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Land management change greatly impacts biofuels' greenhouse gas emissions

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Abstract

Harvesting corn stover for biofuel production may decrease soil organic carbon (SOC) and increase greenhouse gas (GHG) emissions. Adding additional organic matter into soil or reducing tillage intensity, however, could potentially offset this SOC loss. Here, using SOC and life cycle analysis (LCA) models, we evaluated the impacts of land management change (LMC), that is, stover removal, organic matter addition, and tillage on spatially explicit SOC level and biofuels' overall life cycle GHG emissions in US corn–soybean production systems. Results indicate that under conventional tillage (CT), 30% stover removal (dry weight) may reduce baseline SOC by 0.04 t C ha^{-1} yr^{-1} over a 30-year simulation period. Growing a cover crop during the fallow season or applying manure, on the other hand, could add to SOC and further reduce biofuels' life cycle GHG emissions. With 30% stover removal in a CT system, cover crop and manure application can increase SOC at the national level by about 0.06 and 0.02 t C ha^{-1} yr^{-1}, respectively, compared to baseline cases without such measures. With contributions from this SOC increase, the life cycle GHG emissions for stover ethanol are more than 80% lower than those of gasoline, exceeding the US Renewable Fuel Standard mandate of 60% emissions reduction in cellulosic biofuels. Reducing tillage intensity while removing stover could also limit SOC loss or lead to SOC gain, which would lower stover ethanol life cycle GHG emissions to near or under the mandated 60% reduction. Without these organic matter inputs or reduced tillage intensity, however, the emissions will not meet this mandate. More efforts are still required to further identify key practical LMCs, improve SOC modeling, and accounting for LMCs in biofuel LCAs that incorporate stover removal.

Keywords: cover crop, ethanol, life cycle analysis, manure, soil carbon, tillage

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Introduction

Corn (*Zea mays* L.) stover is currently a targeted feedstock for cellulosic ethanol plants and is projected to be one of the most prevalent biomass types available for conversion into biofuels [USDOE (US Department of Energy), 2016]. Generally viewed as an agricultural residue, corn stover nonetheless fulfills a critical role on the corn field. Its degradation in the field returns carbon and nutrients to the soil. A significant body of research has addressed the development of sustainable stover removal rates that maintain soil health (including SOC levels) and avoid undesirable consequences such as erosion (Mann *et al.*, 2002; Muth *et al.*, 2013; Johnson *et al.*, 2014). Recently, some have raised the concern that if stover is removed, SOC levels would sink (Liska *et al.*, 2014). With this concern, life cycle analyses (LCA) of stover-derived biofuels must take into account this potential loss of SOC as compared to a baseline scenario in which no stover is removed (Liska *et al.*, 2014).

Unlike the concept of land-use change (LUC), that is the shift in land-use and land-cover that could accompany large-scale feedstock production to produce biofuels, which has been incorporated into biofuel LCA for some time (Qin *et al.*, 2016), land management changes (LMC) (e.g., changes in the stover removal rate, changes in tillage, or the adoption of practices such as manure application and planting of cover crops) have not been widely included in biofuel LCA (Sheehan *et al.*, 2003; Adler *et al.*, 2015; Qin *et al.*, 2017). Importantly, manure

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application and cover crop planting could limit or eliminate SOC losses upon stover removal, if farmers adopted these practices once they opted to remove stover (Fronning *et al.*, 2008; Poeplau & Don, 2015). It is important within the framework of biofuel LCA, which considers all stages of the biofuel life cycle from fertilizer production to biofuel combustion, however, to account for additional energy consumption and emissions (e.g., N_2O emissions from manure and emissions from agricultural activities to plant cover crops) that occur when LMC practices are adopted.

In this study, we explore the influence of LMCs including manure application, cover crop adoption (i.e., winter rye), and tillage on life cycle GHG emissions of corn stover and corn grain ethanol, considering how these LMCs could affect SOC change from stover removal. It is important to note that we attribute SOC changes stemming from these three LMCs, manure application, cover crop adoption and tillage, to the stover in our baseline case because we assume that farmers adopt the LMCs to counteract SOC loss from stover removal. Through this analysis, we probe the question of whether corn stover-derived biofuels suffer such a GHG burden stemming from SOC losses compared to a baseline case that they offer a limited GHG reduction compared to conventional gasoline.

Materials and methods

Overview

Corn stover and corn grain ethanol's life cycle GHG emissions were estimated with a LCA model, the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET®) Model (Argonne National Laboratory, 2015). LMC affects the feedstock production stage of a biofuel's life cycle, causing GHG emissions from energy and chemical inputs and fertilizer decomposition. Furthermore, GHG emissions or sequestration can result from SOC changes and, in the case of cover crop adoption and manure application, decomposition of organic matter. For this analysis, SOC changes were modeled with a parameterized CENTURY model (Qin *et al.*, 2016) simulating US county-level SOC dynamics. SOC modeling output was incorporated into GREET, along with chemical and energy inputs from LMC adoption to model ethanol life cycle GHG emissions.

