Producing energy while sequestering carbon? The relationship between biochar and agricultural productivity

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Abstract

A partial solution to problems associated with anthropogenic greenhouse gas (GHG) emissions could be the development and deployment of carbon-negative technologies, i.e., producing energy while reducing atmospheric carbon dioxide levels. Biofuels have been considered a possibility but have faced limitations due to competition with food production and GHG emissions through indirect land-use change (ILUC). In this article, we show how emissions from ILUC can potentially be reduced by producing food and bioenergy from biochar amended soils. The possibility of yield improvements from biochar would reduce the land requirement for crop production and thus, lead to a reduction in emissions from ILUC. In our application, biochar and bio-oil are produced via fast pyrolysis of corn stover. Bio-oil is subsequently upgraded into a fuel suitable for use in internal combustion engines. Applying the U.S. regulatory method used to determine biofuel life cycle emissions, our results show that a biochar-induced yield improvement in the U.S. Midwest ranging from 1% to 8% above trend can lead to an ILUC credit between 1.65 and 14.79 t CO_2-equivalent ha^{-1} $year^{-1}$ when future emissions are assessed over the next 30 years. The model is generalizable to other feedstocks and locations and illustrates the relationship between biochar and crop production.

Keywords: Biochar, life cyle analysis, biofuel, yield improvement

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1. Introduction

Producing food and energy while sequestering carbon is a difficult goal to achieve. Biofuels produce energy but directly compete with food production and have carbon-positive life cycles.

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Bioenergy could achieve carbon-neutrality from a life cycle perspective if the amount of CO_2 removed from the atmosphere, directly and indirectly, is equal to the amount emitted into the atmosphere over the entire fuel cycle. Conventional biofuels, such as corn grain ethanol, are considered carbon-positive since more greenhouse gases (GHG) are emitted especially through indirect land-use change (ILUC). ILUC is a component of GHG emissions calculations that is required by law in biofuel life cycle analysis (LCA). Regulatory policy therefore adopts a consequential life cycle methodology[2]. The economic and life cycle logic behind ILUC for biofuel production used by the U.S. Environmental Protection Agency (EPA) is as follows: Increased demand for biofuel feedstock causes crop prices to rise. This price increase provides farmers a greater incentive to utilize land, possibly forest, to replace crops being used for energy production. This land conversion generates significant emissions, particularly in the case of deforestation, which results in soil and biomass carbon to be released into the atmosphere. Although controversial since it is difficult to estimate, ILUC effects result in positive GHG emissions for some biofuels such as corn ethanol (Searchinger et al., 2008; Fargione et al., 2008; Melillo et al., 2009; Keeney and Hertel, 2009; Dumortier et al., 2011).

Theoretically, carbon-negative biofuels are attainable if the pathway releases a smaller amount of GHG emissions than what it extracts from the atmosphere, most likely by employing carbon sequestration. Including ILUC effects in life cycle calculations can result in negative emissions through avoided deforestation or afforestation. This could occur if the pathway used to produce biofuels generates sufficient crop yield increases such that less land is needed for agriculture and if the permanent increase in crop yields is attributed to the biofuel pathway. The objective of this study is to explore whether carbon-negative biofuels are attainable from a fast pyrolysis system when biochar is used as an agricultural soil amendment, resulting in an increase in crop yields, and when offsetting effects associated with ILUC are used as part of a consequential LCA. This LCA uses EPA's methodology for measuring indirect land-use change, but in this case the impact of the ILUC calculation is to improve the carbon balance of the system by reducing the need for new land hectares by improving yields on existing hectares.

It is important to note that for our results to hold, it does not matter whether grain is used to produce food or fuel. We just require an "interior solution" where both food and biofuels (ethanol in our case) must be produced somewhere and that neither ever goes to zero. The ILUC credit is independent of ethanol production if we make the assumption that the yield increases can displace acreage used to produce ethanol elsewhere and that the biochar does not necessarily have to go back to the same hectare it was extracted from (which might be used for food production).

2. Biochar Characteristics

There has been increasing recognition that biochar could play a significant role in the realization of carbon-negative bioenergy production when used as a soil amendment (Lehman, 2007;

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[2] Throughout the paper, we are considering consequential life cycle analysis (LCA) as opposed to attributional LCA. Attributional life cycle analysis includes direct effects such as carbon sequestered by the biofuel feedstock. Consequential life cycle analysis includes also indirect effects such as cropland reallocation and the resulting indirect land-use change emissions.

Renner, 2007; Mathews, 2008). Using biochar for this purpose dates back to the pre-Columbian Amazon where natives are believed to have applied it to agricultural soils, resulting in what is known locally as *terra preta*, or black earth soils (Blackwell et al., 2009). Hundreds of years later, these soils have been found to be significantly more fertile than comparable surrounding regions (Marris, 2006). Within the context of our biofuel pathway, there are four general merits of biochar application to agricultural soils: its role in carbon sequestration, potential reduction in nitrous oxide (N_2O) emissions, its impact on soil organic carbon levels, and its effect on crop yields.

