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Set-asides can be better climate investment than corn ethanol

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Abstract. Although various studies have shown that corn ethanol reduces greenhouse gas (GHG) emissions by displacing fossil fuel use, many of these studies fail to include how land-use history affects the net carbon balance through changes in soil carbon content. We evaluated the effectiveness and economic value of corn and cellulosic ethanol production for reducing net GHG emissions when produced on lands with different land-use histories, comparing these strategies with reductions achieved by set-aside programs such as the Conservation Reserve Program (CRP). Depending on prior land use, our analysis shows that C releases from the soil after planting corn for ethanol may in some cases completely offset C gains attributed to biofuel generation for at least 50 years. More surprisingly, based on our comprehensive analysis of 142 soil studies, soil C sequestered by setting aside former agricultural land was greater than the C credits generated by planting corn for ethanol on the same land for 40 years and had equal or greater economic net present value. Once commercially available, cellulosic ethanol produced in set-aside grasslands should provide the most efficient tool for GHG reduction of any scenario we examined. Our results suggest that conversion of CRP lands or other set-aside programs to corn ethanol production should not be encouraged through greenhouse gas policies.

Key words: biofuel; CO_2; Conservation Reserve Program, CRP; corn ethanol; greenhouse gases; land-use change; renewable energy; soil carbon storage.

Introduction

Rising petroleum prices and tax incentives for ethanol production are increasing the demand for land used to grow corn and other ethanol feedstocks (Searchinger et al. 2008). Corn-grain-based ethanol production in North America is increasing rapidly, with more than 100 existing plants in the United States, ~50 more under construction, and a production capacity of 5 billion gallons (18.92×10^9 L) in 2006 expanding to ~10 billion (37.84×10^9 L) by 2009 (Westcott 2007). To meet the targets of the Energy and Independence and Security Act of 2007 (producing 36 billion gallons [136.23×10^9 L] of biofuel per year in the United States by 2022), corn production will need to increase by improving yields, substituting other crops with corn, and expanding corn acreage to currently uncultivated land. This last case, including converting both natural ecosystems and those in which cultivation has been interrupted (e.g., set-aside programs in the United States), can cause large shifts in C storage (Jobbágy and Jackson 2000) that need to be fully evaluated to assess the net greenhouse gas (GHG) reductions accompanying corn ethanol production (Adler et al. 2007, Fargione et al. 2008, Gibbs et al. 2008, Searchinger et al. 2008).

The extent to which GHG emissions can be reduced through corn ethanol fuels depends strongly on how and where the corn is produced. Corn ethanol production reduces net GHG emissions by substituting renewable for fossil fuels. Although one liter of corn ethanol has about 70% of the energy contained in a litter of gasoline, reductions in GHG emissions average ~20% on a per-MJ basis when considering a complete life-cycle assessment (including all GHG emitted during the entire

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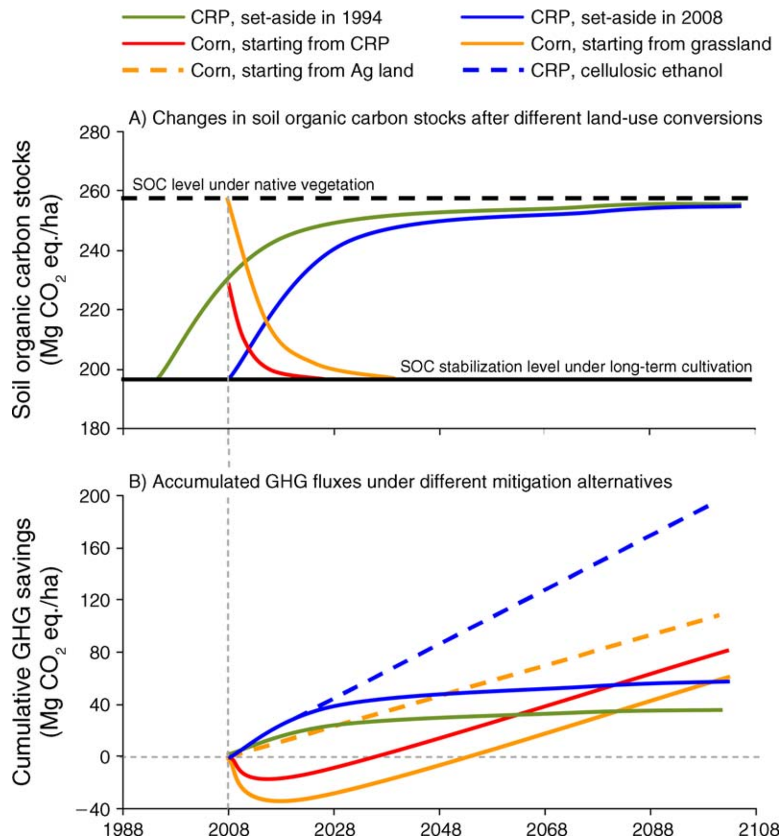