In general, the modeling effort estimated the life cycle GHG emissions from biofuels produced from corn stover collected from fields on which LMCs (i.e., stover removal, organic matter inputs of either cover crop or manure, and tillage) may be adopted (Table S1). The net SOC change caused by the LMC was assessed as the difference in SOC between the selected LMC scenario (with stover removal, with or without organic matter inputs) and baseline, in a sense business-as-usual, scenario without stover removal or any organic matter inputs (Fig. 1). The relative SOC sequestration rate (SOC_r) is used in the analysis to depict this difference; a positive value indicates net soil carbon gain while a negative value indicates net loss relative to the baseline scenario. The allocation of several process-based GHG emissions associated with corn farming between corn grain and corn stover was based on either marginal (all to stover), energy or mass allocation (between grain and stover). Marginal allocation was used as primary approach because corn stover removal incurs discrete additional fuel and fertilizer use. Energy and mass allocation-based results were included as sensitivity cases in the discussion section. Qin *et al.* (2015) provide a full description of data sources and methods.

LMC scenarios and assumptions

Stover removal, organic matter input, and tillage were examined for their impacts on SOC and associated biofuels' GHG emissions in US corn–soy rotation systems (Table S1). The anticipated baseline is a scenario without corn stover removal or any additional organic matter input. The stover removal rate

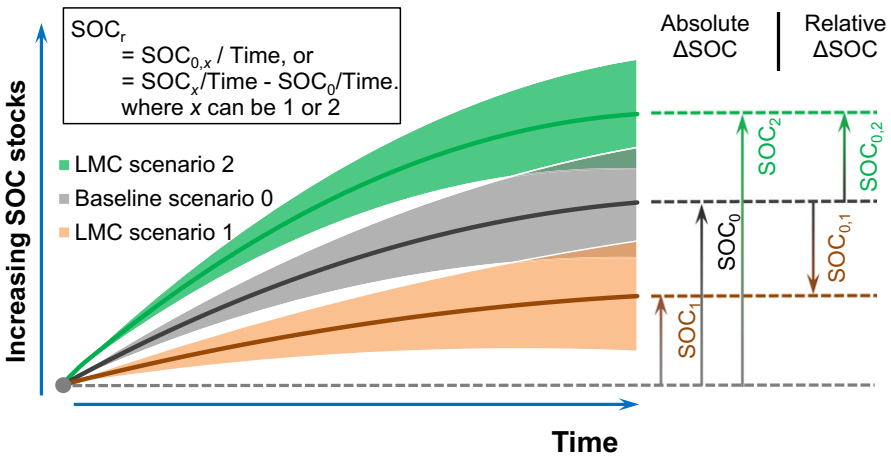

Fig. 1 Illustration of the relative SOC sequestration rate calculation based on scenario-specific SOC dynamics.

in other scenarios was set at 30%, 60%, and or 100% on a mass basis for each rotation, corresponding to low, high, and/or extremely high (unrealistic) removal rates. Three separate organic matter input scenarios were established for simulations with corn stover removal: no additional input, cover crop addition, and manure application. Three tillage types, conventional tillage (CT), reduced tillage (RT), and no tillage (NT), were included in the analysis. Winter rye (*Secale cereal* L.) is planted as a cover crop after corn season (once every two years). It is killed before reaching its maximum yield potential to minimize nitrogen tie-up and conserve soil moisture (Feyereisen *et al*., 2013). Its biomass is returned to the soil (Qin *et al*., 2015). Animal manure can be used as an organic fertilizer to improve soil quality by adding organic carbon and nutrients. Manure from different livestock types (based on the USDA Agricultural Resource Management Survey) is applied during the corn season every four years. Energy use and materials consumption associated with cover crop planting and manure application were also included in the life cycle GHG emissions estimates.

The GHG emissions credits (e.g., SOC increase, fertilizer displacement) or emissions (e.g., SOC decrease, energy use) associated with LMC are allocated in two different methods between the grain and stover. One method, marginal allocation, attributes all impacts to corn stover so stover ethanol bears all the burdens and benefits resulted from LMC. The other method, allocation by energy or mass, divides the burdens and benefits of LMC between corn grain and stover on an energy or mass basis.

SOC modeling and SOC change

The parameterized CENTURY model has been well documented regarding model modification and parameterization (Kwon & Hudson, 2010; Kwon *et al*., 2013), its capability of inverse modeling (Kwon & Hudson, 2010; Kwon *et al*., 2017), and its use in SOC change estimation (Kwon *et al*., 2013; Qin *et al*., 2016). It was used in this study to simulate US domestic county-level SOC dynamics (0–100 cm) for four LMC scenarios (i.e., the baseline, stover removal with no additional input, and either cover crop or manure as organic matter input). Under each LMC scenario, different stover removal rates and tillage types were modeled separately. The SOC dynamics for each county were simulated for over 160 years with an assumed land-use history. This history began with native grassland prior to 1881. Between 1881 and 2010, corn, soybean (*Glycine max* L.), and wheat (*Triticum aestivum* L.) grew on the land. The years 2011 through 2040 were the LMC period for corn stover and grain production within corn–soybean rotation systems. The historical crop yields are based on a USDA census (Fig. S1a, b) (Qin *et al*., 2015). Future corn and soybean yields were projected with historical yield data (Kwon *et al*., 2013), and rye yields are based on the modeled biomass production with a 1% annual increase rate (Feyereisen *et al*., 2013; Qin *et al*., 2015). Due to data limitations, the manure application rate was aggregated to an agro-ecological zone level based on the USDA Agricultural Resource Management Survey (ARMS) database (Qin *et al*., 2015). County-level soil type and climate data were employed (Qin *et al*., 2015). Irrigation was not specifically simulated, but its impacts on SOC change and overall GHG emissions need to be further explored for regions receiving intensive irrigation (Verma *et al*., 2005; Schmer *et al*., 2014).