Biochar is composed of a large amount of highly stable carbon and sequesters carbon if used as an agricultural soil amendment (Brewer et al., 2009). Biochar quality, as measured by the amount of labile versus recalcitrant carbon, influences its carbon sequestration potential (Bruun et al., 2011). Labile carbon will be mineralized by soil microorganisms in a relatively short period of time whereas recalcitrant carbon will be stable for hundreds or possibly thousands of years (Lehmann et al., 2009). Furthermore, biochar containing labile carbon can stimulate soil organic matter mineralization through a priming effect. However, in the long-term biochar enhances stabilization of biogenic organic compounds through adsorption and humification (Zimmerman et al., 2011; Rogovska et al., 2011).

Reduced need for synthetic nitrogen fertilizer in crop production is anticipated because biochar decreases losses of nitrogen due to nitrate leaching and because biochar may reduce N_2O emissions. Biochar applications decrease soil bulk density and thereby increase porosity and enhance soil aeration (Laird et al., 2010). Hence reduced denitrification is one potential explanation for reported reductions in N_2O emissions from biochar-treated soils (Rogovska et al., 2011; Yanai et al., 2007). Another potential mechanism for decreased N_2O emissions in biochar-amended soils may be an increased adsorption of ammonium cations (NH_4^+) and/or N-containing organic compounds, which reduce both N leaching and N_2O emissions (Singh et al., 2010). While most studies have shown reductions in N_2O emissions for soils amended with biochar relative to control soils (Angst et al., 2013; Cayuela et al., 2013), no significant differences and even small increases between biochar-amended soil and controls in N_2O emissions have been reported (Karhu et al., 2011; Scheer et al., 2011).

Biochar amendments have the potential to enhance the retention of plant nutrients and water by soils. This results in a decrease in nutrient leaching (Singh et al., 2010; Liang et al., 2006; Laird et al., 2010; Novak et al., 2010) and an increase in plant available water retention (Laird et al., 2010; Karhu et al., 2011). Both are anticipated to increase net primary production and/or improve nutrient and water use efficiency in crop production. Any increase in net primary production due to biochar will increase the input of plant residue carbon to soils, which will help build biogenic soil organic matter. While increasing soil carbon sequestration, this would also lessen the need to leave corn stover unharvested to maintain soil organic matter, allowing a larger share to be sustainably removed (Mullen et al., 2010; Wilhelm et al., 2007).

Several studies show a positive effect on crop yields, particularly when applied to degraded soils in the tropics (Glaser et al., 2002; Kimetu et al., 2008; Major et al., 2010). In the case of biochar applied to corn in Colombia, yield increases as high as 140% were observed, with a 28% increase in the second year of the study (Major et al., 2010). The Columbian corn study was conducted on degraded soil in the tropics using slow pyrosis biochar from wood which is different from the analysis in the present paper. The yield increase above trend on already highly productive

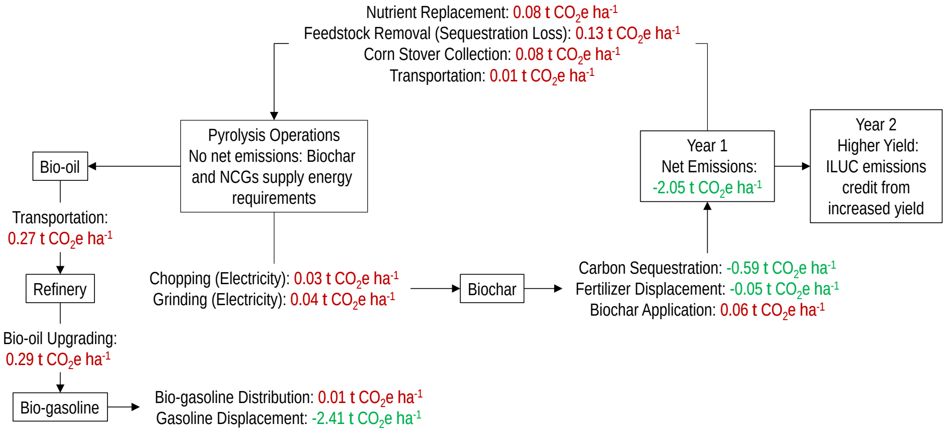

Figure 1: Static stages and emissions associated with fast pyrolysis of corn stover. The process begins with 1 hectare of corn in the box labeled "Year 1" and continues counter-clockwise. At the end of the process, biochar is applied to cropland soil which generates a potential increase in crop yields.

soils in the U.S. Midwest might be difficult to achieve. Thus, we calculate the break-even yield improvement necessary over the life cycle of 30 years. In addition, the effects of biochar on yield are highly variable and not all studies have shown a positive impact of biochar on crop yields (Spokas et al., 2010). However, interactions between biochar quality, soil quality, climate, and cropping systems are still in early stages of investigation, highlighting a need for further research on the interactions between biochar and agricultural soil (Gaskin et al., 2010).

Our approach highlights the yield improvement necessary and we conduct a sensitivity analysis as well. The method is not limited to a particular feedstock or location and shows that the potential yield improvement can alter LCA significantly.