FIG. 1. (A) Changes in soil carbon stocks and (B) net reductions in greenhouse gas (GHG) emissions under different land-use conversions; negative values indicate net emissions. The land-use changes presented here are Conservation Reserve Program (CRP) land withdrawn from cultivation in 1994; new CRP withdrawals from continuous cultivation in 2008; a CRP land withdrawn from cultivation in 1994 and returned to corn production in 2008; and the conversion of native grasslands to corn in 2008. In addition, we evaluated net reductions in GHG emissions from corn ethanol production starting from agricultural ("Ag") land with no loss of soil carbon and a CRP grassland where biomass is used for ethanol production via cellulosic digestion.

process of producing corn ethanol) (Farrell et al. 2006, Hill et al. 2006). On the other hand, corn ethanol production may substantially reduce soil organic carbon (SOC) when planted on native or set-aside lands, releasing CO_2 to the atmosphere (Davidson and Ackerman 1993, Collins et al. 1999, Ogle et al. 2003). For example, cropping native grasslands for the first time or returning set-aside lands into production releases SOC to the atmosphere, while producing corn ethanol on existing agricultural lands typically produces little change in SOC (Ogle et al. 2005). Set-aside projects have been shown almost universally to sequester C in soils (Guo and Gifford 2002).

To sustain biofuel and food production, lands in the Conservation Reserve Program (CRP) or other set-aside programs can potentially return to corn production, with many contracts expiring between 2007 and 2009. The CRP is a set-aside program that has paid U.S. farmers to restore native vegetation on >13 million ha of crop lands, reducing erosion and increasing soil C storage (Ogle et al. 2003). The CRP program establishes 10–15 year contracts with farmers to keep land out of production. In this article, we evaluate the effectiveness and economic value of corn- and cellulosic ethanol production for reducing net GHG emissions when produced on lands that were previously under crop production, previously set aside, or remained as native vegetation, comparing them with C sequestration rates achieved by conservation programs.

METHODS

We estimated changes in soil organic carbon (SOC) from different starting points for corn ethanol production, including existing croplands, CRP lands, and grasslands. We used these data to refine estimates of net GHG produced by corn ethanol, including changes in SOC. We also estimated SOC changes occurring in set-aside lands with and without cellulosic ethanol production and compared them to the rates of GHG savings produced by corn ethanol. Finally we determined the net present value (NPV) for each mitigation strategy, a summary measure of current economic value ($US/ha) in terms of GHG emissions over time; NPV is a standard economic accounting tool (Just et al. 2004).

TABLE 1. Average soil organic carbon sequestration after setting aside agricultural lands.

Reference	Soil organic carbon sequestration after set-aside		
	Average time span (yr)	No. sites compared	Mg CO_2 equivalents·ha^{-1}·yr^{-1}
Jastrow et al. (1998)	1	1	37.01
Karlen (1999)	2	6	4.194
Jastrow et al. (1998)	4	1	3.298
Karlen (1999)	5	43	1.516
Gebhart et al. (1994)	5	5	3.063
Camill et al. (2004)	6	1	NS
Karlen (1999)	6	11	2.373
Amelung et al. (2001)	6	1	2.460
Jastrow et al. (1998)	7	1	4.659
Amelung et al. (2001)	7	2	10.12
Bowman and Anderson (2002)	8	6	0.412
Amelung et al. (2001)	8	2	1.288
Amelung et al. (2001)	9	1	1.144
Baer et al. (2000)	10	1	NS
Amelung et al. (2001)	10	4	1.003
Kucharik (2007)	10	39	1.830
Bronson et al. (2004)	12	4	0.419
Sherrod et al. (2005)	12	3	0.657
Jastrow et al. (1998)	13	1	4.177
Potter (1999)	31	3	0.816
Burke et al. (1995)	50	1	0.120
Ihori et al. (1995)	50	5	1.007
Average	10	142	2.088†

Note: NS indicates no significant change.
† Confidence interval of the mean at $\alpha = 0.05$ is 0.679.