The SOC sequestration rate was calculated as the annual SOC change over the LMC period (2011–2040), which is determined by the difference between the final and initial SOC content divided by the LMC time period. The relative SOC sequestration rate (SOC*r*), however, was calculated as the difference of SOC sequestration rate between the LMC scenario and baseline scenario (Fig. 1). Alternatively, SOC*r* can be calculated as the relative SOC change annualized by LMC time period (Fig. 1), which is used to estimate the contribution of SOC change to life cycle GHG emissions. In this study, the baseline scenario has no corn stover removal or organic matter inputs and it is under CT. LMC scenarios include corn stover removal, tillage, and potential application of cover crop and manure. The SOC effects of LMC depend on spatially explicit factors and so SOC levels in these scenarios can fall below or exceed those in the baseline scenario (Fig. 1).

LCA and GHG emissions

The system boundary for this analysis considers an integrated production facility for corn grain and corn stover ethanol (Fig. S2) (Canter *et al*., 2015; Qin *et al*., 2015). It includes the biofuel production stages of feedstock production (including land management), feedstock logistics/storage/transportation, feedstock-to-fuel conversion, fuel transportation/distribution, and fuel combustion (Qin *et al*., 2015, 2016). Note that manure collection and storage, which occur off the farm producing corn, were excluded. It was presumed that the manure would be generated and handled in a manner consistent with existing practice regardless of the use of manure (Qin *et al*., 2015). Manure is used as crop fertilizer, with very limited use for energy (e.g., biogas) [USDA (US Department of Agriculture), 2009]. According to global scale analysis, only about 20% of manure produced (in terms of nitrogen) has been used, mainly as crop fertilizer, worldwide, and similarly in the United States (Potter *et al*., 2010; Zhang *et al*., 2017). Over 88% of planted corn areas in the United States has no manure application [USDA (US Department of Agriculture), 2009]. Using manure as an organic matter input after stover removal is not likely to compete with current manure use as it is currently underutilized (Potter *et al*., 2010; Zhang *et al*., 2017). The life cycle GHG emissions account for all material and energy flows in these processes, including the above-mentioned potential SOC changes. Land-use change GHG emissions associated with corn and stover ethanol production were included based on earlier studies (Dunn *et al*., 2013; Qin *et al*., 2016). GREET was expanded to include fuel consumption for cover crop planting with a grain drill or by broadcasting, and its termination with herbicide. No additional fertilizer was used in cover crop scenarios, and we assumed soil nutrient levels were unchanged. We accounted for N_2O emissions from cover crop and stover decomposition using the IPCC (Intergovernmental Panel on Climate Change) Tier 1 method (Qin *et al*., 2015). Additionally, fuel consumed during transportation and application of manure was included in the analysis. Energy use and GHG emissions were estimated for

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these two steps based on manure type, application amount, energy intensity of transportation and application, and nutrient content (Qin *et al*., 2015). IPCC methods were used to estimate N_2O emissions from manure [IPCC (Intergovernmental Panel on Climate Change), 2006]. Manure can provide additional nutrients (i.e., nitrogen and phosphorus) to crops, which partially or even fully displace the nutrients provided by fertilizers, depending on total nutrients required and those provided by manure (Qin *et al*., 2015). For this analysis, the CO_2 released during ethanol combustion was treated as offset by CO_2 uptake during corn growth. As a result, the net GHG emissions from ethanol combustion are small (approximately 0.4 g CO_2e MJ^{-1} ethanol) and are not included in the results. Please refer to Qin *et al*. (2015) for additional information on LCA methodology.

Results

Soil carbon responding to cover crop and manure application

Our SOC modeling indicates that, with corn stover removal (30%, by dry weight) and CT, SOC_r becomes negative in most US regions, meaning an SOC decrease relative to a scenario in which no stover is removed (Fig. 2a). However, with cover crop application, SOC increases, even with 30% stover removal, and shows an overall positive SOC sequestration rate (SOC_r) (Fig. 2b), meaning that cover crop growth could not only prevent a reduction in SOC from stover removal but also elevate SOC levels beyond what may be expected if no stover was removed and cover crops were not planted. This is especially true for the southern United States where cover crop yields are relatively high (Fig. S1c), while less significant in the northern areas of North Dakota, Minnesota, and Wisconsin where winter rye is low-yielding (Feyereisen *et al*., 2013). With manure application every four years, the SOC_r is around zero in most regions, suggesting that the SOC levels could be on par with levels that would occur if no stover was removed (Fig. 2c). A higher manure application rate can maintain or even increase the SOC level. For instance, SOC_r is the highest in west Oklahoma and north Texas where more manure is applied than the national average (Fig. S1d).

On a national average basis (in CT system), compared to a scenario in which all corn stover stays on fields, SOC can decrease 0.04 t C ha^{-1} yr^{-1} if 30% of the stover is removed over a 30-year simulation period (Fig. 3). However, cover crop and manure application can increase the baseline SOC by about 0.06 and 0.02 t C ha^{-1} each year, respectively, on a national average basis. If the stover removal rate exceeds 30%, SOC can decrease further, even when manure is applied or cover crops are planted. For example, if 60% of stover is removed, manure application can only partially restore the SOC decrease (-0.08 t C ha^{-1} yr^{-1}), resulting in a national average net annual SOC loss of 0.03 t C ha^{-1} (Fig. 3). In extreme, generally unrealistic (Lal, 2005; Bentsen *et al*., 2014; Sheehan *et al*., 2014) cases in which 100% of stover is removed and no additional organic matter inputs are added (Fig. 3), on national average basis, SOC levels can decrease 2–6 t ha^{-1} over the feedstock production period (i.e., 30 years). Farmers will likely avoid such practices that grossly deplete SOC and, given the ongoing work to identify sustainable removal rates, high stover removal rates are unlikely (Lal, 2005; Sheehan *et al*., 2014).

