In general, the decision should reflect the relative environmental harm of earlier versus later emissions and relative cost of addressing them. These are matters of great uncertainty that the selection of a discount rate has to treat as certain. The incorporation of a discount rate directly into the model to count today the value of future reductions therefore has great potential to obscure the actual effect on emissions of biofuels for policy-makers in the near-term.

- Fourth, and most significantly, from a global-warming perspective, crop-based biofuels are generally viewed as at most a short-term strategy to provide immediate reductions in greenhouse gasses as the world pursues more transformative energy strategies. The IPCC has specifically warned against delaying emissions reductions because of the risk of harsh, long-term, unavoidable impacts without immediate reductions. (*S32*) Strategies that increase emissions over a 30 year period require offsetting additional reductions over that period to achieve near-term goals, and those additional offsetting reductions must be achieved at the highest point of the cost curve. Emission reductions during early years will also be more expensive than maintaining those reductions in the long-term once technologies have evolved. For these reasons, we believe the net impact on greenhouse gas emissions over a 30 year period provides a reasonable test of greenhouse impacts.

VIII. Illustrative Possible Land Conversion Emissions from Other Forms of Ethanol.

Land use change emissions are not limited to corn-based ethanol. Whenever a biofuel uses a plant grown for feedstock, and not merely a waste product, some greenhouse gas emissions due to land use change are likely to occur. The amount may vary greatly depending on the feedstock and the kind of land used.

Most biofuel advocates focus heavily on cellulosic materials. As shown in Table1, GREET projects that producing biomass-based ethanol using switchgrass will be highly efficient from a greenhouse gas perspective, leading to a 194g/km or a 70% reduction in GHG's compared to gasoline. Estimating likely land use change emissions from cellulosic ethanol is less predictable than corn-based ethanol because no one knows the kinds of lands that might be employed to grow it. Cellulose made from waste organic matter should cause no land use change if truly a waste product. But many analysts contemplate growing cellulosic materials on corn or soybean fields, which are typically grown in rotation. If each hectare of switchgrass uses a hectare now used to produce corn, that diversion would still cause land emissions and our existing estimate for diversion of corn can be used. (From the standpoint of land use change, using a hectare to grow cellulose for biomass is equivalent to diverting that hectare's corn production to ethanol.)

One adjustment is needed. In the case of corn-based ethanol, DDGs reduce the amount of feed-grain needed to replace the diverted corn by one third. In effect, for every three hectares of diverted corn, only two hectares of corn must be made-up (subject to small reductions in demand due to higher prices.) We assume at this time that cellulosic ethanol will not have an animal feed by-product. As a result, three hectares of diverted corn cropland to switchgrass require replacement by three hectares worth of grain (subject to the same reductions in demand related to prices). Compared to corn ethanol, each hectare diverted for switchgrass will cause a 50% higher increase in land use change.

Assuming fields of average corn yield, we calculated that a hectare of diverted corn for corn ethanol would trigger 297.4. MT of GHGs from land use change.[20] Adjusted by 50% as explained above, that translates into 446.15 MT/ha of corn land diverted to produce cellulosic biomass. GREET's 2015 scenario for cellulosic ethanol assumes 343.3 liters per dry MT.

[20] The land use change of 3.801 billion metric tonnes reflected the diversion of 12.78 million hectares, triggering emissions of 297.4 MT per *diverted* hectare. This figure is not to be confused with MT per *converted* hectare discussed above.

GREET does not use a biomass yield per unit area in its calculations, so we used yields from a study at Oak Ridge Laboratory for switchgrass, (*S33*) which predicted that with "intensive genetic selection and research" yields of 18 MT/ha were achievable. That means that each diverted hectare would generate 6180 liters of ethanol, for a rate of emissions from land use change of 72,129 g/l (446.15 MT/ha of emissions divided by 6,180 l/ha). Amortized over 30 years, land use change emissions are 336.6 g/km. Over 30 years, that increases emissions by 50% and the payback period is 52 years.

Our emissions for indirect land use change above reflect the emissions from converting land to cropland to replace cropland diverted to switchgrass. GREET separately incorporates into its calculation of producing biomass a carbon credit in the amount of 53,462 g/MT of biomass to reflect the increased soil carbon sequestration from grasslands. (It calls this credit a "land use change" effect, and it can be viewed as a "direct" effect, but it is part of GREET's overall calculation of feedstock production emissions, including use of fertilizer and tractor fuel.) At the estimated yield of 18 MT/ha/yr, this credit translates into 962,318 g/ha/yr and a total of 28.9 MT over a 30 year period. The estimate of roughly 1 MT/ha/yr in CO2 equivalents could be low for land in continuous switchgrass cultivation, and some lands might maintain switchgrass continually. But farmers who grow switchgrass would presumably also be free to plow it up to grow other crops, and many might do so at least once or occasionally as crop prices fluctuate over 30 years. Doing so would release much of the stored carbon. We consider GREET's estimate of direct carbon gain reasonable and leave it unchanged in the calculations pursuant to our policy of using GREET for all calculations other than land use change from induced agricultural expansion.

Increased ethanol could also use sugarcane grown in Brazil. Macedo et al. (*S34*) have estimated GHG benefits of anhydrous ethanol from sugarcane at 86% compared to the use of gasoline in Brazil. (The exact savings depend on the form of sugarcane ethanol and the production method, and some of the savings are derived by using sugar bagasse to produce electricity and displace fossil fuel emissions in that way.) These analyses do not include land use change emissions. Sugarcane is generally grown in the south of Brazil, and advocates for greater reliance on sugarcane ethanol claim that increased sugarcane land will come out of pasture, coffee and citrus lands. However, conservation groups have raised concerns that these kinds of expansion trigger indirect conversions, as displaced ranchers move into forest.

We have not attempted to estimate likely conversion but offer the following rough estimate of the potential impacts of land use change based on Mercado's estimates excluding land use change. If sugarcane lands convert tropical pasture, and there is no additional indirect conversion, there would be a four-year payback period according to Mercado's estimates of GHG benefits for anhydrous ethanol.[21] But if grazers displaced for sugarcane burn down

[21] Mercado estimates that each MT of sugarcane generates savings of 220 grams of GHGs for anhydrous and 147.4 for hydrous ethanol, which at his estimated average yield of 82.4 MT/ha, translates into GHG savings of 18 MT/ha savings for anhydrous and 12 MT/ha savings for hydrous. (*S34*) According to our estimates as shown in Appendix C, conversion of Latin American grassland causes the loss of 74 MT (CO2 equivalent), which translates into a payback period of 4 years, and conversion of tropical forest can reach as high as 824 MT/ha, which translates into a payback period

rainforest to replace grazing land, the payback period could rise to 46 years, depending on the type of forest. If sugarcane is produced in wetlands other countries, which has been common in the United States, the emissions could be significantly greater.

