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Biofuels, Land Use Change, and Greenhouse Gas Emissions: Some Unexplored Variables

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Greenhouse gas release from land use change (the so-called "carbon debt") has been identified as a potentially significant contributor to the environmental profile of biofuels. The time required for biofuels to overcome this carbon debt due to land use change and begin providing cumulative greenhouse gas benefits is referred to as the "payback period" and has been estimated to be 100–1000 years depending on the specific ecosystem involved in the land use change event. Two mechanisms for land use change exist: "direct" land use change, in which the land use change occurs as part of a specific supply chain for a specific biofuel production facility, and "indirect" land use change, in which market forces act to produce land use change in land that is not part of a specific biofuel supply chain, including, for example, hypothetical land use change on another continent. Existing land use change studies did not consider many of the potentially important variables that might affect the greenhouse gas emissions of biofuels. We examine here several variables that have not yet been addressed in land use change studies. Our analysis shows that cropping management is a key factor in estimating greenhouse gas emissions associated with land use change. Sustainable cropping management practices (no-till and no-till plus cover crops) reduce the payback period to 3 years for the grassland conversion case and to 14 years for the forest conversion case. It is significant that no-till and cover crop practices also yield higher soil organic carbon (SOC) levels in corn fields derived from former grasslands or forests than the SOC levels that result if these grasslands or forests are allowed to continue undisturbed. The United States currently does not hold any of its domestic industries responsible for its greenhouse gas emissions. Thus the greenhouse gas standards established for renewable fuels such as corn ethanol in the Energy Independence and Security Act (EISA) of 2007 set a higher standard for that industry than for any other domestic industry. Holding domestic industries responsible for the environmental performance of their own supply chain, over which they may exert some control, is perhaps desirable (direct land use change in this case). However, holding domestic industries responsible for greenhouse gas emissions by their competitors worldwide through market forces (via indirect land use change in this case) is fraught with a host of ethical and pragmatic difficulties. Greenhouse gas emissions associated with indirect land use change depend strongly on assumptions regarding social and environmental responsibilities for actions taken, cropping management approaches, and time frames involved, among other issues.

Introduction

Critical political, economic, and environmental security concerns are increasingly linked to petroleum dependence. Thus, finding alternatives to petroleum has become a high priority worldwide. One proposed solution is biofuels: liquid fuels such as ethanol derived from plant biomass. Ethanol from biomass has been viewed as a viable alternative to petroleum in part because of its projected greenhouse gas emission benefits compared to the gasoline fuel system. The United States is expected to produce 136 billion L (36 billion gal) of renewable fuels by 2022, including 79 billion L (21 billion gal) of cellulosic ethanol, and this is expected to reduce greenhouse gas (GHG) emissions by at least 20% in comparison to fossil fuels (*1*). Approximately 57 billion L (15 billion gal) of ethanol will probably be derived from corn.

While ethanol derived from corn has previously been thought to reduce GHG emissions, a recent study has argued that ethanol from corn does not provide any GHG benefit in the foreseeable future if the effects of land use change (LUC) are taken into account. Instead, corn ethanol is projected to increase overall GHG emissions (*2*). Two different mechanisms of LUC have been identified: indirect LUC and direct LUC. Indirect LUC analysis links (through market forces) the use of corn for ethanol production to the conversion of undisturbed land elsewhere in the world and the resulting GHG emissions (*2*). In contrast, direct LUC is supply-chain oriented and links conversion of a specific piece of land in a given biofuel supply chain to resulting GHG emissions. GHG releases due to direct LUC within various ecosystems have also been estimated (*3*).

Direct LUC might well be an appropriate subject for life cycle analysis of biofuel systems. All fuel producers could conceptually be held responsible for the performance of their own supply chains, although this is almost never done in practice. In contrast, indirect LUC is highly controversial for many reasons. For example, according to Searchinger and his colleagues' study (*2*), indirect LUC essentially makes biofuel industries responsible for the environmental consequences of decisions over which they have no control. In effect, an environmentally conscious corn grower or ethanol producer using best management practices may be held responsible for his own environmental impacts <u>as well as</u> those of a competitor thousands of miles away who clears savannah or rain forest to plant corn or soybeans. This outcome runs directly contrary to the "polluter pays" principle and to the "think globally, act locally" concept that have done so much to advance environmental improvements.