In order to compare GHG mitigation alternatives, the rate of GHG savings generated by each strategy needs to be calculated across years because such rates may change over time. The time at which the crossover of cumulative GHG savings for two alternative land-use trajectories occurs, defined here as the "carbon equivalence time," illustrates the sensitivity of these strategies to the time frame of analysis. The carbon equivalence time is thus the number of years at which two land-use alternatives have a similar net GHG balance.

Changes in SOC that occurred under different land-use trajectories were evaluated using the conceptual framework proposed by the IPCC (Ogle et al. 2003, 2005). We first estimated changes in SOC contents under native vegetation and after long-term cultivation once lands are put into or taken out of production (Fig. 1A); typically, total SOC losses after long-term cultivation range from 30% to 50% of SOC compared with native vegetation (Davidson and Ackerman 1993, Ogle et al. 2005). We then analyzed SOC changes that occurred after setting aside land from crop production, including programs such as the CRP. We identified 142 comparisons in the literature that evaluated SOC accretion with an average time span of 10 years, ranging from 1 to 50 years (Table 1). The average SOC accretion in this comprehensive data set was 570 kg C·ha^{-1}·yr^{-1} (2.088 Mg CO_2 equivalents·ha^{-1}·yr^{-1}). The scatter plot of SOC accrual and time elapsed since set aside showed that SOC accumulation rates were relatively high and variable during the first 15 years and then decreased to lower but more stable accumulation rates. Our calculations for net GHG changes through time assumed that CRP lands accumulate SOC at the average rate during the first 15 years after removal from cultivation and then accumulate SOC at half this rate for the next 15-year period (Kucharik 2007) (see Fig. 1A). After that time, SOC content in CRP lands increases slowly for the next 80 years eventually reaching a value similar to native vegetation. For the opposite transformation, native or CRP lands placed in cultivation, these lands were assumed to lose SOC exponentially (Davidson and Ackerman 1993), with most of the losses occurring in the first years after cultivation, until reaching a value similar to that in long-term agriculture. Corn used for ethanol production was assumed to be grown on plowed lands, the most common practice for corn production in the United States (Ogle et al. 2003).

Estimated carbon savings generated by corn ethanol production were taken from studies compiling a complete life-cycle assessment and were added to our own estimates of SOC changes accompanying the onset of corn production for different land-use histories (see Fig. 1A). Complete life-cycle studies include the CO_2 released during ethanol production (transportation, agrochemicals, CH_4 and N_2O emissions, facility energy use, co-products, and so on) and the fossil fuel displaced by ethanol use (Farrell et al. 2006, Hill et al. 2006). We converted the net GHG savings per MJ reported by these authors to a per hectare basis, considering an average U.S. corn yield of 9313 kg/ha, a conversion efficiency of corn grain to ethanol of 39%, and an energy content of 21.26 MJ/L of ethanol (Farrell et al. 2006)

TABLE 2. Net reductions in greenhouse gas (GHG) emissions produced by corn ethanol in the United States without including changes in soil organic carbon.

Reference	Mg CO_2 equivalents·ha^{-1}·yr^{-1}
Patzek (2004)†	−0.548
Pimentel and Patzek (2005)†	−0.008
De Oliveira et al. (2005)†	1.151
Shapouri and McAloon (2004)†	1.305
Graboski (2002)†	−0.780
Wang (2001)†	1.768
Farrell et al. (2006)	0.764
Hill et al. (2006)	0.934
Average	0.573‡
Average of positive studies only	1.184§

† As reanalyzed by Farrel et al. (2006) with updated coefficients. Negative values indicate net GHG emissions.
‡ Confidence interval of the mean at $\alpha = 0.05$ is 0.68.
§ Confidence interval of the mean at $\alpha = 0.05$ is 0.28.

(Table 2). Based on only those studies that report positive GHG savings (Table 2), an estimate that may actually overestimate the benefits of corn ethanol, we determined that corn ethanol reduces net GHG emissions on average by 1.184 Mg CO_2 equivalents·ha^{-1}·yr^{-1}. Furthermore, our estimate of GHG savings from corn ethanol produced from CRP grasslands is also conservative because we considered average corn yields for the United States, even though many CRP grasslands are in marginal habitats likely to sustain below-average yields.