3. Scope of Study

The function of the product system is to produce ethanol and bio-oil from corn and corn stover for use in transportation vehicles with a system that results in carbon-neutrality. The functional unit is 1 MJ of energy. The system boundaries are spatially defined to include both corn grain and corn stover from one hectare of land harvested over a 30 year period. As can been seen in Figure 1, the system begins with fertilizer and equipment used to produce the corn and ends with the delivery of the fuel to a gasoline station. Total pathway emissions are attributed to ethanol and determined based on the use of the entire hectare. Any saved emissions from marginal bio-gasoline or biochar production are subtracted from this total, where marginal bio-gasoline is taken to displace gasoline and diesel (half of each).

4. Life Cycle Analysis

The agricultural and forestry sector can produce biochar from crop residues (corn stover, wheat straw, sugar cane), forestry residues, and animal manures. As mentioned before, biochar has the potential to increase yields if applied to cropland. If biochar is amended to the soil and enhances crop yields permanently above the trend, less land will be needed for crop production in the future or, put differently, more production is possible on the same area of land. We model the production of biochar and bio-gasoline using fast pyrolysis and apply the resulting biochar to cropland (Laird et al., 2009). We chose fast pyrolysis to produce biochar because it also yields a valuable by-product, bio-oil, which can be upgraded into a drop-in fuel. Fast pyrolysis produces 10-20 wt% which seems a modest yield compared to the 40 wt% resulting from slow pyrolysis. The drawback of slow pyrolysis is that it produces "producer gas" as a co-product which is of relatively low economic value. The amount of biochar produced from fast pyrolysis during the production of transportation fuels would be large. Brown et al. (2011) demonstrate that fast pyrolysis has superior economics for the production of biochar compared to slow pyrolysis because of the higher value of the energy co-products. As detailed in Brown et al. (2011), all process energy requirements for pyrolysis have been accounted for.

Following the biochar application, we assume a range of yield improvements ranging from 0% to 8% in addition to calculating the break-even yield improvement necessary to achieve carbon neutrality. Given yield improvements after biochar application, we can determine the ILUC credit for avoiding expansion of cropland. The harvested corn can either be used for food production or corn ethanol production. The fundamental stages and static baseline emissions of fast pyrolysis of corn stover are illustrated in Figure 1. Aspects surrounding bio-oil as an alternative energy source for electricity generation have been studied fairly extensively (Grassi and Bridgwater, 1993; Bridgwater et al., 2002). In recent years, interest in the potential for bio-oil to be upgraded via hydro-processing to bio-gasoline has grown (Wright et al., 2010; Hsu, 2011). The key feature that makes this an attractive process is the ability to use bio-gasoline as a drop-in fuel in existing internal combustion engines, displacing conventional crude-based transportation fuels and generating a further reduction in GHG emissions.

Our pathway assumes that ethanol is produced from corn grain. A fraction of the remaining corn stover is harvested and subjected to fast pyrolysis to produce biochar and bio-oil. The bio-oil is then upgraded to bio-gasoline (naphtha and diesel range stock fuel) and the biochar is returned to cropland soil as an agricultural amendment. Emission factors for the segment of production associated with corn stover are taken from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model. Our life cycle emissions calculations include processes from field to wheels in producing ethanol. Following the literature on LCAs for cropping systems and interdependent crop rotations, we adopt a system expansion approach with the functional unit defined as 1 MJ of energy to facilitate comparisons between ethanol (E10 fuel) and gasoline (Kim and Dale, 2005; Kim et al., 2009; Luo et al., 2009). System boundaries are spatially defined to include both corn grain and corn stover from one hectare of land. Total pathway emissions are attributed to ethanol and determined based on the use of the entire hectare. Any saved emissions from marginal bio-gasoline or biochar production are subtracted from this total, where marginal bio-gasoline is taken to displace gasoline and diesel (half of each). Life cycle emissions associated with corn grain ethanol are taken from the EPA 2012 analysis[3]. Life cycle processes and emission calculations for fast pyrolysis of corn stover are presented in what follows for the first year of the

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[3] U.S. Congress, Energy Independence and Security Act of 2007 (Public Law No: 110-140, Washington D.C.,2007)

biofuel pathway. This implies that the corn stover removal rate is 40% and any yield improvements from biochar application have not yet taken effect. These effects would begin in the second year.

4.1. Corn Stover Harvesting and Transportation

Once harvested, the corn stover is transported to a pyrolysis facility assumed to process 70,000 tons per year in an area where 20% of the land is allocated to corn, i.e., a crop density of 0.2. This results in an average hauling distance of 13.4 kilometers, where the hauling distance is a function of corn stover yield, crop density, and plant size (French, 1960). We also allow for a loss in carbon sequestration due to feedstock removal where it is assumed that 45% of corn stover is comprised of carbon, of which 2% is taken from the soil (McCarl et al., 2009).

4.2. Corn Grain Ethanol Life Cycle Emissions

Emissions from corn grain ethanol are held fixed on a “per MJ” basis with the exception of emissions from land-use change, which are fixed on a “per ha” basis. These emissions are based on the EPA 2012 life cycle calculations to represent a near-term scenario. A summary of the EPA 2012 life cycle emissions calculations is provided in the table 1 under the assumption that yields are 11.6 t ha^{-1}.