Life cycle allocation issues for indirect LUC are is likewise troublesome. A fundamental assumption behind indirect LUC is that the system in question is the entire world market for grains. Indirect LUC analysis makes corn used for biofuel production responsible for all of the hypothetical incremental world demand for corn without assigning any of the resulting environmental burdens to other uses of corn. Over 70% of all corn grown worldwide is fed to animals. It does not seem intellectually justifiable to give animal feed uses of corn this privileged position on greenhouse gas releases relative to

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corn used for biofuels. Competent life cycle analysis allocates environmental burdens among all of the various uses of a product, not just to one use.

Finally, it is overly simplistic and inaccurate to view land use change worldwide as being driven primarily by increased agricultural production, as has been assumed (*2*). There is a rich academic literature on the subject of land use change (*4, 5*). According to these studies, land use change is driven by three primary forces: timber harvest, infrastructure development (e.g., road building), and agricultural expansion. Any one of these variables taken alone explains less than 20% of documented land use changes worldwide. Taken together, they explain over 90% of observed cases of land use change. Agricultural expansion alone is therefore seldom the reason for land use change. Thus it is arbitrary and unreasonable to assume that all land use change worldwide is driven primarily by agricultural expansion.

Whatever the final result of the ongoing debate about the validity and limits of the indirect land use change analysis, both direct and indirect LUC analyses depend on a number of variables and assumptions. The existing studies have not considered some important alternative assumptions and scenarios. One of the most significant sources of GHG emissions in LUC is from soil organic carbon (SOC). Tillage methods greatly influence SOC dynamics. However, the existing studies (*2, 3*) did not take into account the effects of different tillage methods on land use change. Other cropland management approaches, such as no-tillage or the use of winter cover crops, can improve soil organic carbon levels and increase carbon sequestration rates in comparison to plow tillage (*6*−*8*).

In this paper, we revisit the greenhouse gas profile of the E85 fuel system as affected by LUC by accounting for the effect of different tillage practices on SOC carbon dynamics. In our analysis, corn grain is used as a raw material for ethanol production. Corn stover is assumed to be harvested and burned as a boiler fuel to replace coal at the ethanol production facility. Corn stover includes cobs, leaves, and stems; all of the aboveground parts of the plant except the grain. We calculate the cumulative GHG emissions of the E85 fuel system, including corn cultivation, biorefinery operations, transportation and distribution of the ethanol fuel, gasoline production, E85 fueled vehicle operation, and upstream processes, for up to 100 years after the conversion of undisturbed land (either grassland or forest) to cropland in several corn-producing states of the United States. In addition, we include gasoline-fueled vehicle operation as greenhouse gas credits in the E85 fuel system to calculate GHG benefits. We also explore a number of other assumptions and scenarios not explored in the existing LUC studies. These assumptions/scenarios are summarized in the next section.

Methodologies

Additional economic modeling studies (*9, 10*) have called into question the assumption (made without any modeling or data) that indirect land conversion takes place primarily outside the United States (*2*). Instead, if more recent global economic equilibrium studies are correct, most of the hypothetical land use conversion will take place in the United States (*9, 10*). Therefore we consider U.S. grassland and forest conversion rather than tropical or other ecosystems. Greater information availability in the United States also permits more accurate assessment of land use change effects.

We selected forty counties from nine corn producing states (Illinois, Indiana, Iowa, Michigan, Minnesota, Nebraska, Ohio, South Dakota, and Wisconsin) as sites for the analysis. These states represent a wide variety of soil, climate, and crop production practices. The counties selected are given in the Supporting Information. The results are presented as arithmetic averages rather than weighted (by corn production) values because the amount of land in each country that is converted into cropland is unknown.

The reference scenario is that farmers divert existing cornfields to ethanol production and then convert temperate grassland or forest to cornfields, i.e., this is explicitly an indirect land use change analysis. We calculate the grassland conversion and forest conversion cases separately. Current corn tillage practices (*11*) are applied to existing and newly converted cornfields in the reference scenario. No-tillage and plow tillage practices are investigated in the analysis to determine the effects of tillage on GHG emissions. Winter cover crop practice is also included in the analysis. A winter cover crop is planted in the fall after harvesting the corn and killed by plowing or herbicides prior to planting corn in the subsequent growing season. Cover crops are traditionally used to protect and improve soil quality as well as to provide animal feed (*12*). Winter cover crop cultivation in combination with corn production consumes more herbicides and more diesel fuel than does traditional corn cultivation practice (*13*). We select winter wheat as the winter cover crop in this analysis. We do not include here the possibility of harvesting the cover crop to provide animal feed protein and fiber for biofuel production or animal feed. That analysis is left for a subsequent study.