LMC impacts on life cycle GHG emissions

For corn stover ethanol, with 100% stover removal and no additional organic matter inputs, the exhibited net GHG emissions are 105 g CO_2e MJ^{-1} (in CT system) (Fig. 4). This figure includes LUC GHG emissions associated with stover ethanol which we have estimated at -0.7 g CO_2e MJ^{-1} (Qin *et al*., 2016). Reducing the stover removal to 60 and 30% alone reduces these GHG emissions to 55 g CO_2e MJ^{-1} for both cases. On a national average basis, adopting a cover crop or applying manure cuts those emissions to 36 and 34 g CO_2e MJ^{-1}, respectively, for the scenarios with 60% stover removal. At 30% stover removal, these emissions are reduced even further to 18 and 14 g CO_2e MJ^{-1} for scenarios with cover crop planting and manure application, respectively. For comparison, neat gasoline without blended ethanol has life cycle GHG emissions of approximately 93 g CO_2e MJ^{-1} (Argonne National Laboratory, 2015). Without additional organic matter inputs, corn stover ethanol life cycle GHG emissions, regardless of stover removal rate, do not meet the 60% GHG emissions reduction (relative to gasoline) required by the mandate for cellulosic ethanol [EPA (US Environmental Protection Agency), 2010]. With land management practices of cover crop planting or manure application, however, corn stover ethanol (with 30% stover removal) life cycle GHG emissions are over 80% lower than gasoline.

For 30% and 60% stover removal levels on fields in CT system without organic matter inputs, the SOC loss constitutes half of stover ethanol life cycle GHG emissions (Fig. 4). More carbon is removed from the soil on a per area basis for the 60% stover removal scenario, but per unit of energy produced, the SOC loss-induced GHG emissions contribution are essentially the same (<0.1%) as the 30% scenario because more stover is available for ethanol production. Once cover crops are adopted or manure is applied, however, corn stover ethanol's GHG emissions vary with stover removal rate primarily due to differences from SOC change and emissions resulted from use of organic matter and/or fertilizer (Fig. 4). For instance, cover crops increase SOC

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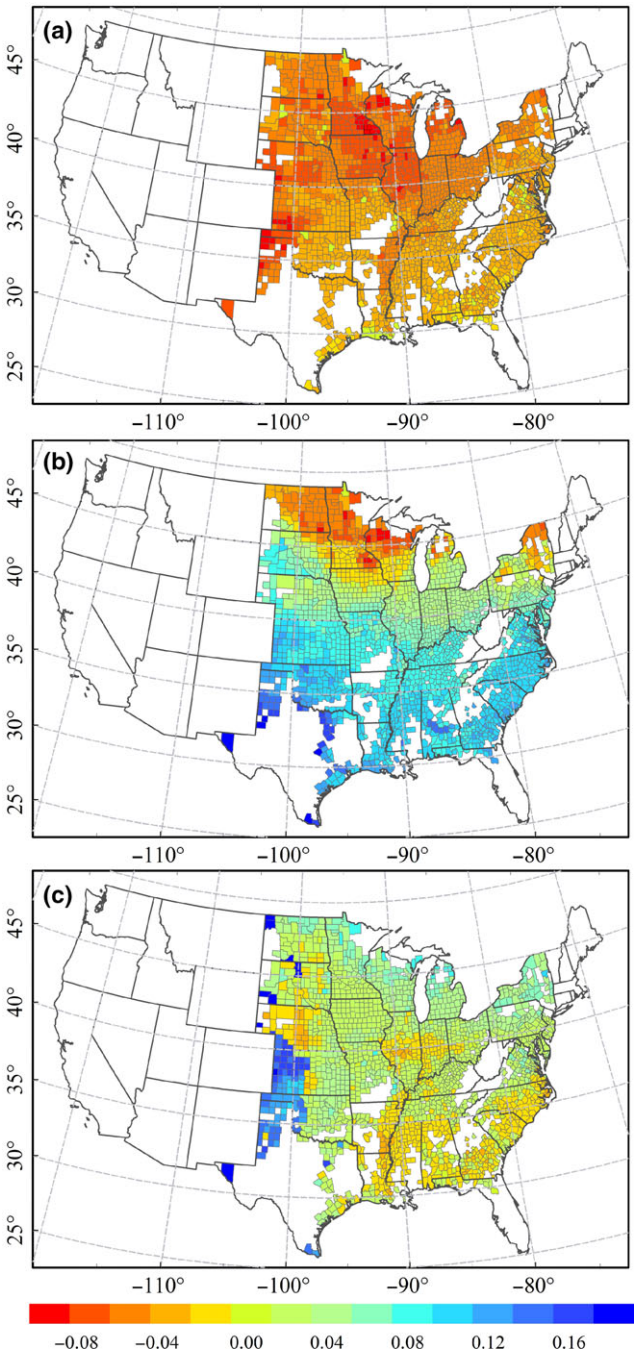

Fig. 2 Relative SOC sequestration rate responding to land management change. The rates (t C ha^{-1} yr^{-1}) are for 30% stover removal in CT system with (a) no additional organic matter input (b) cover crop and (c) manure application.

which significantly lowers SOC loss-induced GHG emissions. In the scenarios with manure application, fertilizer-associated emissions are reduced significantly as compared to the corresponding scenarios without additional organic matter inputs. The underlying reason for this result is that manure application, which deposits nitrogen and phosphorous, displaces both supplemental fertilizer applied to compensate for stover removal and a portion of the conventional fertilizer application for corn farming, requiring that less or even no conventional fertilizer be applied to the corn field.