4.3. Pyrolysis and Upgrading Operations

It is assumed that additional nutrients must be provided to compensate for the loss due to corn stover removal, generating further emissions. Once the corn stover has been transported to the pyrolysis facility, it is pre-treated, through chopping and grinding, to a final size of 3 mm. Electrical energy needed for chopping is 31.9 MJ t^{-1} (Mani et al., 2004) and for grinding is 39.6 MJ t^{-1} (Bitra et al., 2009). We assume that the pyrolysis process is fully integrated and that one-third of biochar produced, in addition to all non-condensable gases (NCGs), are sufficient to provide all of the internal process heat (Wright et al., 2010). Bio-oil, biochar, and NCG yields are taken to be 61.7%, 17.0%, and 21.9%, respectively (Mullen et al., 2010). Collected biochar is transported back to the field and applied to the soil as an amendment. It is assumed that the trucks delivering corn stover also haul biochar back to the field so that emissions for this segment have already been accounted for in the transportation of stover. Bio-oil is subsequently transported to existing refineries to be upgraded into bio-gasoline with the average one-way hauling distance assumed to be 400 km (approximately the west-to-east distance of the state of Iowa). The last phase of bio-gasoline production is hydroprocessing and refining where we assume that refining is possible with negligible modifications in infrastructure (Huber and Corma, 2007). Pyrolysis is gaining traction among many integrated energy companies because it comes closest to resembling standard refining operations among the many options for producing sustainable transportation fuels from lignocellulose. This does not mean that significant infrastructure changes are unnecessary if lignocellulose is to be converted into gasoline and diesel. Our paper is based on the process modeling of pyrolysis-based fuels of Wright et al. (2010), which accounts for all infrastructure needed to produce bio-oil and upgrade it to finished fuels. Thus, the extent of build out is not limited by current infrastructure but

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and U.S. Environmental Protection Agency, Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program; Final Rule (Federal Register, 40 CFR Part 80, Washington D.C., 2010) upon societal acceptance of biofuels as a means to reduce GHG emissions. The carbon balance is not dependent on the level of adoption. For hydroprocessing, it is assumed that 38% of bio-oil produced is used to generate the necessary hydrogen Wright et al. (2010). As detailed in Wright et al. (2010), deoxygenation of heavy fraction of bio-oil is accomplished with hydrogen obtained through steam reforming of the aqueous phase of the bio-oil.

4.4. Biochar Application, Fertilizer Displacement, and Carbon Sequestration

Once returned to the field, biochar is applied at a rate of 24.7 t ha^{-1} (10 t $acre^{-1}$) and generates an emissions credit by sequestering carbon. The fixed carbon content of fast pyrolysis biochar made from herbaceous biomass is approximately 37.8% (Brewer et al., 2009). There is also likely to be a synergistic relationship between biochar and cropland soil that would result in decreased synthetic fertilizer needs. As discussed earlier, it is possible that this decrease may be substantial. For the baseline as well as the above-trend yield improvement, we have included fertilizer application and the resulting emissions from the EPA GHG emissions for corn grain ethanol. For the scenario, we correct this emission factor by allowing a decrease in the fertilizer application rate by reducing fertilizer application by 0.394 kg N_2O t^{-1} of biochar applied (Roberts et al., 2010). This generates an emissions credit of 0.013 t CO_2e t^{-1} of corn stover removed (0.05 t CO_2e ha^{-1}). As presented here, this pathway results in net GHG emissions of -2.05 t CO_2e ha^{-1} as shown in figure 1. In our sensitivity analysis, we also include the reduction of N_2O emissions after biochar application.

4.5. Indirect Land-Use Change Emissions Credit

For land that has been treated with biochar, we allow for the possibility that this treatment provides an increase in yield trends. Corn yield projections are calculated by fitting a linear trendline to the 2011 FAPRI Outlook (15 year) projections and extending this projection to 30 years [4]. An increase in yields allows a greater amount of ethanol, bio-gasoline, and biochar to be produced from a given plot of land. Intensification of ethanol production allows land elsewhere, which would have been converted to cropland to produce this additional amount of ethanol, to return to its native state. This avoided land-use change brought about by yield improvements results in an emissions credit associated with the marginal increase in ethanol production. The credit obtained is taken to be equal to the 30-year average annualized international ILUC emissions as determined by the EPA, i.e., 76 g CO_2e MJ^{-1}. An essential element of our modeling approach is to show that crop yield increases could only have occurred if the particular biofuel production system were in operation.

4.6. Life Cycle Emissions Per Hectare

There are three life cycle components that determine the magnitude of emissions in a given year. The first is life cycle emissions attributed to corn grain ethanol. The second component is life cycle emissions attributed to biochar and bio-gasoline produced via fast pyrolysis of corn stover. Emissions for this portion of the pathway are calculated based on yields and other parameters as

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[4] Food and Agricultural Policy Research Institute (FAPRI), World Agricultural Outlook Database. (2011). http://www.fapri.iastate.edu/tools/outlook.aspx