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of 46 years for anhydrous. This rough estimate differs from estimates for corn and biomass ethanol in that it assumes no reduction in demand for non-fuel purposes due to higher sugar prices.

TABLES

Table 1A – Comparison of GHG Well-to-Wheel Emissions by Stage from Gasoline and Ethanol-Fueled Vehicles – Grams (CO_2 equivalent) Per Kilometer Driven

	Making Feedstock	Refining Fuel	Vehicle Operation (Burning Fuel)	Net Land Use Effects: GREET Feedstock Uptake Credit	Net Land Use Effects: Land Use Change	Total GHG	Change in net GHGs vs. Gasoline
Gasoline	11	47	220	0		278	
Pure Corn Ethanol	72	121	215	-188		221	-20%
Corn Ethanol with Our Land Use Change Emissions	72	121	215	-188	316	536	93%
Biomass Ethanol	29	26	215	-188		83	-70%
Biomass Ethanol with our carbon charge	29	26	215	-188	336	418	50%

Source: Calculated with GREET 1.7(4) using default assumptions for 2015 scenario. Gasoline is a combination of conventional and reformulated gasoline. Ethanol emissions remove emissions of 15% gasoline from E85 fuels. GREET assumes 7.15 km/liter for ethanol (and rates for gasoline adjusted for higher energy content). The table deletes from Making Feedstock column the GREET 2.5 grams/km estimate of emissions from land conversion for corn ethanol but includes credit for direct soil carbon gain by switching cropland to switchgrass. Land use change emissions are amortized over 30 years. The land use change estimate for biomass assumes switchgrass produced on average-yielding U.S. corn fields, at 18 MT/ha (*S33*) without feed by-product. Numbers in columns may not sum due to rounding.

Table 1B – Comparison of GHG Well-to-Wheel Emissions by Stage from Gasoline and Ethanol-Fueled Vehicles –
Grams (CO2 equivalent) Per Mega joule of Fuel

	Making Feedstock	Refining Fuel	Vehicle Operation (Burning Fuel)	Net Land Use Effects		Total GHG	Change in net GHGs vs. Gasoline
				GREET Feedstock Uptake Credit	Land Use Change		
Gasoline	4	15	72	0		92	
Corn Ethanol	24	40	71	-62		74	-20%
Corn Ethanol + Our Estimate of Land Use Change	24	40	71	-62	104	177	93%
Pure Biomass Ethanol	10	9	71	-62		27	-70%
Pure Biomass Ethanol with Our Estimate of Land Use Change	10	9	71	-62	111	138	50%

Source: Calculated with GREET 1.7(4) using default assumptions for 2015 scenario for E-85. Gasoline is a combination of conventional and reformulated gasoline. Ethanol is pure corn or biomass ethanol adjusted from emissions of E-85 by removing gasoline component. GREET calculates emissions per mile (converted to kilometer) driven using fuel efficiency assumptions, which are converted to mega joules using GREET's estimate of MJ/liter of fuel. The table deletes from Making Feedstock column the GREET .82 g/MJ estimate of emissions from land conversion for corn ethanol but maintains soil carbon gain from switching cropland to switchgrass under biomass. Land use change emissions are amortized over 30 years. The land use change estimate for biomass assumes switchgrass produced on average-yielding U.S. corn fields, at 18 MT/ha without feed by-product. Columns may not sum due to rounding.

Table 2A – Change in Agricultural markets Due to Rise in Corn Ethanol
From 55.84 to 111.76 Liters in 2016/17– English Units

Crops					
Agricultural Product	**Unit**	**Change in Price**	**Change in Domestic Planted Hectares (Million hectares)**	**Change in Exports (Million units)**	**Change in Export Percentage**
Corn	Bu.	$3.15 to $4.42	**+8.2**	-1523.1	-62%
Wheat	Bu.	$4.29 to $5.04	-2.1	-320.4	- 31%
Soybeans	Bu.	$6.56 to $7.85	-3.9	-252.6	-29%
Livestock					
Agricultural Product	**Unit**	**Change in Price**	**Change in Domestic Consumption (Million units)**	**Change in Exports (Million units)**	**Change in Export Percentage**
Beef	Lb.	$4.52 to $4.73	-551.3	**+200.9**	**+9%**
Pork	Lb.	$3.30 to $3.43	-330.1	-759.4	-18%
Chicken, broilers	Lb.	$1.96 to $2.04	-1,149.2	-861.6	-13%

Table 2B – Change in Agricultural Markets due to Rise in Corn Ethanol from 55.84 to 111.76 Liters in 2016/17– Metric Units

Crops					
Agricultural Product	**Unit**	**Change in Price**	**Change in Domestic Planted Hectares (Million hectares)**	**Change in Exports (Million units)**	**Change in Export Percentage**
Corn	MT	$124 to $174	**8.2**	-38.5	-62%
Wheat	MT	$169 to $198	-2.1	-8.1	-31%
Soybeans	MT	$258 to $309	-3.9	-6.4	-28%
Livestock					
Agricultural Product	**Unit**	**Change in Price**	**Change in Domestic Consumption (units?)**	**Change in Exports (Million units)**	**Change in Export Percentage**
Beef	MT	$9,965 to $10,428	-550.1	**0.09**	**9%**
Pork	MT	$7,275 to $7,562	-327.2	-0.34	-18%
Chicken, broilers	MT	$4,321 to $4,497	-1,139.60	-0.39	-13%

Table 3 – Comparison of GHG Losses by Ecosystem Type Assuming Loss of 25% of Carbon in Soil and all Carbon in Vegetation

Ecosystem Type	IPCC GHGs/ha (CO_2 eq.)[a]	Our Analysis GHGs/ha (CO_2 eq.)
Tropical Forest	553 to 824	604 to 824
Temperate Forest	297 to 627	688 to 770
Tropical Grassland And Savannas	189 to 214	75 to 305
Temperate Grasslands	139 to 242	111 to 200
Wetlands	748 (worldwide figure)	1146 for tropical moist forest of southeast Asia

[a] Range is from different studies cited in (*S24*).

Appendix A
Summary of Discussion of Land Use Change in Other Ethanol GHG Papers
(excluding those discussed in text)

Many papers have mentioned the potential significance of land use changes without calculating them although some papers appear to be focused solely on direct land use change, not indirect change, and thus do not appear to recognize that using existing cropland will still require agricultural expansion to replace those crops.