Tillage as an important land management practice

Conservation tillage is generally recognized as a sustainable land management practice that helps

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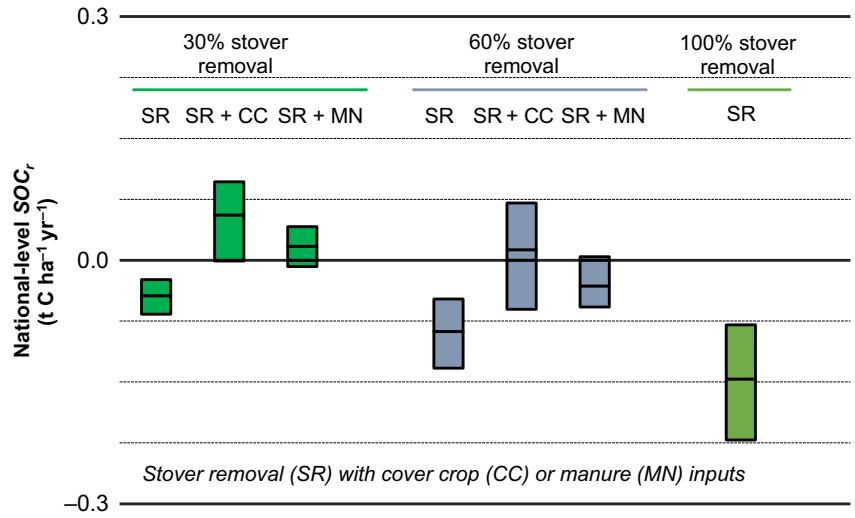

Fig. 3 National-level SOC sequestration rate responding to stover removal and organic matter inputs. The values indicate the relative SOC sequestration rate (SOC*r*) under conventional tillage, with the solid line showing the national average rate and the box lower and upper bounds showing the 10th and 90th percentiles, respectively, based on spatial SOC change results. A positive value indicates net carbon gain while a negative value indicates carbon loss.

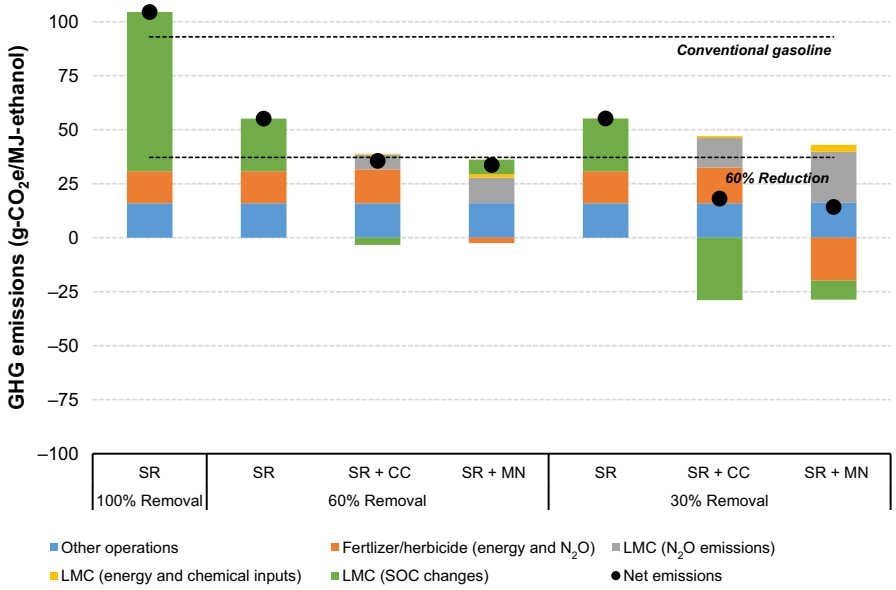

Fig. 4 Stover ethanol life cycle GHG emissions for different stover removal rates. The estimates reflect CT and marginal allocation. Results marked 'SR' are for scenarios with stover removal and no organic matter inputs, while 'SR+CC' and 'SR+MN' designations represent scenarios for stover removal with either cover crops or manure, respectively. The SOC changes are relative to corresponding baseline scenario without stover removal and without additional organic matter inputs. The other operations category includes land-use change, feedstock farming/collection, feedstock and ethanol transportation, and an energy credit taken during ethanol production for displaced electricity. Key parameters (grain yield, cover crop yield, manure application rate, manure application type) are for national average values. In the United States, cellulosic biofuel must meet a 60% life cycle GHG emissions reduction (lower dashed line) relative to conventional gasoline (upper dashed line).

maintain SOC levels and allows moderate stover removal (Halpern *et al.*, 2010; Sheehan *et al.*, 2014). Besides cover crop adoption and manure application land management changes, we explored how tillage practice influences life cycle GHG emissions associated with stover ethanol produced with a 30% stover