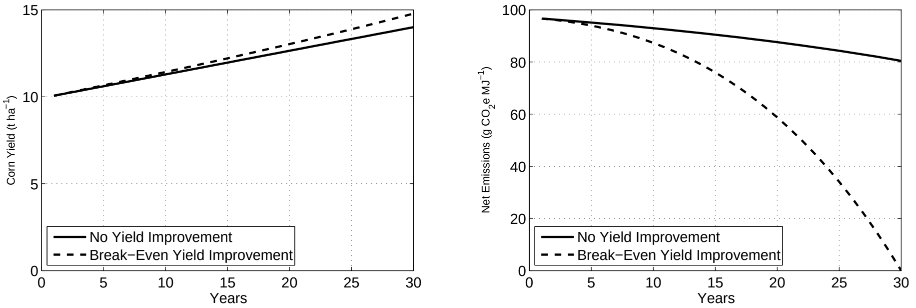

Figure 2: Yield and accumulated net GHG emissions assessed over 30 years without biochar-induced yield improvement and with break-even biochar-induced yield improvement of 5.89%.

reported in table 2 and the supplementary Information for each year in the time horizon. The final component is the credit obtained from a biochar-induced increase in yield on ethanol production above the baseline. It is important to recognize that it is the cumulative net emissions of all future years combined that determines the percentage of emissions reduction in the first year. The pathway is not carbon-negative in the first year alone, or any other year individually. The consideration of emissions over a 30 year time horizon is consistent with the EPA regulatory approach.

5. Results

Our baseline is called “No Yield Improvement” and we assume no yield-improving effects of biochar. In the baseline, yield grows at the projected increase from the previously mentioned 2011 FAPRI Outlook. Net pathway emissions are 80.4 g CO_2e MJ^{-1} which is 15.9% lower than the 96 g CO_2e MJ^{-1} for gasoline (Searchinger et al., 2008). Figure 2 depicts the yield under the baseline which corresponds to the trend yield and the net pathway emissions assessed over 30 years. The scenario is called “Break-Even Yield Improvement” in which we calculate the yield improvement from biochar necessary to achieve zero net pathway emissions over the 30 year period. This yield amounts to an above-trend yield improvement of 5.89%. Given our assumptions and the yield improvement of 5.89%, 93% of a specific plot of land will have received biochar treatment at the end of the 30 year time period. Thus, yields are 5.5% higher (panel (a) in Figure 2) than the baseline case by the end of 30 years (0.93 x 0.0589). If biochar applied to cropland increases yields by 5.89% above trend, then we have a carbon neutral system, i.e., the net pathway emissions are zero. As shown in figure 3b, for yield improvements above 5.89%, net pathway emissions are negative. The net pathway emissions in figures 3b, 4, 5 are cumulative figures assessed over 30 years. Therefore the carbon-neutrality of the system depends on the assumption that we can obtain credit today for yield improvements that will last for thirty years. This accounting procedure uses the exact procedure used by the EPA to calculate ILUC. We then evaluate the effects based on the contribution of the system to the stock of CO_2 in the atmosphere. As an example, consider the case for 2025. The baseline yield projection (as determined from FAPRI) is 11.82 t ha^{-1}. With biochar applied to portions of a given field each year, this yield is increased to 12.05 t ha^{-1}. The

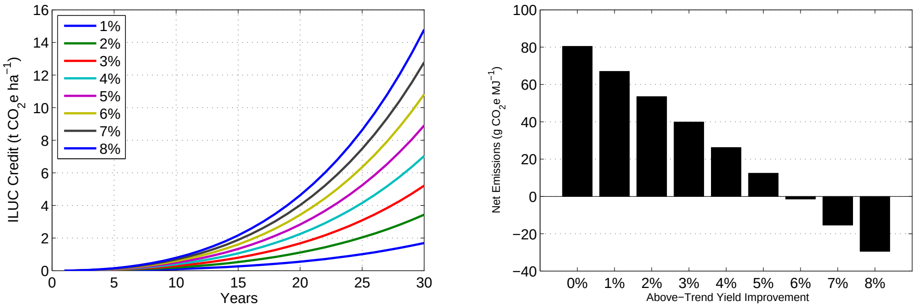

Figure 3: Indirect land-use change (ILUC) credit and net GHG emissions assessed over 30 years for biochar-induced yield improvements ranging from 0% to 8%.

increased yield improves net biochar and bio-oil production, which is taken into account when determining life cycle emissions. Based on this 0.23 t ha^{-1} yield increase, an additional 38.9 L of ethanol (824 MJ of bioenergy) is produced and attributed to biochar application. With international ILUC emissions taken as 76 g CO_2e MJ^{-1}, this marginal increase in ethanol production generates an emissions credit of 0.025 t CO_2e. Similar calculations are done for each year in the 30 year time horizon under consideration. The ILUC credit is cumulative over the years because the yield increase is permanent. A summary of the dynamic calculation of each of these components for each of the 30 years in the time horizon is presented in tables 3 and 4. Total emissions per hectare are also presented in those tables. The total per hectare is converted to a measure of g CO_2e MJ^{-1} based on the energy yield of ethanol per hectare. Table 1 in the manuscript illustrates the importance of international land-use change emissions which account for 63.79% of total corn grain ethanol emissions. The carbon stock in a hectare of native vegetation can be significant especially in the case of forest. So even if a relatively small area of forest is "saved", the GHG balance is affected significantly. This has been illustrated by Hertel et al. (2010) and Dumortier et al. (2011). How important those savings can be illustrated with a different example involving stocking rates, i.e., animal units per hectare. If the stocking rate of cattle was improved by only 2% in Brazil, enough pasture would made available to accommodate all of the biofuel production of the United States (Gorter and Just, 2010). So the yield improvement of 5.89% might seem small but the effects are significant. The EPA methodology assumes that the yield improvement lasts at least thirty years and it accounts for this carbon savings at the time the char is applied.