We assume that the forest cleared for corn production consists of coniferous forest (50%) and deciduous forest (50%). The "carbon debt" or "carbon deficit" attributed to LUC as given in previous analyses (*2, 3*) is the carbon loss from biomass during the conversion event. We assume that aboveground carbon (wood) in the forest conversion case is harvested and used as a solid fuel, replacing coal. We use the DAYCENT model—an agroecosystem model—to predict the soil organic carbon along with carbon in above- and belowground biomass, and nitrous oxide emissions from soil (*14*). The DAYCENT model simulates soil organic carbon level in the top 20 cm depth.

Cumulative GHG emissions associated with LUC in a given year t [Mg of CO_2 equivalent per hectare] are defined as

$$\mathrm{GHG_{LUC}}|_t = \mathrm{Direct\ GHG_{LUC}}|_t + \mathrm{Indirect\ GHG_{LUC}}|_t \qquad (1)$$

Direct $\mathrm{GHG_{LUC}}|_t$ is cumulative GHG emissions associated with direct LUC, i.e., cultivation of an existing cornfield to produce corn for ethanol fuel. Indirect $\mathrm{GHG_{LUC}}|_t$ is cumulative GHG emissions associated with indirect LUC, i.e., conversion of grassland or forest to corn production to "replace" the corn used for ethanol production. Direct $\mathrm{GHG_{LUC}}|_t$ and indirect $\mathrm{GHG_{LUC}}|_t$ are estimated by eqs 2 and 3.

$$\mathrm{Direct\ GHG_{LUC}}|_t = [\mathrm{SOC}|_0^c - \mathrm{SOC}|_t^c] \cdot \frac{44}{12} \qquad (2)$$

$$\mathrm{Indirect\ GHG_{LUC}}|_t = [\mathrm{SOC}|_0^u - \mathrm{SOC}|_t^{cc}] \cdot \frac{44}{12} + [\mathrm{GHG\ from\ carbon\ debt}]_u - [\mathrm{SOC}|_0^{ec} - \mathrm{SOC}|_t^{ec}] \cdot \frac{44}{12} \cdot \frac{Y_{\mathrm{nc}}}{Y_{\mathrm{ec}}} \qquad (3)$$

where $\mathrm{SOC}|_t^c$ is the soil organic carbon (SOC) level in the existing cornfield diverted to ethanol production at the end of year t, and $\mathrm{SOC}|_0^c$ is the initial SOC level in the existing cornfield used for ethanol production. $\mathrm{SOC}|_t^{cc}$ is the SOC level in the newly converted cornfield at the end of year t, and $\mathrm{SOC}|_0^u$ is the SOC level in grassland or forest before its conversion to corn production. Thus the first term in eqs 2 and 3 is greenhouse gas emissions associated with changes in SOC levels due to LUC. [GHG from carbon debt]$_u$ is GHG emissions associated with carbon losses from existing biomass during the land conversion event. The last term in eq 3 is changes in SOC levels in an existing cornfield elsewhere dedicated to food (mostly as animal feed) production. $\mathrm{SOC}|_t^{ec}$ is the SOC level in an existing cornfield elsewhere dedicated to animal feed production at the end of year t, and $SOC|_0^{ec}$ is the initial SOC level in an existing cornfield elsewhere dedicated to animal feed production. Y_{nc} is the corn yield in a newly converted cornfield, while Y_{ec} is the corn yield in an existing cornfield elsewhere dedicated to animal feed production. The last term in eq 3 reflects incremental changes due to land conversion.

Note that framing the analysis in this way makes biofuel uses of corn "responsible" for all of the greenhouse gas emissions of the land use conversion event (referred to as GHG from carbon debt in eq 3). We have taken this step so that our results can be more directly compared with existing LUC studies (*2, 3*). This assumption represents a worst case for biofuels with respect to the land conversion event. It is much more intellectually rigorous and compliant with life cycle principles to allocate the environmental burdens of corn production in newly converted croplands among all of the uses of corn, not just to the biofuel uses. Thus, we include animal feed production in an existing cornfield system in eq 3.