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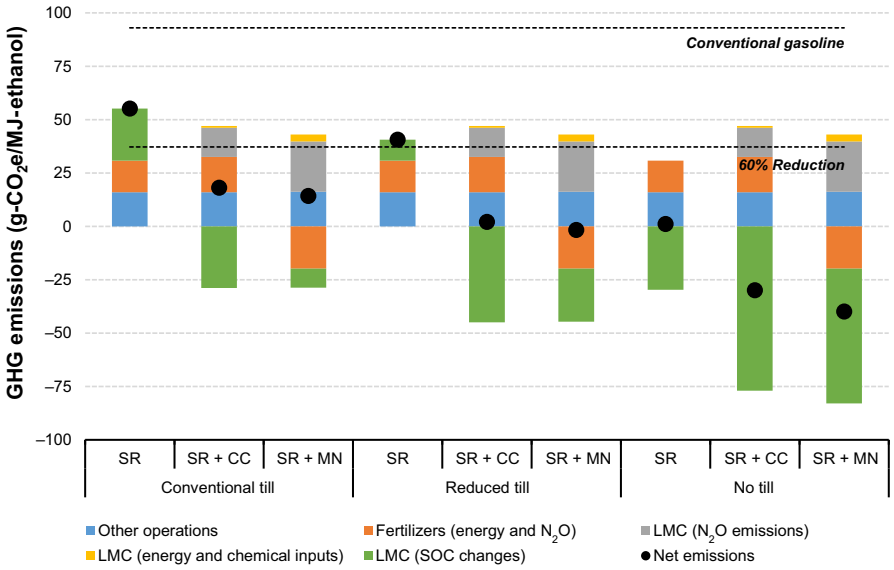

Fig. 5 Stover ethanol life cycle GHG emissions for different tillage systems. The estimates reflect 30% stover removal and marginal allocation. Acronyms and legend are same as in Fig. 4.

removal level under a marginal allocation approach (Fig. 5).

Our analysis suggests that with adoption of RT or NT practices in place of CT, the GHG emissions for stover ethanol can be mildly or significantly reduced depending on stover removal rate, tillage type, and organic matter input management (Fig. 5). In the absence of organic matter inputs, corn stover ethanol life cycle GHG emissions can be reduced by 26% under RT systems (40.6 g CO_2e MJ^{-1}) and 98% under NT systems (1.1 g CO_2e MJ^{-1}), compared with CT systems (55.2 g CO_2e MJ^{-1}) (Fig. 5). If cover crop or manure is applied, the RT and NT systems emit even less GHG emissions or become GHG sinks. When cover crops are planted and 30% of stover is removed, reducing or eliminating tillage reduces the life cycle GHG emissions by 16 and 38 g CO_2e MJ^{-1}, respectively, compared with CT system. When manure is applied, life cycle GHG emissions can be reduced by 16 and 54 g CO_2e MJ^{-1} in RT and NT systems, respectively. In these cases with both additional organic matter input and tillage intensity reduction, stover ethanol could become GHG emissions neutral or even negative (Fig. 5).

Even though CT has been one of the most dominant single tillage types, adoption of conservation tillage has increased during the past two decades [USDA (US Department of Agriculture), 2012]; and it may become even convenient to apply conservation tillage together with stover removal without stover management issues associated with CT (e.g., plant diseases) (Mann *et al.*, 2002). In the study, we treated CT as the most conservative assumption for baseline tillage and simulated CT, RT, and NT separately in the stover removal scenarios, considering that tillage intensity can be reduced if stover is partially removed. While in practice tillage may change spatially and even temporally depending on factors such as location, crop system, and farmers' preferences, the SOC change associated with tillage change could be lessened if RT or NT were the baseline. For instance, with 30% stover removal in a cover crop application scenario, changing from CT (baseline) to NT system could result in a SOC gain of 0.06 t C ha^{-1} yr^{-1} which would mitigate GHG emissions of about 77 g CO_2e MJ^{-1} (Fig. 5). However, if RT or NT were the baseline tillage, the GHG emissions would still be mitigated but about 20% or 75% smaller (data not shown). Future LCA may consider multiple tillage types in the baseline or vary tillage change to reflect large-scale framing practices change due to stover removal.

Discussion

Coproduct handling techniques

In the above analysis, life cycle GHG emissions of stover ethanol are calculated based on a marginal allocation approach that assigns all burdens (e.g., energy to apply manure or plant cover crops) and benefits (e.g., SOC gains in some locations) to stover ethanol. Another approach allocates burdens and benefits to the two feedstocks on a mass (i.e., mass allocation) or energy basis (i.e., energy allocation). Here, we explore life cycle GHG emissions of stover and grain ethanol using energy allocation because both the grain and stover are destined to