5.1. *Sensitivity Analysis*

Since we are considering a process that is not currently in commercial operation, we conduct a sensitivity analysis on variables that are either most crucial or have a high degree of uncertainty associated with them. The two most important parameters are the degree of biochar-induced yield growth and the corn stover removal rate. The ILUC credit after 30 years ranges form 1.65 and 14.79 t CO_2-e ha^{-1} year^{-1} for yield increases from 1% to 8% above trend (Panel (a), Figure 3). Panel (b) in Figure 3 summarizes net emissions under various biochar-induced above-trend yield improvements. Yield assumptions are important in terms of ILUC because a hectare of native vegetation can contain a large amount of carbon and small changes in yield can have a significant

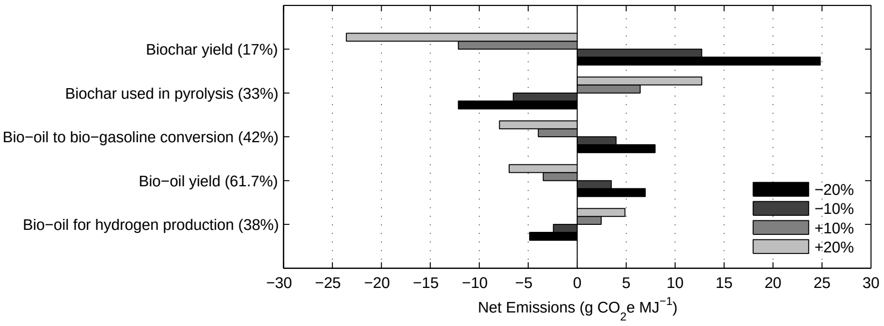

Figure 4: Net GHG emissions under the break-even yield improvement assessed over 30 years for different removal fractions with and without biochar application.

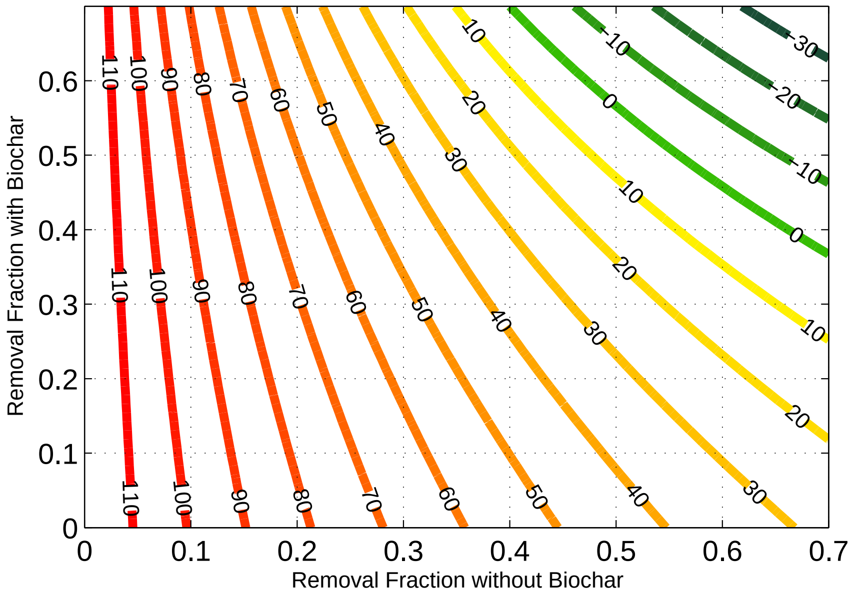

Figure 5: Net GHG emissions under the break-even yield improvement assessed over 30 years by varying key parameters +/- 10% and 20% from their base values (in parenthesis)

effect (Hertel et al., 2010; Dumortier et al., 2011). Even a 1% yield improvement above trend reduces emissions by 17%.

The amount of corn stover that can be sustainably removed from a given plot of land has been somewhat controversial. Some studies have allowed as much as 70% to be removed whereas others have suggested as little as 25% in some areas (Sheehan et al., 2003; Kim et al., 2009). The updated U.S. Billion Ton study finds that 45% to 50% (national average) can be sustainably removed under no-till practices (Perlack and Stokes, 2011). Removal of 45-50% of surface residue in a no-till system reduces annual inputs of labile carbon to the soil and therefore GHG emissions from the soil. Labile crop residue has a half-life in soils of approximately 6 months. By contrast, biochar carbon is highly recalcitrant and has a half-life of several hundred to over 1000 years. This difference in the intrinsic stability between biochar carbon and residue carbon is responsible for the net carbon credit. Reduced emissions of N_2O are considered separately as noted above.

In our study, we allow for two different removal rates: one on land which has not been amended with biochar and a somewhat higher rate on land which has received the amendment as motivated earlier. There is still some uncertainty surrounding this rate and we also recognize that it is an important assumption affecting all subsequent results. We report baseline emissions under the assumption of 40% corn stover removal on land that has not been amended with biochar and 70% on land that has received the amendment. Variations on this assumption are provided in the sensitivity analysis (Figure 4). The results for other key parameters can be found in figure 5 where we vary the parameters by +/-10% and +/-20%. Note that the variations of those parameters and the resulting effect on the GHG balance are linear. The effects of varying the hauling distance on GHG emissions is negligible.