Farrell et al. (*S35*), finds that corn ethanol generates a 19% reduction in GHGs, but it's supporting materials (*S36*) state at page 12:

> "Significantly greater use of biofuels might shift marginal or unused lands into crop production, however, potentially resulting in significant changes in net GHG emissions due to land use changes alone. The possibility of importing ethanol suggests that land use changes as a result of U.S. ethanol use could occur outside of the country, raising concerns about, for instance, the conversion of rainforest into plantations for fuel production. Estimating the magnitude of such effects would be very difficult, requiring analysis of land productivity and availability, commodity markets, and other factors, none of which are considered in the studies evaluated here. For these reasons, we ignore GHG emissions due to potential changes in land use."

Commission of the European Communities (18) finds a variety of reductions in GHGs for various ethanols but states, at page 20:

> "The JEC data do not take account the effect of land use change, notably changes in soil and plant carbon stocks. This can be positive (as it would be, for example, if sugar cane plantations replaced degraded pasture land), largely neutral (where biofuel demand leads to higher yields from areas that are already cultivated), largely neutral (where biofuel demand leads to higher yields from areas that are already cultivated) or severely negative (for example, if soybean cultivation replaced rain forest). In the absence of a global land use model, it has not been possible to estimate the greenhouse gas effect of the land use changes likely to be associated with these scenarios."

Smeets (*S37*) reports GHG savings for sugarcane ethanol but states at page 54:

> "Quantifying [land conversion] effects and their uncertainty clearly exceeds the scope of this research, but is deemed very important and strongly recommended for further research. . . For new sugar cane plantations, direct and indirect GHG emissions due to land use change may have a (potentially large) impact on the GHG balances."

Hill et al. (*S38*), estimates a 12% gain from the use of corn-based ethanol compared to gasoline without calculating conversion cost while stating, "It is important to note that these estimates assume these biofuels are derived from crops harvested from land already in production; converting intact ecosystems to production would result in reduced GHG savings or even net GHG release from biofuel production."

Zah et al (*S26*) estimates greenhouse gas reductions for biofuels that leaves out indirect land use effects.

Other papers have calculated GHG impacts without calculating or mentioning land conversion costs.

Patzek (*S39*) estimates a 48% increase in GHG emissions from corn ethanol compared to gasoline without calculating in any cost for land conversion.

Kim & Dale (*S40*) finds greenhouse gas benefit would reduce greenhouse gasses and factors in ongoing carbon loss in the soil used for growing corn but does not factor in land conversion.

Adler, Grosso & Parton (*S41*) finds significant greenhouse gas benefits from all biofuel sources using a methodology that credits soil carbon sequestration from feedstock production but ignores land use change and existing carbon sequestration on lands devoted to biofuel.

Appendix B
Reductions in demand for dairy and livestock as a result of higher prices from expanded ethanol scenario

Table B-1 – Changes in world dairy and livestock consumption (in thousands of MTs)

	Scenario			Baseline			Difference			
	Dev*	Undev†	Total	Dev*	Undev†	Total	Dev*	Undev†	Total	Total % Change
Fluid milk	93,130	117,659	210,790	93,351	117,926	211,277	-221	-267	-487	-0.23%
Butter	3,392	5,783	9,176	3,398	5,789	9,187	-6	-6	-7	-0.08%
Cheese	14,462	3,201	17,663	14,504	3,210	17,714	-42	-9	-50	-0.28%
Nonfat Dry Milk	1,817	1,843	3,659	1,824	1,858	3,683	-7	-15	-32	-0.87%
Whole Milk Powder	472	3,462	3,934	474	3,469	3,943	-2	-7	-5	-0.13%
Total Dairy (fluid milk eq.)	**279,276**	**293,602**	**572,878**	**279,958**	**294,111**	**574,069**	**-682**	**-509**	**-3,195**	**-0.56%**
Beef	30,828	29,924	60,752	31,035	29,913	60,948	-207	11	-218	-0.36%
Pork	40,106	73,819	113,925	40,445	74,441	114,886	-339	-622	-977	-0.85%
Broiler	33,196	35,885	69,081	33,763	36,262	70,025	-567	-377	-963	-1.38%
Turkey	2,456	0	2,456	2,519	0	2,519	-63	0	-84	-3.33%
Lamb and Mutton	1,424	0	1,424	1,420	0	1,420	4	0	3	0.21%
All Livestock	**108,011**	**139,628**	**247,639**	**109,183**	**140,616**	**249,799**	**-1,172**	**-988**	**-2,239**	**-0.90%**

*Developed countries.
†Developing countries.

Appendix C
Predicted Changes in Cropland Worldwide in Response to Increased Ethanol Production in U.S.

Table C-1 – Changes in Cropland Predicted from 55.92 Billion Liters Increase in U.S. Corn Ethanol Compared to Baseline Scenario in Thousands of Hectares

Country	Crop									
	Barley	Corn	Peanut	Rape-seed	Sorghum	Soybeans	Sugar	Sunflower	Wheat	Total
Algeria	13	0	0	0	0	0	0	0	52	65
Argentina	13	457	-17	0	18	-215	1	-193	-43	20
Australia	27	2	0	-1	7	0	1	0	45	82
Brazil	11	832	0	0	0	2,072	-72	0	-12	2,831
Bulgaria/ Romania	2	14	0	0	0	3	0	50	14	83
Canada	0	34	0	-47	0	19	0	0	32	39
China	1	754	11	21	0	34	1	-9	298	1,110
CIS	0	0	0	-5	0	-16	0	23	0	3
Colombia	0	0	0	0	0	0	2	0	0	2
Cuba	0	0	0	0	0	0	3	0	0	3
Egypt	0	72	0	0	0	0	1	0	-24	49
EU-25	109	47	0	-161	0	6	-6	40	119	154
Guatemala	0	0	0	0	0	0	1	0	0	1
India	0	576	63	-171	163	191	12	0	348	1,183
Indonesia	0	299	0	0	0	0	0	0	0	299
Iran	0	0	0	0	0	0	1	0	79	80
Japan	4	0	0	0	0	7	0	0	4	15
Malaysia	0	4	0	0	0	0	0	0	0	4
Mexico	-5	149	0	0	115	0	5	0	31	295
Morocco	0	0	0	0	0	0	0	0	115	115
Nigeria	0	0	0	0	280	0	0	0	0	280
Other Africa	15	465	0	0	0	0	0	0	178	657
Other Asia	8	50	0	0	0	0	0	0	108	166
Other CIS	11	6	0	0	0	0	0	0	41	58
Other Eastern Europe	6	30	0	0	0	0	0	0	-9	27
Other Latin America	7	187	0	0	0	0	0	0	13	207
Other Middle East	10	31	0	0	0	0	0	0	0	41
Pakistan	6	18	0	0	-9	0	4	0	121	140
Peru	0	0	0	0	0	0	0	0	0	0
Philippines	0	242	0	0	0	0	2	0	0	244
ROW	5	96	-64	5	145	10	30	-14	-6	208
Russia	-96	28	0	0	0	0	1	0	-117	-185
South Africa	0	201	0	0	0	0	2	0	0	203
South Korea	0	0	0	0	0	5	0	0	0	5
Taiwan	0	2	0	0	0	0	0	0	0	2
Thailand	0	46	0	0	0	0	1	0	0	47
Tunisia	0	0	0	0	0	0	0	0	31	31
Turkey	0	0	0	0	0	0	1	0	0	1
Ukraine	-37	62	0	0	0	0	0	0	-55	-30
US	108	7,864	-2	14	82	-3,884	13	-18	-1,932	2,245
Venezuela	0	0	0	0	0	0	0	0	0	0
Vietnam	0	36	0	0	0	0	0	0	0	36
World	**219**	**12,603**	**-9**	**-344**	**802**	**-1,767**	**2**	**-121**	**-568**	**10,817**