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become ethanol, an energy product. Furthermore, we also consider a 'combined' gallon of both stover and grain ethanol because ethanol leaving the integrated facility may not be separated by feedstock type. The type of renewable identification numbers (RIN) that the US Environmental Protection Agency assigns a biofuel, however, carry an economic value and differ by feedstock type, so each type of ethanol (grain and stover) needs to have separately calculated life cycle GHG emissions to determine their eligibility to receive either 'renewable biofuel' (for corn grain ethanol) or 'cellulosic biofuel' (for corn stover ethanol) RINs. When a marginal allocation approach is adopted, all energy and chemicals associated with the LMC scenarios (diesel fuel input, cover crop herbicide, and manure nutrient application), as well as the SOC changes, are assigned to the corn stover (Table S2). Also, the energy consumed during stover collection and supplemental fertilizer applied when stover is removed is assigned to the stover ethanol, with grain ethanol assigned the burden of corn planting, fertilizer application, and harvesting. When an energy allocation approach is adopted, the burden of all inputs for corn planting, fertilization (initial and supplemental due to stover removal), harvesting, stover collection, LMC inputs, and SOC changes is split between the grain and stover ethanol based on the energy content of the biomass. When 30% of stover is removed, 78% of the total energy from the field comes from corn grain. This value drops to 64% for the 60% stover removal scenario. At the integrated ethanol facility, the heat and power demands of stover ethanol are met first, with excess heat and power used during grain ethanol production (Canter *et al.*, 2015).

Results for both marginal and energy allocation-based analyses are presented in Fig. 6 for stover and grain ethanol, as well as the combined ethanol gallon from the integrated facility. The LUC GHG emissions associated with grain ethanol were estimated at 7.8 g CO_2e MJ^{-1} (Qin *et al.*, 2016). For all ethanol types, emissions associated with agricultural operations (excluding LMC) and the conversion process are roughly the same regardless of LMC because key factors (e.g., conversion process energy consumption and existing agricultural operations such as harvesting) do not change significantly (Table S3). Results for the combined gallon of ethanol are relatively insensitive to changes in allocation technique (Fig. 6). When no organic matter input is added, using energy allocation produces net GHG emissions of 46 g CO_2e $MJ^{-1,}$ whereas marginal allocation yields a result of 48 g CO_2e MJ^{-1} (Fig. 6). The energy allocation technique results in a lower estimate of life cycle GHG emissions due to lower SOC emissions being shared between both feedstocks (i.e., corn grain and corn stover) when compared to the baseline scenario, and allocation differences in the field and at the integrated facility (Canter *et al.*, 2015). For the cover crop and manure scenarios, the net GHG emissions exhibit the opposite behavior; life cycle GHG emissions estimated with energy allocation are higher than those estimated with marginal allocation. Relative SOC gains are larger under marginal allocation in scenarios with cover crop planting or manure application. However, N_2O

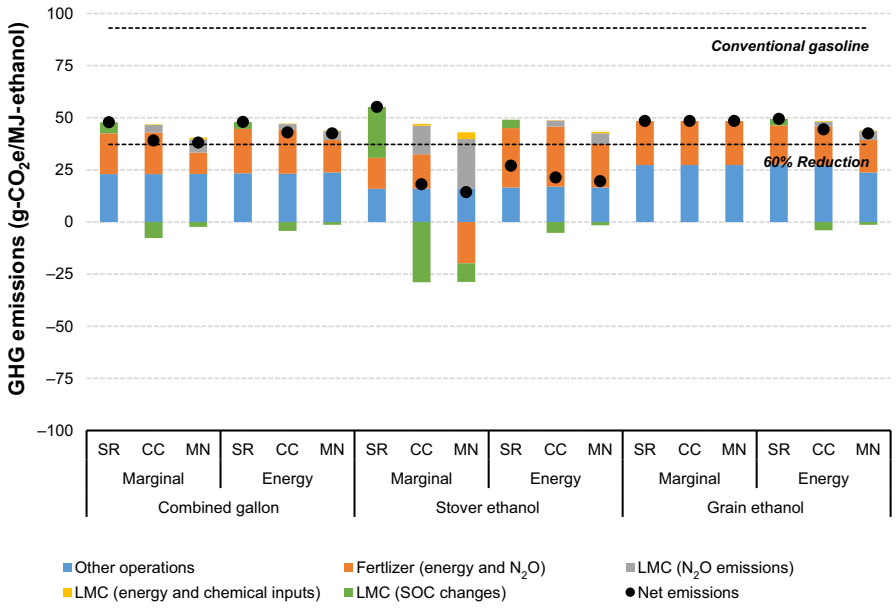

Fig. 6 Combined gallon, stover, and grain ethanol life cycle GHG emissions for marginal and energy allocation approaches. The estimates reflect CT and 30% stover removal. Acronyms and legend are same as in Fig. 4.

emissions from cover crop decomposition are larger under marginal allocation, which increases life cycle GHG emissions. The same trend is seen for the manure scenario.

Of the three ethanol types in Fig. 6, stover ethanol is most sensitive to the coproduct handling technique. In this case, the net GHG emissions are lower when energy allocation is applied compared to when the marginal approach is taken and no organic matter inputs are added because the relative SOC losses from stover removal are spread between the grain and the stover as are the burdens associated with supplemental fertilizer and stover harvesting (Canter *et al.*, 2015). Corn stover ethanol has slightly higher emissions (27 g CO_2e MJ^{-1}) in the cover crop scenario when energy allocation is adopted because the stover shares the relative SOC gains with the grain. On the other hand, in the marginal allocation approach, the stover alone benefits from SOC gains, which outweigh the increased N_2O emissions assigned fully to stover. In this case, corn stover life cycle GHG emissions are lower (18 g CO_2e MJ^{-1}) (Fig. 6). When manure application is used as an organic matter input, stover ethanol life cycle GHG emissions are also higher under the energy allocation approach (20 g CO_2e MJ^{-1}) as compared to under the marginal allocation approach (14 g CO_2e MJ^{-1}) because in the former approach, stover must share the benefits of increased SOC and fertilizer displacement with the grain. Increased N_2O emissions are essentially offset by these benefits (Fig. 6).