As aforementioned, uncertainty about the reduction of nitrous oxide emissions remains. We have conducted a sensitivity analysis with respect to emissions from reduced fertilizer application and domestic farm inputs and fertilizer N_2O. In our scenario, the fertilizer need is reduced by 0.394 kg N_2O t^{-1} of biochar applied. Varying this value from 0 to 0.788 kg N_2O t^{-1} changes the yield improvement required for carbon neutrality to 5.96% and 5.83%, respectively. Reducing the emissions from domestic farm inputs and fertilizer N_2O to 0 requires a yield improvement of 5.51%. This suggests that our results are robust to changes with respect to nitrous oxide emissions. This is consistent with domestic farm inputs and fertilizer N_2O being relatively small compared to the international land-use change emissions of 76.1 g MJ^{-1}.

“Land Sparing” has been analyzed previously and found two have opposing effects. Ewers et al. (2009) argue that if yields increase, less land is needed for a given level of production which is the argument made in this paper. This is contrasted by Rudel et al. (2009) who claim that higher yields also increase the land profitability and farmers have the incentive to put the land in production to increase revenue. The elasticity of demand for agricultural products determines the magnitude of the second effect.

6. Discussion

Economically viable carbon-negative technologies have proven to be an elusive goal for alternative energy researchers, particularly for biofuel production. By itself, corn grain ethanol generates a non-trivial but only modest reduction in emissions as determined by the EPA in a long-term

(2022) scenario and an increase in emissions in a near-term (2012) scenario relative to gasoline. Cellulosic technologies to produce ethanol from corn stover have been unable to overcome issues of commercial scaling. Combining the two feedstocks into a single pathway to produce ethanol from corn grain and bio-oil/biochar from corn stover via fast pyrolysis is a pathway that has the potential to be carbon-neutral or even negative given sufficient yield improvement. This is predominantly a result of the yield benefit realized by applying biochar to cropland soil.

We recognize that this system is only one of many possible carbon-negative pathways. The key to the carbon-negative result in this article is that biochar-induced yield improvements lead to an offset of emissions associated with ILUC by intensifying ethanol production. By evaluating performance over 30 years, the effects of these yield improvements are cumulative because the yield improvements are permanent.

By sequestering carbon and mitigating or reversing the effects of ILUC, this platform provides an opportunity to produce energy (ethanol and bio-gasoline) while simultaneously reducing atmospheric CO_2 levels. It is a platform that could alter the perception of biofuels as a component of climate change policy.

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Figure Captions

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Category	Emissions (g MJ^{-1})
International Land-Use Change	76.1
Fuel and Feedstock Transport	4.4
Domestic Farm Inputs and Fertilizer N2O	5.4
Domestic Soil Carbon	0.1
Domestic Livestock	-3.4
Domestic Rice Methane	-1.6
Intl Farm Inputs and Fertilizer N2O	9.3
International Livestock	-1.3
International Rice Methane	-1.2
Tailpipe	0.8
Fuel Production Emissions	30.7
Total	119.3

Table 1: EPA Corn Grain Ethanol Greenhouse Gas Emissions (2012)

Parameter	Value	Source
Global warming potential of CH_4	25	IPCC (2007)
Global warming potential of N_2O	298	IPCC (2007)
Biochar yield (%) *	17	Mullen et al. (2010)
Stover removal without biochar (%) *	40	Assumed value
Stover removal with biochar (%) *	70	Assumed value
Bio-oil yield (%) *	61.7	Mullen et al. (2010)
Biochar used in pyrolysis (%) *	33.3	Wright et al. (2010)
Bio-oil to bio-gasoline conversion (%) *	42	Wright et al. (2010)
Bio-oil for hydrogen production (%) *	38	Wright et al. (2010)
Biomass at pyrolysis facility (t yr^{-1})	70,000	McCarl et al. (2009); Wright et al. (2010)
Carbon content of biochar (%)	37.8	Brewer et al. (2009)
Percentage of carbon in feedstock	45	McCarl et al. (2009)
Carbon taken from sequestered soil (%)	2	McCarl et al. (2009)
Dry Mill Plants (%)	63	
Moisture content (%)	15	
Emissions in kg CO_2e t^{-1} stover		
Corn stover collection	19.936	GREET V1.8c.0
Nutrient replacement	20.572	GREET V1.8c.0
Stover transportation	1.704	GREET V1.8c.0
Gasoline displacement	-600.049	
Pyrolysis operations	17.237	GREET V1.8c.0
Bio-oil transportation	65.302	GREET V1.8c.0
Upgrading bio-oil into bio-gasoline	73.080	GREET V1.8c.0
Bio-gasoline distribution	3.077	GREET V1.8c.0
Fertilizer displacement	-12.375	Roberts et al. (2010)
Biochar application	10.477	
Biochar sequestration gain	-146.084	Roberts et al. (2010)
Biochar sequestration loss	33.000	McCarl et al. (2009)

Table 2: Key assumptions and references for the life cycle calculations. The emissions in kg CO_2 t^{-1} wet stover have several components that are outlined in detail in the supporting information. The parameters marked with a “*” are subject to a sensitivity analysis.