We estimated net GHG reductions generated by producing cellulosic ethanol from biomass harvests in a CRP grassland. We considered the scenario of land set aside in 2008, with cellulosic ethanol production beginning after year 2023, since this technology is not universally available commercially. We used estimates from Tilman et al. (2006) for net GHG reductions and our own SOC estimates for the land-use trajectories described in Fig. 1A. Currently more than eight refineries produce cellulosic ethanol in the United States (data *available online*).[8]

We calculated the net present value (NPV) for each GHG mitigation alternative by discounting the future stream of marginal benefits from C flows. To calculate the benefits of each mitigation alternative, we multiplied the marginal change in C fluxes from Fig. 1B by a stochastic CO_2 equivalent price which is allowed to vary from year to year. Using historical data from the European Climate Exchange (October 2007), the computed mean and standard deviation values were US$29.7 and US$4.96 per Mg CO_2 equivalents. These values served as parameters for a normal distribution used to randomly generate CO_2 prices in each year. We simulated the NPV of the marginal benefits of C accumulation for each alternative land-use using a 3% discount rate for 93 years (beginning in 2008 up to 2100). The results reported in the Table 3 represent the mean values from 500 stochastic simulation iterations.

[8] ⟨http://www.ethanolrfa.org/resource/cellulosic/⟩

Finally, we estimated the average expenditure by the U.S. government per Mg of GHG savings by dividing the average rental rates paid under CRP (US$115·$ha^{-1}$·$yr^{-1}$) or tax incentives paid for ethanol production (US$0.51/gallon [US$1.93/L]) by the GHG savings achieved with each land use. With these calculations we do not intend to estimate the costs of sequestrating C but instead to estimate the public money spent on GHG reductions; we acknowledge that financial incentives for both activities have additional objectives besides C sequestration. The CRP, for instance, also reduces erosion and can help improve water quality (Huang et al. 2002), and both types of payments support farmers and rural economies (Mabee 2007).

RESULTS AND DISCUSSION

Our analysis suggests that maintaining land in set-aside programs and allocating more agricultural lands to them would have a greater net GHG savings than having the same plots under corn ethanol production for at least four decades (Fig. 1B). For instance, maintaining a 15-year-old CRP plot vs. converting it to corn ethanol production has a carbon equivalence time of 48 ± 14 (mean ± SE) years in our calculations (Fig. 1B, green vs. red lines). For time frames shorter than this, maintaining the CRP plot yields a more positive net GHG balance than converting it to corn ethanol production; for time frames longer than 48 years, corn ethanol production has a more positive balance. The same analysis for a native grassland that can be maintained as is or converted to corn ethanol has a carbon equivalence time of 49 (±11) years, assuming that grasslands are in steady state in terms of SOC stocks (Fig. 1B, orange line and the intersection with the 0 value). Interestingly, CRP and native grasslands have similar carbon equivalence times when converted to corn ethanol production because even though native grassland plots lose more SOC, converted CRP plots both lose additional C and stop accumulating SOC. Perhaps most surprisingly, converting land under long-term cultivation to CRP has a more positive GHG balance than corn ethanol production, with a carbon equivalence time of 42 (±20) years (Fig. 1B, solid-blue vs. dashed orange lines). This result arises because cropland soil has substantial potential to sequester SOC when grasslands are restored.

TABLE 3. Net present value (NPV) of GHG fluxes under different land-use conversions.

Land-use trajectories	Net present value (US$/ha)
CRP, set aside in 1994	523
CRP, set aside in 2008	1127
Corn ethanol, starting from CRP	333
Corn ethanol, starting from grassland	−6.6
Corn ethanol, starting from agriculture land	1135
CRP, cellulosic ethanol	1307

Note: CRP stands for the Conservation Reserve Program.

Our analysis provides a dynamic comparison of GHG savings under alternative land-use strategies, improving previous approaches in several ways. In addition to including initial carbon losses following land-use conversions (see "carbon debt," Fargione et al. 2008), our analysis quantifies the contribution of prospective GHG savings under alternative scenarios. For the case of set-aside vs. corn ethanol, the carbon equivalence time increases from 29 to 48 years when SOC sequestration achieved in the set-aside land is included (Fig. 1B, compare the intersection of the red line and the 0 value with the intersection of the red and green lines). Our estimates of SOC accretion rates in set-aside lands, based on a comprehensive SOC accretion data set, are also more precise than previous estimates and allowed us to estimate confidence intervals for changes in SOC (Table 1). In addition to the C analysis we also present the net economic value and average expenditures paid by the U.S. government for different GHG mitigation strategies.