Appendix D
Land Conversion to Cultivation by Region 1990-99
and Associated Releases of Carbon

The analysis presented in this Appendix is used in Appendix E to estimate the average emissions rate per hectare by region. The tables below present the amount of land conversion to cultivation in ten world regions from different ecosystem types in the 1990's and the associated release of carbon based on methods summarized in (*S42-43*). We used different sources of information for each region. For tropical regions, the rates of expansion were obtained from the Food and Agricultural Organization Forest Resources Assessment based on data in the FAO Statistical Database. (S*44*). This FAOSTAT data provides estimates of the change in area in forest, cropland, and pasture, by country for the 1990's. When the increase in cropland was less than the rate of deforestation, we assumed the land came out of forest. When the cropland increase was greater, we assumed that the amount of the increase above the rate of deforestation came from pasture.

Per hectare carbon loss is determined by the levels of carbon per hectare held in the vegetation (biomass) and soils of different types of ecosystems. With cultivation, we assumed loss of 25% of the soil organic carbon in the top meter. (*S15-S16*). These carbon stocks were initially determined from summaries of global vegetation.(*S45-S48*). These analyses have been revised using biomass and soil carbon values from a variety of sources, generally specific for the region.(*S49-S50*).

Tables D-1 through D-8 represents regions that lost forest and grassland to cropland in the 1990's. Tables D-9 and D-10 cover Europe and the former Soviet Union, which saw a decrease of cropland in the 1990's. The tables for these regions indicate the type of ecosystem into which the cropland transitioned and associated changes in carbon

The data from individual regions is used in Tables D-11 and D-12 to calculate an average emission per hectare using a weighted average of each region. Regions represented in D-11 experienced forest and grassland conversion to cropland in the 1990's. In these regions, we assume that new cropland will also come out of these ecosystem types, and the loss of carbon is 25% loss in soils, the loss of vegetation, and for re-growing forests the loss of ongoing carbon gain. D-12 calculates carbon for regions that lost cropland in the 19990's. In these regions we assumed that an expansion of cropland because of ethanol would result in a reduction in hectares shifting out of cropland. In that event, the GHG cost would be the loss of the carbon that would be sequestered on these lands over 30 years. This carbon gain is calculated as regaining 75% of the original 25% of carbon lost from the original conversion to agriculture, i.e., 18.5% of carbon in undisturbed lands of the ecosystem type, plus a rate of growth of vegetation equal to re-growing ecosystems of that type. In the Soviet Union, we lack reliable data on the carbon accumulating on re-growing forests. We therefore use the data on carbon gain in growing forests of the similar type in Europe.

Table D-1 – Ecosystem Sources of Conversion to Cropland in 1990s and Associated Changes in Pure Carbon – United States

	Region	United States						
	Ecosystem	Broad leaf forest	Mixed forest	Wood land	Coniferous / Mountain Forest	Coniferous Pacific Forest	Chaparral	Grassland
1.	**Clearing by ecosystem (million ha/yr)**	0.0084	0.17824	0	0	0.012	0	0.31916
2.	**Clearing by ecosystem (%)**	2%	34%	0%	0%	2%	0%	62%
3.	**C in Vegetation (tonnes C/ha)**	150	170	90	150	200	40	10
4.	**25% of C in soils (tonnes C/ha)**	37.5	40	22.5	25	40	20	20
5.	**Subtotal (3 + 4) (tonnes C/ha)**	187.5	210	112.5	175	240	60	30
6.	**C in Soils (tonnes C/ha)**	150	160	90	100	160	80	80
7.	**Forest area (million ha)**	54.6	88.2	38.5	24.1	29.2	6.2	–
8.	**Gross uptake by re-growing forests (million tonnes C/yr)**	-34.7	-36.4	-2.1	0.0	-23.6	–	–
9.	**Uptake/Forest Area (tonnes C/ha/yr)**	0.64	0.41	0.06	0.00	0.81	–	–
10.	**Re-growing Forest Area (million ha)**	38	47	47	1	15	–	–
11.	**Uptake/Re-growing forest area (tonnes C/ha/yr)**	0.9	0.8	0.0	0.0	1.6	–	–
12.	**Total C in Vegetation (million tonnes C)**	5300	7742	1434	2624	2418	211	4639
13.	**Total C in Soil (million tonnes C)**	8181	14123	3475	2405	4666	491	15808

Row 1: Rate of clearing for crops (when crops were last expanding in the region) (million ha/yr).
Row 2: Distribution of the clearing from each ecosystem (percentages add to 100 within a region).
Row 3: Average carbon stocks in undisturbed vegetation of that ecosystem (MT C/ha).
Row 4: 25% of the average soil carbon stocks in an undisturbed ecosystem (MT C/ha) 25% represents the amount of carbon lost with cultivation or gained with cropland abandonment and recovery.
Row 5: The sum of rows 3 and 4; i.e., the carbon/ha that would be lost from vegetation and soils (MT C/ha) with deforestation and cultivation for croplands.
Row 6: The carbon in undisturbed soils of an ecosystem type (MT C/ha).
Row 7: Ecosystem area circa 2000 (million ha).
Row 8: Total uptake of carbon by re-growing forests (million MT/yr).
Row 9: Total carbon uptake divided by total forest area (MT C/ha/yr).
Row 10: Area of forest re-growing (million ha).
Row 11: Total carbon uptake divided by area of re-growing forest (MT C/ha/yr).
Rows 12 and 13: Total carbon in vegetation and soil of an ecosystem type circa 2000 (million MT)

Table D-2— Ecosystem Sources of Conversion to Cropland in 1990s and Associated Changes in Pure Carbon – North Africa and Middle East