We assume that starch-based ethanol is produced via dry milling. Dry milling is the dominant ethanol production process in the United States. A coproduct of the dry milling process, dried distiller grains with solubles (DDGS), is used as animal feed and is a viable replacement for corn, soybean meal, and nitrogen in urea (*15, 16*). We adopt the assumption from the GREET model that 1 kg of DDGS displaces 0.95 kg of dry corn grain, 0.3 kg of dry soybean meal, and 0.03 kg of nitrogen in urea (*16*). Corn stover is used as an energy source in the dry milling process to generate steam. Only about 50% of total corn stover produced from cornfields under conservation tillage is assumed to be harvested since the balance must remain on the soil for erosion control (*17−19*). Note that it is not necessary that corn stover is harvested in the cornfield involved in the ethanol fuel system. To allocate the environmental burdens to corn stover, we use the "system expansion" approach (*17, 20*).

The cumulative GHG benefit of the E85 fuel system in year t [Mg of CO_2 equivalent per hectare] is estimated as follows

$$\begin{aligned}\text{GHG benefit}|_t = \sum_i^t [&\text{GHG from gasoline fueled system}|_i - \\ &\text{GHG from cultivation}|_i - \text{GHG from biorefinery}|_i - \\ &\text{GHG from gasoline production}|_i - \\ &\text{GHG from E85 fueled vehicle operation}|_i + \text{GHG}_{\text{DDGS}}|_i] - \\ &\text{GHG}_{\text{LUC}}|_t \qquad (4)\end{aligned}$$

where $\text{GHG}_{\text{LUC}}|_t$ is cumulative GHG emissions associated with LUC in a given year t, defined by eq 1. $\text{GHG}_{\text{DDGS}}|_i$ is the GHG credits associated with DDGS displacement in a given year. GHG from cultivation$|_i$ is GHG emissions associated with corn cultivation (e.g., fertilizers, fuels, upstream processes, N_2O emissions from soil, etc.) and also includes GHG emissions associated with transportation of corn grain to the biorefinery in a given year. GHG from biorefinery$|_i$ is the GHG emissions associated with the biorefinery, corn stover production/transportation, and transportation/distribution of ethanol in a given year. GHG from gasoline production$|_i$ is GHG emissions associated with gasoline production and transportation/distribution of gasoline involved in the E85 fuel system in a given year. GHG from E85 fueled vehicle operation$|_i$ is GHG tailpipe emissions from driving an E85 fueled vehicle at a given year. GHG from gasoline fueled system$|_i$ is GHG emissions from gasoline production and transportation/distribution of gasoline involved in the gasoline-fueled vehicle operation in a given year.

Life cycle inventory data (e.g., biomass yield, ethanol yield, life cycle GHG emissions, etc.) are obtained from the literature (*15, 21−24*). We project the biomass yield (i.e., corn and soybean), ethanol yield, and fuel economy. Soybean yield is used in estimating the environmental burdens of soybean meal. The most recent data for energy use in ethanol production are used (*22*), but we do not project any improvements in these parameters. The parameter projections are summarized in various figures in the Supporting Information. Scenario and sensitivity analyses are carried out to determine the effects of these assumptions. We do not regard carbon dioxide derived from combusting ethanol in E85-fueled vehicle operation or carbon dioxide released during corn stover combustion as greenhouse gases because of the biological origin of these fuels.

To summarize, the following variables are studied in scenario (scenarios A−D) and sensitivity (scenarios E−K) analysis:

1. Land management post land use change was not explicitly considered in either of the existing land use change studies (*2, 3*). This is an important consideration since a variety of management practices are in fact used by corn producers. Therefore, we determine the GHG effects if the land is managed under different practices including the following:

- Current average tillage in both diverted and newly converted cornfields (the reference case). This represents the actual mix of tillage practices currently used in U.S. corn agriculture. Conservation tillage accounts for about 40% of total corn acreage, and the remaining corn acreage is grown under conventional tillage (*11*).
- No-tillage practice in both diverted and newly converted cornfields (referred to as scenario A). About 21% of U.S. corn is grown under no-till conditions (*11*). Higher diesel prices (well over \$4 per gallon now versus around \$2 per gallon in the recent past) are likely to significantly increase the percentage of no-tilled corn agriculture because farmers are now highly incentivized to make fewer trips through the field.
- No-tillage plus a cover crop in both diverted and newly converted cornfields (referred to as scenario B). Cover crops (annual grasses planted in the fall after the corn crop is harvested) build soil organic matter and trap nitrogen and phosphorus that might otherwise escape to air or water. Nitrogen leaching from corn fields is a major contributor to the anoxic zone in the Gulf of Mexico. Increasing pressures for more sustainable agricultural practices as well as increasing demand for cellulosic biomass for a cellulosic biofuels industry are likely to increase the percentage of corn grown using cover crops. Thus cover crops combined with no-tillage represent the current best management practices for corn agriculture.
- Plow tillage in both diverted and newly converted cornfields (referred to as scenario C). This represents the "worst case" as far as environmental management of corn agriculture is concerned. Plow tillage was apparently assumed by both existing studies on land use change (*2, 3*).