	Emissions in t CO_2 ha^{-1}					
Year	Grain to Ethanol	Pyrolysis	ILUC Credit	Total	Energy Yield (MJ ha^{-1})	Total (g MJ^{-1})
2011	10.79	-2.05	0.00	8.74	0.09	96.60
2012	10.94	-2.11	0.00	8.83	0.09	96.30
2013	11.09	-2.17	0.00	8.91	0.09	95.90
2014	11.23	-2.24	0.00	8.99	0.09	95.50
2015	11.38	-2.30	0.00	9.07	0.10	95.10
2016	11.52	-2.37	0.00	9.15	0.10	94.70
2017	11.67	-2.44	0.00	9.22	0.10	94.30
2018	11.82	-2.52	0.00	9.29	0.10	93.80
2019	11.96	-2.59	0.00	9.36	0.10	93.40
2020	12.11	-2.67	0.00	9.43	0.10	92.90
2021	12.25	-2.75	0.00	9.50	0.10	92.50
2022	12.40	-2.83	0.00	9.56	0.10	92.00
2023	12.54	-2.92	0.00	9.62	0.11	91.50
2024	12.69	-3.01	0.00	9.68	0.11	91.00
2025	12.84	-3.10	0.00	9.73	0.11	90.50
2026	12.98	-3.19	0.00	9.78	0.11	89.90
2027	13.13	-3.29	0.00	9.83	0.11	89.40
2028	13.27	-3.39	0.00	9.88	0.11	88.80
2029	13.42	-3.49	0.00	9.92	0.11	88.20
2030	13.57	-3.60	0.00	9.96	0.11	87.60
2031	13.71	-3.71	0.00	9.99	0.11	87.00
2032	13.86	-3.83	0.00	10.03	0.12	86.30
2033	14.00	-3.94	0.00	10.05	0.12	85.70
2034	14.15	-4.07	0.00	10.08	0.12	85.00
2035	14.30	-4.19	0.00	10.10	0.12	84.30
2036	14.44	-4.32	0.00	10.11	0.12	83.60
2037	14.59	-4.46	0.00	10.12	0.12	82.80
2038	14.73	-4.60	0.00	10.13	0.12	82.00
2039	14.88	-4.74	0.00	10.13	0.12	81.30
2040	15.02	-4.89	0.00	10.13	0.13	80.40

Table 3: Baseline ”No Yield Improvement”: Emissions components of the dynamic calculation with no biochar-induced yield improvement

Year	Emissions in t CO_2 ha^{-1}				Energy Yield (MJ ha^{-1})	Total (g MJ^{-1})
	Grain to Ethanol	Pyrolysis	ILUC Credit	Total		
2011	10.79	-2.05	0.00	8.74	0.09	96.60
2012	10.95	-2.11	-0.01	8.83	0.09	96.31
2013	11.11	-2.18	-0.03	8.90	0.09	95.80
2014	11.27	-2.25	-0.06	8.96	0.09	95.18
2015	11.44	-2.32	-0.11	9.01	0.10	94.43
2016	11.60	-2.39	-0.17	9.04	0.10	93.55
2017	11.76	-2.46	-0.24	9.05	0.10	92.53
2018	11.93	-2.54	-0.34	9.04	0.10	91.26
2019	12.09	-2.62	-0.45	9.02	0.10	89.93
2020	12.26	-2.71	-0.58	8.97	0.10	88.33
2021	12.42	-2.79	-0.73	8.90	0.10	86.66
2022	12.59	-2.88	-0.90	8.80	0.10	84.70
2023	12.76	-2.98	-1.10	8.68	0.11	82.54
2024	12.93	-3.07	-1.33	8.53	0.11	80.18
2025	13.11	-3.17	-1.58	8.34	0.11	77.59
2026	13.28	-3.27	-1.87	8.13	0.11	74.69
2027	13.45	-3.38	-2.18	7.88	0.11	71.62
2028	13.63	-3.49	-2.54	7.59	0.11	68.21
2029	13.81	-3.61	-2.93	7.26	0.11	64.52
2030	13.98	-3.73	-3.36	6.88	0.11	60.55
2031	14.17	-3.85	-3.83	6.46	0.11	56.26
2032	14.35	-3.98	-4.36	5.99	0.12	51.59
2033	14.53	-4.12	-4.93	5.47	0.12	46.64
2034	14.72	-4.26	-5.55	4.89	0.12	41.26
2035	14.90	-4.40	-6.23	4.25	0.12	35.50
2036	15.09	-4.56	-6.97	3.55	0.12	29.33
2037	15.28	-4.71	-7.78	2.78	0.12	22.70
2038	15.48	-4.88	-8.65	1.93	0.12	15.63
2039	15.67	-5.05	-9.60	1.01	0.12	8.08
2040	15.87	-5.23	-10.62	0.00	0.13	0.00

Table 4: Scenario "Break-Even Yield Improvement": Emissions components of the dynamic calculation with biochar-induced yield improvement of 5.89%