	Region	North Africa and Middle East				
	Ecosystem	TEMPEF	TROPMF	TROPGL	DESCRB	TROPW
1.	**Clearing by ecosystem (million ha/yr)**	0	0	2.966	2.381	0.606
2.	**Clearing by ecosystem (%)**	0%	0%	50%	40%	10%
3.	**C in Vegetation (tonnes C/ha)**	160	200	18	3	27
4.	**25% of C in soils (tonnes C/ha)**	33.5	29.25	10.5	14.5	17.25
5.	**Subtotal (3 + 4) (tonnes C/ha)**	193.5	229.25	28.5	17.5	44.25
6.	**C in Soils (tonnes C/ha)**	134	117	42	58	69
7.	**Forest area (million ha)**	6.8	2.1	44.2	793.1	18.5
8.	**Gross uptake by re-growing forests (million tonnes C/yr)**	-14.5	-6.1	0.0	0.0	0.0
9.	**Uptake/Forest Area (tonnes C/ha/yr)**	2.1	2.9	–	–	–
10.	**Re-growing Forest Area (million ha)**	5.0	1.4	–	–	–
11.	**Uptake/Re-growing forest area (tonnes C/ha/yr)**	2.9	4.4	–	–	–
12.	**Total C in Vegetation (million tonnes C)**	412	139	796	2379	500
13.	**Total C in Soil (million tonnes C)**	813	187	1858	45998	1277

For row explanations, see Table D-1
Columns are ecosystem types in each region. TEMPEF is temperate evergreen forest, TROPMF is tropical moist forest, TROPGL is tropical grassland, DESCRB is desert scrub, TROPW is tropical woodland. See table D-1 for row explanations.

Table D-3 Ecosystem Sources of Conversion to Cropland in 1990s and Associated Changes in Carbon - Canada

	Region	Canada				
	Ecosystem	TEMPEF	TEMPDF	BORLF	TEMPGL	TUNDRA
1.	**Clearing by ecosystem (million ha/yr)**	0.44	0	0	1.78	0
2.	**Clearing by ecosystem (%)**	20%	0%	0%	80%	0%
3.	**C in Vegetation (tonnes C/ha)**	160	135	90	7	5
4.	**25% of C in soils (tonnes C/ha)**	33.5	33.5	51.5	47.25	41.25
5.	**Subtotal (3 + 4) (tonnes C/ha)**	193.5	168.5	141.5	54.25	46.25
6.	**C in Soils (tonnes C/ha)**	134	134	206	189	165
7.	**Forest area (million ha)**	37.3	46.1	461.0	10.9	322.7
8.	**Gross uptake by re-growing forests (million tonnes C/yr)**	-18.5	-3.0	-17.7	–	–
9.	**Uptake/Forest Area (tonnes C/ha/yr)**	0.50	0.06	0.04	–	–
10.	**Re-growing Forest Area (million ha)**	7.8	1.7	13.0	–	–
11.	**Uptake/Re-growing forest area (tonnes C/ha/yr)**	2.4	1.7	1.4	–	–
12.	**Total C in Vegetation (million tonnes C)**	5152	6142	40697	77	1614
13.	**Total C in Soil (million tonnes C)**	4999	6177	94966	2067	53246

Columns are ecosystem types in each region. TEMPEF is temperate evergreen forest, TEMPDF is temperate deciduous forest, BORLF is boreal forest. TEMPGL is temperate grassland. See table D-1 for row explanations.

Table D-4—Ecosystem Sources of Conversion to Cropland in 1990s and Associated Changes in Carbon

	Region	Latin America						
	Ecosystem	TROPEF	TROPSF	TROPF	TEMPEF	TEMPSF	Grassland	Desert
1.	**Clearing by ecosystem (million ha/yr)**	0.677	4.8716	10.3022	0.677	0.1616	5.3077	0.1136
2.	**Clearing by ecosystem (%)**	3%	22%	47%	3%	1%	24%	1%
3.	**C in Vegetation (tonnes C/ha)**	200	140	55	168	100	10	6
4.	**25% of C in soils (tonnes C/ha)**	24.5	24.5	17.25	33.5	33.5	10.5	14.5
5.	**Subtotal (3 + 4) (tonnes C/ha)**	224.5	164.5	72.25	201.5	133.5	20.5	20.5
6.	**C in Soils (tonnes C/ha)**	98	98	69	134	134	42	58
7.	**Forest area (million ha)**	296.3	537.3	252.5	53.6	55.4	6.9	30.7
8.	**Gross uptake by re-growing forests (million tonnes C/yr)**	0.0	-164.2	0.0	-48.9	0.0	–	–
9.	**Uptake/Forest Area (tonnes C/ha/yr)**	0.0	0.3	0.0	0.9	0.0	–	–
10.	**Re-growing Forest Area (million ha)**	0	45.5981	0	14.6781	0	–	–
11.	**Uptake/Re-growing forest area (tonnes C/ha/yr)**	–	3.6	–	3.3	–	–	–
12.	**Total C in Vegetation (million tonnes C)**	59099	70291	13606	8630	5536	459	193
13.	**Total C in Soil (million tonnes C)**	28958	50970	17070	7081	7418	180	1775

Columns are ecosystem types in each region. TROPEF is tropical evergreen forest, TROPSF is tropical seasonal forest, TROPF is tropical open forest, TEMPEF is tropical evergreen forest, TEMPSF is tropical seasonal forest. See table D-1 for row explanations.

Table D-5—Carbon accounting in recent land conversion, by region and ecosystem

	Region	Pacific Developed				
	Ecosystem	TEMPEF	TEMPDF	TROPMF	TROPGL	TROPW
1.	**Clearing by ecosystem (million ha/yr)**	0	0	0.507	1.999	0.837
2.	**Clearing by ecosystem (%)**	0%	0%	15%	60%	25%
3.	**C in Vegetation (tonnes C/ha)**	160	135	200	18	27
4.	**25% of C in soils (tonnes C/ha)**	33.5	33.5	29.25	10.5	17.25
5.	**Subtotal (3 + 4) (tonnes C/ha)**	193.5	168.5	229.25	28.5	44.25
6.	**C in Soils (tonnes C/ha)**	134	134	117	42	69
7.	**Forest area (million ha)**	14.0	14.0	63.6	70.5	106.1
8.	**Gross uptake by re-growing forests (million tonnes C/yr)**	-33.3	-26.5	-6.0	–	–
9.	**Uptake/Forest Area (tonnes C/ha/yr)**	2.4	1.9	0.1	–	–
10.	**Re-growing Forest Area (million ha)**	13.9	13.3	1.9	–	–
11.	**Uptake/Re-growing forest area (tonnes C/ha/yr)**	2.4	2.0	3.1	–	–
12.	**Total C in Vegetation (million tonnes C)**	908	807	12485	1269	2864
13.	**Total C in Soil (million tonnes C)**	1648	1659	7386	2961	7318

See D-1 for row explanations

Columns are ecosystem types in each region. TEMPEF is temperate evergreen forest, TEMPDF is temperate deciduous forest, TROPMF is tropical moist forest, TROPGL is tropical grassland, TROPW is tropical woodland.