Corn production in the following scenarios occurs under current tillage practices as defined above.

2. Oil sands. The Athabasca oil sands are likely to supply an increasing fraction of U.S. petroleum demand, but at a much higher incremental GHG emissions rate than conventional gasoline (*25*). It seems more appropriate to compare the environmental performance of new, incremental biofuel production with that of new, incremental petroleum production, rather than with the old petroleum GHG baseline (*15*). Thus we compare the GHG emissions of ethanol fuel versus a baseline of the GHG emissions of petroleum substitutes derived from the tar sands (referred to as scenario D).

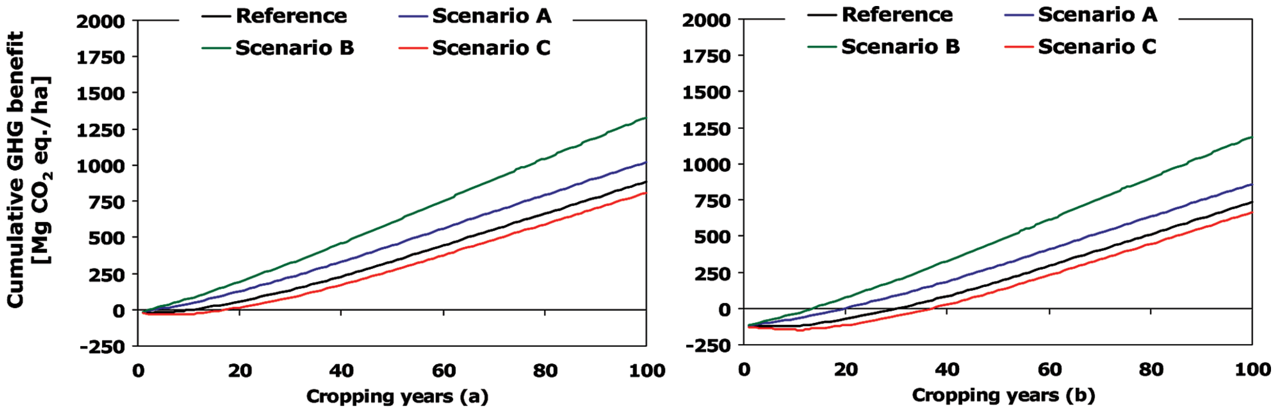

FIGURE 1. Mean cumulative greenhouse gas benefits for the E85 fuel system: (a) grassland conversion case; (b) forest conversion case.

3. Energy source in the dry mill. Fossil energy (i.e., natural gas and coal) is used as an energy source in the dry mill instead of corn stover (referred to as scenario E).
4. Energy use efficiency in the dry mill. We do not project increases in energy use efficiency with time in this study. The energy use data in GREET (*15*) instead of the most recent data are used in a sensitivity analysis to scrutinize the effects of energy use in the dry mill process (referred to as scenario F).
5. DDGS displacement ratio. A report published by the U.S. EPA (*26*) shows that 1 kg of DDGS displaces 0.5 kg of dry corn grain and 0.5 kg of dry soybean meal. In a sensitivity analysis, we use this displacement ratio for DDGS (referred to as scenario G).
6. No utilization of wood. No wood is harvested during the land conversion event for forest lands. This analysis determines the effects of wood utilization as an energy source and applies only to the forest conversion case (referred to as scenario H).
7. No technology improvement in ethanol yield. We do not project increases in ethanol yield with time in a sensitivity analysis (referred to as scenario I).
8. Corn yield. Recent trends in corn yield increase have been greater than historical rates of yield increase (*27*). In a sensitivity analysis, we double the annual corn yield increase rates and assume that these increases in yield continue up to a maximum of about 18 t per hectare per year (285 bushels per acre per year) at which point no further increase in yield occurs (referred to as scenario J).
9. Allocation in corn stover production. Output mass is used as an allocation factor in assigning GHG associated with corn agriculture to corn stover (referred to as scenario K).