Cellulosic ethanol production from biomass, likely to become commercially available within a few decades (Himmel et al. 2007), could have the most beneficial GHG balance of all the options that we examined (Fig. 1B, dashed blue line). Cellulosic ethanol production from grasslands has higher rates of GHG savings compared to corn ethanol (Tilman et al. 2006). In addition, using grasslands to produce cellulosic ethanol does not reduce SOC stocks, but instead may increase C storage in soils if grasslands are replanted on abandoned agricultural lands (Ogle et al. 2003, Tilman et al. 2006). Thus, setting aside lands for cellulosic ethanol production represented the most favorable scenario, having benefits similar to, or higher than, the other alternatives through time (Fig. 1B, dashed blue vs. all other lines).

Corn ethanol production typically has a lower net present value (NPV), or discounted stream of future GHG savings (in dollar terms), than set-aside programs such as the CRP (Table 3) and a higher cost to the U.S. government. When NPV is compared across different alternatives, keeping land as CRP has a 57% higher NPV than converting the same land to corn ethanol (Table 3). Converting former agricultural land to CRP has a similar NPV to producing corn ethanol there, while the greatest value is obtained by producing cellulosic ethanol on CRP grasslands. Considering current ethanol incentives and typical CRP contracts, extending current CRP contracts or enrolling new CRP lands appear to be cheaper strategies for sequestering GHG than converting such lands to corn ethanol for at least a century. In a former agricultural field that is sown for corn ethanol (and ignoring changes in SOC), the average expenditure by the U.S. government is $399 per ton of CO_2 equivalents saved due to fossil fuel displacement; converting this land to CRP will cost an average of $108 per CO_2 equivalent Mg sequestered for the next 100 years. Thus, biofuel payments may increase land conversions that release net GHG. Instead, payments for set-aside programs or other land-uses that have immediate favorable GHG balances, even including the C costs of land conversion, may be a better strategy for reducing GHG (Fargione et al. 2008).

Our study shows that appropriate C accounting from biofuel production requires a complete ecosystem analysis. Net GHG emissions are strongly influenced by altered soil C stocks accompanying land-use change, particularly whether and how recently the lands were in agricultural production. Additional factors may modify estimates of the net GHG balance of biofuel production. First, complete life-cycle studies are prone to large assumptions and errors, and thus may alter carbon equivalence times. It is notable, for example, that the average of the studies presented in Table 2 exhibit a net GHG balance not significantly different from zero. Second, future technology improvements in biofuel production, corn or cellulosic, may increase rates of net GHG savings generated by fossil fuel displacement, reducing the carbon equivalence time. Third, our estimates of SOC changes may vary among different soil types. However, corn yields will probably covary with SOC changes across soil types, resulting in similar carbon equivalence times. Fourth, if forests are cleared for corn ethanol production instead of grasslands, C releases from tree biomass will substantially increase the carbon equivalence time (Fargione et al. 2008, Searchinger et al. 2008). Finally, the growth in U.S. corn ethanol production may promote land-use conversions in other regions of the world, releasing even larger amounts of SOC to the atmosphere (Searchinger et al. 2008).

Estimating the amount, the value and the public costs of reducing GHG emissions through time is critical for evaluating alternatives for the U.S. farm and energy bills and for pending climate legislation. We believe that our findings of more favorable alternatives to corn ethanol are robust because we used relatively high estimates for the GHG savings attributable to corn ethanol and because we developed a comprehensive data set of 142 studies of SOC accretion with the CRP. Our results support studies regarding the importance of considering whole ecosystem C changes when estimating biofuels benefits and show the importance of considering the potential as well as present ecosystem C balance of different land-use alternatives. Our results also highlight the potential contribution to GHG reduction of the CRP, a program with many additional benefits, including erosion control and biodiversity conservation (Jackson et al. 2001, Tilman et al. 2006, Lal 2007), and the potential of cellulosic ethanol production as a potentially efficient tool for reducing GHG emissions. Currently, converting set-asides to corn ethanol production is an inefficient and expensive GHG mitigation policy that should not be encouraged until ethanol production technologies improve.

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