Table D-6—Ecosystem Sources of Conversion to Cropland and Associated Changes in Carbon

	Region	South and Southeast Asia		
	Ecosystem	TROPMF	TROPSF	Open forest
1.	Clearing by ecosystem (million ha/yr)	18.3914	4.638	1.2741
2.	Clearing by ecosystem (%)	76%	19%	5%
3.	C in Vegetation (tonnes C/ha)	250	150	60
4.	25% of C in soils (tonnes C/ha)	30	20	12.5
5.	Subtotal (3 + 4) (tonnes C/ha)	280	170	72.5
6.	C in Soils (tonnes C/ha)	120	80	50
7.	Forest area (million ha)	159.4	137.6	44.9
8.	Gross uptake by re-growing forests (million tonnes C/yr)	-171.1	-108.0	-16.0
9.	Uptake/Forest Area (tonnes C/ha/yr)	1.1	0.8	0.4
10.	Re-growing Forest Area (million ha)	70.88	52.39	18.43
11.	Uptake/Re-growing forest area (tonnes C/ha/yr)	2.4	2.1	0.9
12.	Total C in Vegetation (million tonnes C)	34323	19023	2395
13.	Total C in Soil (million tonnes C)	17792	10776	2203

See table D-1 for row explanations
Columns are ecosystem types in each region. TROPF is tropical moist forest. TROPSF is tropical seasonal forest.

Table D-7—Ecosystem Sources of Conversion to Cropland and Associated Changes in Carbon

	Region	Africa				
	Ecosystem	TROPRF	TROPMF	TROPDF	Shrub	Mont
1.	**Clearing by ecosystem (million ha/yr)**	2.5487	8.844	5.1332	3.1988	3.486
2.	**Clearing by ecosystem (%)**	11%	38%	22%	14%	15%
3.	**C in Vegetation (tonnes C/ha)**	126.7	60.2	12.6	4.6	79.9
4.	**25% of C in soils (tonnes C/ha)**	47.5	28.75	17.5	7.5	25
5.	**Subtotal (3 + 4) (tonnes C/ha)**	174	89	30	12	105
6.	**C in Soils (tonnes C/ha)**	190	115	70	30	100
7.	**Forest area (million ha)**	222.0	190.2	200.1	47.1	27.7
8.	**Gross uptake by re-growing forests (million tonnes C/yr)**	-20.2	-19.9	0.0	0.0	0.0
9.	**Uptake/Forest Area (tonnes C/ha/yr)**	0.1	0.1	0.0	0.0	0.0
10.	**Re-growing Forest Area (million ha)**	21.2889	23.7342	6.4433	0.6694	0.8552
11.	**Uptake/Re-growing forest area (tonnes C/ha/yr)**	0.9	0.8	0.0	0.0	0.0
12.	**Total C in Vegetation (million tonnes C)**	26787	10971	2216	150	1408
13.	**Total C in Soil (million tonnes C)**	41003	19992	13091	1122	2032

The columns are ecosystem types in each region. TROPRF is tropical rain forest. TROPMF is tropical moist forest. TROPDF is tropical dry forest. Shrub is shrub land. Mont is montane forest.
See table D-1 for row explanations.

Table D-8 - Carbon Accounting in Recent Land Conversion to Cultivation by Region and Ecosystem

	Region	India, China and Pakistan*
	Ecosystem	TEMPGL
1.	**C in Soils (tonnes C/ha)**	189
2.	**C in Vegetation (tonnes C/ha)**	7
3.	**25% of C in soils (tonnes C/ha)**	47.25
4.	**Subtotal (2 + 3) (tonnes C/ha)**	54.25

Row 1: Average carbon stocks in soils
Row 2: Average carbon stocks in undisturbed vegetation of that ecosystem (tonnes C/ha)
Row 3: Loss of carbon stocks in soils due to cultivation
Row 4: The sum of rows 3 and 4; i.e., the carbon/ha that would be lost from vegetation and soils (tonnes C/ha) with deforestation and cultivation for croplands.
TEMPGL is temperate grassland
*The data for land use change in Asia in the 1990s were dominated by conversion of changes in southeast Asia to forest. Because there is less forest in China, India and Pakistan and because our analysis predicts a large amount of conversion in those countries, we made a conservative, simplifying assumption for these countries that all conversion would come out of grassland.

Table D-9—Ecosystem Types of Reversion from Cropland and Associated Changes in Carbon

	Region	Europe				
	Ecosystem	TEMPEF	TEMPDF	BORLF	TEMPWL	TEMPGL
1.	**Clearing by ecosystem (million ha/yr)**	-0.506	-0.506	-0.506	0	-0.5058
2.	**Clearing by ecosystem (%)**	25%	25%	25%	0%	25%
3.	**C in Vegetation (tonnes C/ha)**	160	120	90	27	7
4.	**25% of C in soils (tonnes C/ha)**	33.5	33.5	51.5	17.25	47.25
5.	**Subtotal (3 + 4) (tonnes C/ha)**	25.1	25.1	38.6	12.9	35.4
6.	**C in Soils (tonnes C/ha)**	134	134	206	69	189
7.	**Forest area (million ha)**	71.9	55.5	27.5	45.0	26.7
8.	**Gross uptake by re-growing forests (million tonnes C/yr)**	-137.5	-80.0	-33.1	–	–
9.	**Uptake/Forest Area (tonnes C/ha/yr)**	1.9	1.4	1.2	–	–
10.	**Re-growing Forest Area (million ha)**	66.0	43.2	27.2	–	–
11.	**Uptake/Re-growing forest area (tonnes C/ha/yr)**	2.1	1.9	1.2	–	–
12.	**Total C in Vegetation (million tonnes C)**	4932	3561	901	1215	178
13.	**Total C in Soil (million tonnes C)**	8732	6708	4813	3105	4566

See Table D-1 for row explanations
The columns are ecosystem types in each region. TEMPEF is temperate evergreen forest, TEMPDF is temperate deciduous forest, BORLF is boreal forest, TEMPWL is temperate woodland, TEMPGL is grassland.

Table D-10—Ecosystem Types of Reversion from Cropland and Associated Changes in Carbon.