The effects of these scenarios are considered individually and then in combination to explore the range of GHG emissions attributable to land use change for corn agriculture within the forty counties of our analysis.

Results and Discussion

The E85 fuel systems under current tillage practices (the reference case) offer cumulative GHG benefits of 495−1236 (avg. 882) Mg of CO_2 equivalent per hectare over a period of 100 years after the conversion event in the grassland conversion case and 349−1057 (avg. 734) Mg of CO_2 equivalent per hectare in the forest conversion case. Regional variations among the forty counties are significant (up to 3-fold differences) because of soil texture, climate, cropping management practices, and so on. Mean cumulative GHG benefits of the E85 fuel systems are illustrated in Figure 1. The negative values reflect net GHG emissions, i.e., the E85 fuel system releases more total GHG emissions than the gasoline fuel system does. In 100 years, one hectare of cornfield produces a total of 0.42−0.78 (avg. 0.65) million L of ethanol fuel that can propel an E85 fueled vehicle 5.3−9.7 (avg. 8.1) million km.

Considering the reference case, due to the carbon debt incurred at the land conversion event and declines in SOC, the E85 fuel system in the grassland conversion (or forest conversion) case fails to provide any GHG benefits for 12 years (or 31 years for forest conversion) after the conversion event. Conversion of forest to cropland produces a greater carbon debt than the conversion of grassland by about 9-fold. The carbon density in above- and belowground biomass in both grassland and forest plays an important role in GHG emissions associated with LUC. The DAYCENT model predicts the average carbon density in above- and belowground forest biomass in the counties studied to be 70 ± 31 Mg of carbon per hectare, while the average carbon density of a forest in the United States is 73 Mg of carbon per hectare (*28*). In comparison, the model predicts that the average grassland carbon density is 4.0 ± 1.1 Mg of carbon per hectare. This value is similar to the average carbon density of temperate grassland (4.3−4.7 Mg of carbon per hectare *29, 30*). Higher initial carbon density could result in more GHG emissions (a greater carbon debt), and therefore reduce the GHG benefits of the E85 fuel system involved in LUC.

The grassland conversion case provides more cumulative GHG benefits than the forest conversion case does. Soil organic carbon levels in a cornfield resulting from forest conversion decrease more rapidly than do those in a cornfield converted from grassland. The DAYCENT model predicts soil organic carbon levels of 84 ± 15 Mg of carbon per hectare in temperate zone forests and 65 ± 17 Mg of carbon per hectare in temperate grasslands, while Pouyat and his colleagues (*31*) state that soil organic carbon pools (1-m depth) in the United States are 107 Mg carbon per hectare in forests and 64 Mg carbon per hectare in grasslands. The simulations show that the conversion of forest to corn production under current tillage practices could reduce soil organic carbon by 22% at 30 years after the conversion and up to by 29% at 100 years after the conversion event, while converting grassland to cornfield under the current tillage practice reduces soil organic carbon by 15% at 30 years and by 14% at 100 years (see Supporting Information). Since temperate zone forests have higher initial SOC levels, the size of the change in the forest conversion case is greater than that in the grassland conversion case. The decline in SOC levels decreases in magnitude with the cropping year, implying that soil organic carbon levels are approaching a steady state. Thus the effects of LUC on the GHG profile of the E85 system gradually decrease with time.

The payback period, or the period of time before the E85 fuel system provides cumulative GHG benefits, for the forest conversion case under current tillage practices is 31 years, while the payback period of the grassland conversion case is 12 years. The grassland conversion case has a shorter payback period because a lower carbon debt at the conversion event and lower rates of SOC decrease than the forest conversion case. Significant regional variations are also observed in the payback periods: 2–25 years in the grassland conversion case (16–52 years in the forest conversion case) under current tillage practices.