	Region	Former Soviet Union				
	Ecosystem	TEMPEF	TEMPDF	BORLF	TEMPW	TEMPGL
1.	**Clearing by ecosystem (million ha/yr)**	-0.506	-0.3464	0	0	-2.3684
2.	**Clearing by ecosystem (%)**	16%	11%	0%	0%	74%
3.	**C in Vegetation (tonnes C/ha)**	160	135	90	27	10
4.	**25% of C in soils (tonnes C/ha)**	33.5	33.5	51.5	17.25	47.25
5.	**Subtotal (3 + 4) (tonnes C/ha)**	193.5	168.5	141.5	44.25	57.25
6.	**C in Soils (tonnes C/ha)**	134	134	206	69	189
7.	**Forest area (million ha)**	88.3	53.6	612.9	186.0	31.2
8.	**Gross uptake by re-growing forests (million tonnes C/yr)**	–	–	–	–	–
9.	**Uptake/Forest Area (tonnes C/ha/yr)**	–	–	–	–	–
10.	**Re-growing Forest Area (million ha)**	–	–	–	–	–
11.	**Uptake/Re-growing forest area (tonnes C/ha/yr)**	–	–	–	–	–
12.	**Total C in Vegetation (million tonnes C)**	14120	5923	50055	5022	294
13.	**Total C in Soil (million tonnes C)**	11826	7091	125230	12834	5880

The columns are ecosystem types in each region. TEMPEF is temperate evergreen forest, TEMPDF is temperate deciduous forest, BORLF is boreal forest, TEMPW is temperate woodland, TEMPGL is temperate grassland.

See table D-1 for row explanations.

Table D-11—Estimated Carbon Emission Per Hectare by Region for Regions with Net Conversion of Forest and Grassland to Cropland in 1990s, Compiling Data from Tables D1-10*

Region	Ecosystem unit	Clearing by ecosystem (% of total)	Vegetation C + 25% of soil C† (Tonnes C/ha)	30 years of uptake existing forests (Tonnes C/ha)	Total foregone carbon tons C/hectare (Tonnes C/ha)	Weighted average rate for areas with net conversion‡ *(Tonnes CO2 equivalent/ha)*
Pacific Developed	TEMPEF	0.00%	193.5	71.41703	264.9	
	TEMPDF	0.00%	168.5	56.71445	225.2	
	TROPMF	15.17%	229.25	2.81342	232.1	
	TROPGL	59.80%	28.5	0	28.5	
	TROPW	25.04%	44.25	0	44.3	
	Weighted average	100.00%	62.88917	0.4266838	65.7	241.119
North Africa/Middle East	TEMPEF	0.00%	193.5	63.77011	257.3	
	TROPMF	0.00%	229.25	87.10571	316.4	
	TROPGL	49.82%	28.5	0	28.5	
	DESCRB	40.00%	17.5	0	17.5	
	TROPW	10.18%	44.25	0	44.3	
	Weighted average	100.00%	25.70368	0	25.7	94.319
Canada	TEMPEF	19.82%	193.5	14.85477	208.4	
	TEMPDF	0.00%	168.5	1.92416	170.4	
	BORLF	0.00%	141.5	1.15447	142.7	
	TEMPGL	80.18%	54.25	0	54.3	
	TUNDRA	0.00%	46.25	0	46.3	
	Weighted average	100.00%	81.8491	2.9441887	84.842343	311.3714
United States	Broadleaf forest	1.62%	187.5	19.07674	206.6	
	Mixed forest	34.42%	210	12.38175	222.4	
	Woodland	0.00%	112.5	1.66229	114.2	
	Coniferous/ Mountain	0.00%	175	0	175	
	Coniferous pacific	2.32%	240	24.28481	264.3	
	Chaparral	0.00%	60	0	60	
	Grassland	61.64%	30	0	30	
	Weighted average	100.00%	99.38239	5.1343882	104.5238	383.60236

Table D-11 (continued)						
		Clearing by ecosystem	Vegetation C + 25% of soil C†	30 years of uptake existing forests	Total foregone carbon tons C/hectare	Weighted average rate for areas with net conversion‡
Latin America	TROPEF	3.06%	224.5	0	224.5	
	TROPSF	22.03%	164.5	9.16464	173.7	
	TROPOF	46.59%	72.25	0	72.3	
	TEMPEF	3.06%	201.5	27.37995	228.9	
	TEMPSF	0.73%	133.5	0	133.5	
	Grassland	24.01%	20.5	0	20.5	
	Desert	0.51%	20.5	0	20.5	
	Weighted average	100.00%	88.95351	2.8575625	91.842793	337.06305
South and Southeast Asia	TROPMF	75.67%	280	32.18653	312.2	
	TROPSF	19.08%	170	23.54382	193.5	
	Open forest	5.24%	72.5	10.68679	83.2	
	Weighted average	100.00%	248.1299	29.41007	277.5	1018.425
Africa	TRF	10.98%	174	2.72656	177	
	TMF	38.10%	89	3.13106	92.1	
	TDF	22.12%	30	0	30.1	
	Shrub	13.78%	12	0	12.1	
	Mont	15.02%	105	0	104.9	
	Weighted average	100.00%	77.08137	1.49243	78.6	288.462
India, China, Pakistan	TEMPGL	100.00%	54.25	0	80.6	295.802
World	**Total**	**100.00%**	**5758**	**660.33267**		
	Weighted average		**128.46173**	**9.5836275**	**138.04536**	**351.4268**

Data derives from Tables D-1 through D-10. See those tables for meaning of ecosystem types. This table computes the weighted average of the carbon losses for each hectares of conversion, and these averages are used to estimate the carbon loss emissions per hectare of predicted conversion as the emissions rate per hectare in Table E-1.
*These regions all saw forest and grassland convert to cropland in the 1990s.
†Subtotal of lines 3 + 4 in tables D1-D10
‡convert from metric tons C per hectare to metric tons CO2 equivalent per hectare by multiplying by 3.67.

Table D-12 Carbon Loss of Increased Cropland in Europe and Former Soviet Union (see note)

Region	Ecosystem unit	Reversion by ecosystem (million ha/yr)	Soil uptake* (metric tons C/ha)	30 years of uptake of re-growing forests or grass growth† (metric tons C/ha)	Total Rate for areas reverting‡ (metric tons C/ha)	Weighted average rate per country§ (metric tons of C02 eq. /hectare)
Europe	TEMPEF	25%	25.125	62.49711	87.6221	
	TEMPDF	25%	25.125	55.5664	80.6914	
	BORLF	25%	38.625	36.39813	75.0231	
	TEMPGL	25%	35.437	7	42.4375	
	Weighted average	100.0%	31.0777	40.36871	71.4464	262.2083
Former Soviet Union	TEMPEF	15.71038%	25.125	62.49711	87.6221	
	TEMPDF	10.75509%	25.125	55.5664	80.6914	
	TEMPGL	73.53453%	35.437	7	42.4375	
	Weighted average	100.0%	32.7082	20.94217	53.6504	196.897

*Soil uptake assumes that 30 years of re-growth will rebuild 75% of soil lost from conversion to crops, which originally loses 25% of soil carbon, i.e., soil uptake will rebuild 18.75% of soil in mature ecosystem.