As seen in Figure 1, plow tillage practice (scenario C) reduces cumulative GHG benefits over 100 years after the conversion event by 9% in grassland conversion case and by 10% in the forest conversion case, compared to the reference case. Plow tillage practice extends the payback period to 18 years in grassland conversion (or 37 years in forest conversion case). Furthermore, plow tillage depletes SOC faster than does current tillage practice because of increased soil disturbance. The DAYCENT model predicts that plow tillage reduces SOC levels by 30% over 100 years after conversion of grassland to cornfield, and by 39% over 100 years after the conversion of forest to cornfield. Results from the simulations are similar to experimental results (*32*). The DAYCENT model predicts 21% reduction in SOC levels during 25 years after the conversion of forest to cornfield, while 19% reduction of SOC levels was observed in tilled cornfield converted from mixed hardwood forest in eastern Ontario (*32*).

In contrast, no-tillage practices (scenario A) increase cumulative GHG benefits by 136 Mg of CO_2 equivalent per hectare over 100 years in grassland conversion case, and by 127 Mg of CO_2 equivalent per hectare in the forest conversion case compared to the reference case. Under no-tillage, the SOC level of cornfield converted from grassland increases by about 12% at 100 years after conversion. About 27 Mg of CO_2 equivalent per hectare of GHG benefit over 100 years after the conversion of grassland to cornfield results from changes in SOC level due to no-tillage practices in newly converted cornfield from grassland. Additionally, no-tillage practices also reduce the decline in SOC levels in a cornfield converted from forest. After 100 years, the cornfield converted from forest averaged only an 11% decrease in SOC level. The DAYCENT model predicts 2% reduction in SOC levels over 6 years under no-tillage after the conversion of forest to cornfield, while the same reduction over 6 years is also observed when cornfield under no-tillage in West Africa is converted from forest (*32*). For the grassland conversion case, the E85 fuel system under no-tillage takes 4 years to provide GHG benefits versus 20 years in the forest conversion case.

The use of winter cover crops along with no-tillage practice (scenario B) provides the greatest cumulative GHG benefits of all of the cropland management approaches considered in this study. This approach provides 794–1685 (avg. 1327) Mg of CO_2 equivalent per hectare of GHG benefits over 100 years in the grassland conversion case and 626–1584 (avg. 1185) Mg of CO_2 equivalent per hectare in the forest conversion case. The DAYCENT model predicts that converted cornfields following winter cover crop practices have higher SOC levels than either grassland or forest. After an initial decrease in SOC levels, the SOC levels in the new converted cornfield increase each year because of carbon inputs from the cover crops. After 100 years, the SOC levels of cornfields converted from grassland increase by 35%, and the SOC levels of cornfield converted from forest increase by 10%. The use of winter cover crops could reduce the payback period for the forest conversion case to 14 years and the payback periods for the grassland conversion case to 3 years.

Results from the scenario analysis show that the displacement of Athabasca tar sands based gasoline by E85 fuel increases cumulative GHG benefits over 100 years by about

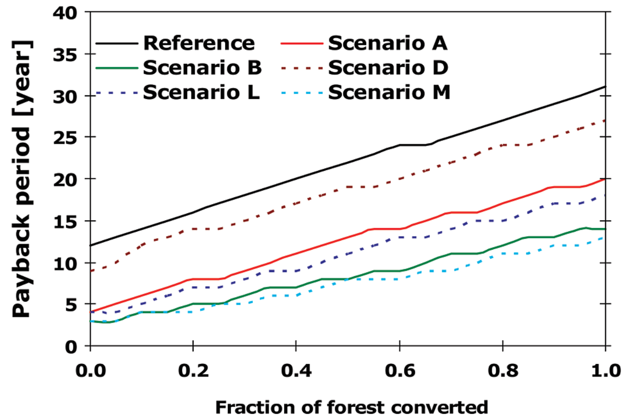

FIGURE 2. Effects of the fraction of land that is forest converted to cornfield on the payback period. Scenario L is similar to scenario D except that corn is grown under no-tillage conditions. Scenario M is similar to scenario D except that corn is grown under no-tillage plus cover crop.

19% in the grassland conversion case and by about 23% in the forest conversion case. The new payback time for the grassland conversion case is 9 years, a reduction of 3 years from conventional gasoline, while the payback time is 27 years for the forest conversion cases, a reduction of 4 years. GHG emissions of Athabasca oil sands based gasoline are assumed to about 1.6 times higher than those of regular gasoline (*15*). GHG emissions of petroleum fuels or petroleum substitutes such as tar sands, oil shale, or coal to liquid fuels are likely to increase in the future rather than decrease as resource quality declines and extraction and refining difficulty increase. Thus the greenhouse performance of E85 fuels is likely to further improve relative to petroleum fuels.

The sensitivity analyses (scenarios E–K) show that the energy source in the dry mill is the most environmentally sensitive factor for both the grassland and forest conversion cases. The utilization of wood during the land use conversion of forest is a key factor. Using fossil energy as an energy source in the dry mill causes a 34–43% reduction in cumulative GHG benefits and extends the payback period to 17 and 43 years for grassland and forest conversion, respectively. Not utilizing wood as an energy source for the biorefinery during forest conversion extends the payback period to 56 years and reduces the cumulative GHG benefits of the E85 fuel system by about 33%. In contrast, other factors (e.g, the DDGS displacement scenario, ethanol yield per bushel, and so on) alter cumulative GHG benefits of the E85 fuel system by less than 10% versus the reference case. Results from scenario and scenario analyses are summarized in the Supporting Information.

Both grassland and forest may be involved in land use conversion, but we do not know in what relative amounts. To better understand the overall effects of LUC on GHG emissions of the E85 fuel system, the effects of the fraction of forest converted on the payback period are determined and shown in Figure 2. The payback period obviously increases with the fraction of forest converted. Figure 2 clearly shows that cropping management strategies are key factors in determining the payback period. For example, Scenario B (no-tillage plus cover crop) can reduce the payback period by 9–17 years compared to the reference case. The dotted lines in Figure 2 represent situations in which E85 fuel displaces Athabasca oil sands based gasoline.

This study shows that appropriate cropland management practices can reduce the GHG emissions associated with direct and indirect LUC. No-tillage practice combined with the use of winter cover crops is the best cropland management practice considered here in order to maximize cumulative GHG benefits of the E85 fuel system and to minimize the payback period. SOC levels in the top 20 cm depth are simulated by DAYCENT and used in the analysis. Some experimental work (which is contradicted by other experimental work) indicates that the SOC content at plow depth in plowed soil is greater than in no-till soil (*33*). Hence, if the whole soil profile (1 m depth) is used in the analysis, the benefits of no tillage practice may or may not be observed (*34, 35*). Further investigations on the effects of soil depth on carbon accumulation with tillage practices are needed.

As mentioned above, GHG emissions associated with indirect LUC in the ethanol fuel system is a highly controversial topic and many issues remain to be addressed. For example, who will be held responsible for GHG emissions associated with the carbon debt—the biofuel industry or the food (animal feed) industry? In this analysis and the previous indirect LUC analysis (*2*), biofuel industries are assumed to take full responsibility for GHG emissions accompanying the land use conversion event (referred to as GHG from carbon debt in eq 3). This is a "worst case" for the biofuel industries. Explicit regulatory policy from government agencies or consensus action by international groups such as the International Standards Organization (ISO) could resolve this issue by allocating environmental burdens in global systems among all the industries using a particular internationally traded commodity such as corn. Another issue related to indirect LUC is the GHG emissions of crop cultivation for newly converted croplands, particularly changes in SOC levels. It is unlikely that the biofuel industries have any influence on the cropping management practices applied to newly converted croplands when newly converted croplands are dedicated to animal feed production. Again, the fundamental question arises: who will be held responsible for GHG emissions associated with changes in SOC levels (and the associated GHG emissions) during crop cultivation? In this study, we assume that both the biofuel and food (actually animal feed) industry sectors are held responsible for these GHG emissions. GHG emissions associated with changes in SOC levels in existing cornfields elsewhere dedicated to food (animal feed) production are included in the analysis as GHG credits. Yet another issue is the appropriate cropping period for newly converted croplands. As shown in this study, the GHG emissions of the indirect LUC vary with time following the LUC event. We chose a cropping period here of 100 years, but newly converted cropland could continue as cropland for more or less than 100 years after the land use conversion event. The cropping period significantly affects GHG emissions for indirect LUC. Thus, methodologies or consensus approaches on how to analyze indirect LUC for biofuel systems should be established to clarify these and other issues.

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Supporting Information Available

Farming sites, fraction of conservation tillage in the current practice, system boundary, results from the DAYCENT simulations, data sources, parameter projection, GHG emissions associated with carbon debt, GHG emissions associated with LUC, GHG benefits of the E85 fuel system in each county, cumulative GHG benefits of the E85 fuel system, payback period, scenario and sensitivity analyses.This material is available free of charge via the Internet at http://pubs.acs.org.

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