†Forest carbon based on 30 years of uptake for that forest type according to tables in Appendix D. Grassland assumes re-growth of grass. In the former Soviet Union, we lacked reliable data on forest uptake and substituted the European rates.

‡Total of soil uptake and forest or grass uptake.

§Convert from metric tons C per hectare to metric tons CO2 equivalent per hectare by multiplying by 3.67.

Note: The FSU lost cropland in the 1990's. We assume that increased crop production in these regions has the effect of keeping croplands in production, which foregoes the carbon they would have sequestered if they had reverted to forest or grassland. Reversion assigned to ecosystems based on the portion of cropland that reverted to different ecosystem types in the 1990s.

APPENDIX E
Calculations of Greenhouse Gas Emissions for Land Converted to Cropland as a Result of Increased Ethanol

Table E-1—Total Computed Carbon Emissions by Region Due to Land Use Change in Response to Rise in U.S. Corn Ethanol from CARD Baseline to CARD Expanded Ethanol Scenario

Region	Area Change (hectares)	CO2 Equivalent per hectare (metric tons per hectare)	Total Emissions, (metric tons CO2 Equivalent)
Canada	38,782	311.2	12,068,768
Africa	1,141,119	288.4	329,059,840
Europe	263,698	262.2	69,143,911
Former Soviet Union	-153,150	196.9	-30,154,728
Latin America	3,358,822	336.9	1,131,743,766
North Africa and Middle East	381,691	94.3	36,005,866
Developed Pacific	104,022	232.4	24,171,504
China/India/Pakistan	2,432,718	199.1	484,348,023
Southeast Asia	795,815	1,018.6	810,594,217
United States	2,245,217	383.6	861,212,723
Rest of the World	207,767	351.4	73,014,961
Total	10,816,502		3,801,208,851

Table combines data from Tables C-1, D-11, D-12

APPENDIX F
Tables for Sensitivity Analysis of Smaller (30.6 Billion Liter) Increase in Corn Ethanol

Table F-1—Total Computed Carbon Emissions by Region Due to Land Use Change in Response to Rise in U.S. Corn Ethanol by 30.6 Billion Liters from 2016/17 Baseline

Region	Area Change (hectares)	CO2 Equivalent per hectare (metric tons per hectare)	Total Emissions (metric tons CO2 Equivalent)
Canada	43,017	769.0	33,078,380
Africa	210,415	712.6	149,934,598
Europe	85,223	647.9	55,218,491
Former Soviet Union	935	486.5	455,024
Latin America	609,635	832.6	507,587,900
North Africa and Middle East	87,030	233.1	20,286,757
Developed Pacific	28,620	574.2	16,433,426
China/India/Pakistan	492,132	492.0	242,118,541
Southeast Asia	147,463	2,516.9	371,155,434
United States	471,247	947.8	446,664,483
Rest of the World	28,996	868.4	25,179,765
Total	2,204,714		1,868,112,801

Table F-2. Changes in Cropland Due to 30.6 Billion Liter Increase (thousands of hectares)

Country	Crop									
	Barley	Corn	Peanut	Rapeseed	Sorghum	Soybeans	Sugar	Sunflower	Wheat	Total
Algeria	7	0	0	0	0	0	0	0	27	34
Argentina	13	248	-8	0	15	-136	0	-94	30	68
Australia	25	1	0	0	3	0	1	0	29	59
Brazil	7	341	0	0	0	919	-41	0	1	1,226
Bulgaria/Romania	2	7	0	0	0	1	0	23	8	42
Canada	17	11	0	-18	0	9	0	0	87	106
China	3	319	5	20	0	19	0	-5	162	525
CIS	0	0	0	-1	0	-8	0	11	0	2
Colombia	0	0	0	0	0	0	1	0	0	1
Cuba	0	0	0	0	0	0	1	0	0	1
Egypt	0	29	0	0	0	0	0	0	-8	22
EU-25	85	34	0	-78	0	3	-4	18	98	156
Guatemala	0	0	0	0	0	0	0	0	0	0
India	0	245	30	-87	60	95	6	0	254	605
Indonesia	0	134	0	0	0	0	0	0	0	135
Iran	0	0	0	0	0	0	0	0	43	43
Japan	2	1	0	0	0	3	0	0	2	9
Malaysia	0	2	0	0	0	0	0	0	0	2
Mexico	-2	51	0	0	51	0	1	0	18	119
Morocco	0	0	0	0	0	0	0	0	62	63
Nigeria	0	0	0	0	122	0	0	0	0	122
Other Africa	12	215	0	0	0	0	0	0	94	321
Other Asia	10	17	0	0	0	0	0	0	57	84
Other CIS	9	2	0	0	0	0	0	0	21	32
Other Eastern Europe	4	12	0	0	0	0	0	0	-3	13
Other Latin America	5	79	0	0	0	0	0	0	7	91
Other Middle East	23	13	0	0	0	0	0	0	0	37
Pakistan	4	5	0	0	-6	0	2	0	82	87
Peru	0	0	0	0	0	0	0	0	0	0
Philippines	0	107	0	0	0	0	1	0	0	108
ROW	4	35	-30	3	49	4	16	-7	-2	72
Russia	-13	11	0	0	0	0	0	0	-24	-25
Russia and Ukraine	0	0	0	0	0	0	0	0	0	0
South Africa	1	76	0	0	0	0	1	0	0	77
South Korea	0	0	0	0	0	2	0	0	0	2
Taiwan	0	1	0	0	0	0	0	0	0	1
Thailand	0	20	0	0	0	0	0	0	0	20
Tunisia	0	0	0	0	0	0	0	0	16	16
Turkey	0	0	0	0	0	0	0	0	0	0
Ukraine	-12	25	0	0	0	0	0	0	-20	-6
US	40	4,033	1	14	32	-1,658	13	8	-1,319	1,164
Venezuela	0	0	0	0	0	0	0	0	0	0
Vietnam	0	16	0	0	0	0	0	0	0	16
World	**246**	**6,090**	**-1**	**-146**	**325**	**-746**	**2**	**-46**	**-277**	**5,447**

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