The life cycle GHG emissions of grain ethanol (48 g CO_2e MJ^{-1}) are not affected by the LMC scenario in the marginal allocation approach because all burdens and benefits of the LMC practices are assigned to stover ethanol (Fig. 6). In the energy allocation scenario, however, the grain ethanol is burdened with a portion of the GHG emissions associated with stover removal in the scenario without organic matter inputs, causing grain ethanol life cycle GHG emissions to rise to 52 g CO_2e MJ^{-1}. In the cover crop and manure scenarios, grain ethanol benefits from a portion of SOC gains in the cover crop and manure scenarios and its life cycle GHG emissions decline slightly.

Spatially explicit factors

The life cycle GHG emissions estimate is sensitive to model inputs including corn yield, cover crop yield, manure application rate, and soil and climate factors. Life cycle GHG emissions on a unit energy basis can vary among counties primarily due to spatially explicit changes in SOC depending on model inputs. Here, we explore two cases, Wichita County, Kansas and Kossuth County, Iowa, to reflect these changes (Fig. 7). Presented in Table S4 are spatially explicit input values along with their national average counterpart. Wichita County has a lower corn grain yield than the national average, but the rye cover crop yield is higher. On the other hand, in Kossuth County, the grain yield is higher than the national average and the rye yield is lower.

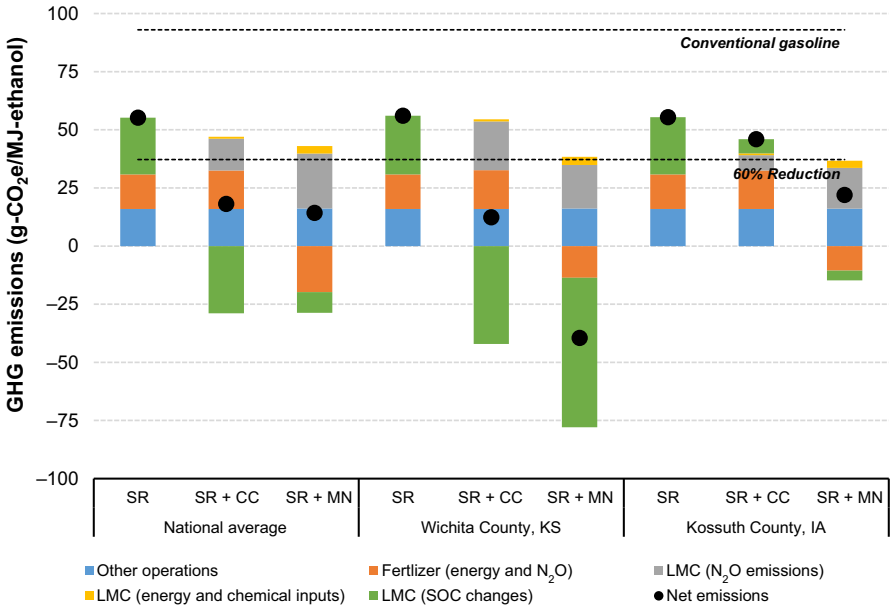

Fig. 7 Stover ethanol life cycle GHG emissions for the national average and two US counties. The estimates reflect CT and 30% stover removal and marginal allocation. Key parameters (grain yield, cover crop yield, manure application rate, manure application type) are for corresponding national or local values. Other acronyms and legend are same as in Fig. 4.

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Both counties have a lower manure application rate than the national average and the percentages of manure types vary. All of the manure for Wichita County comes from beef cattle (Table S4). This manure type has a higher carbon content per mass of manure than dairy cow or swine manure [ASAE (American Society of Agricultural Engineers), 2005].

Life cycle stover ethanol GHG emissions are calculated with marginal allocation approach for the national average, Wichita County, KS and Kossuth County, IA cases (Fig. 7). For stover ethanol scenarios without organic matter inputs, the national average and Wichita County GHG emissions are 56 g CO_2e MJ^{-1}, while Kossuth County emissions are slightly lower at 55 g CO_2e MJ^{-1}. The slight differences between the results are due to the SOC changes for each scenario, which depend on corn grain yield, soil properties, and climate. For the cover crop scenarios, the net GHG emissions are 19, 12, and 46 g CO_2e MJ^{-1}, for the national average, Wichita County, and Kossuth County, respectively. The largest contributor to these results is the SOC changes, which mostly depend on the winter rye cover crop yield, with a higher rye yield resulting in a larger SOC sequestration value. For Kossuth County, the soil carbon sequestration due to cover crop planting is not large enough to offset the carbon loss due to stover removal, which results in a 6.1 g CO_2e MJ^{-1} emission loss. Also associated with an increased rye yield are increased N_2O emissions due to cover crop decomposition. However, these emissions are offset by the increased SOC sequestration.

The life cycle stover ethanol GHG emissions in the manure scenarios are 15, −40, and 22 g CO_2e MJ^{-1} for the national average, Wichita County, and Kossuth County cases, respectively (Fig. 7). Importantly, stover ethanol can emit or mitigate GHGs on net depending on where the stover is grown. Both the manure application rate and manure type applied affect the results. The manure application rate is the highest in the national average case (Table S5), and as a result, this case has the highest nutrient application rate (nitrogen plus phosphorus). This results in a fertilizer GHG emissions of −20 g CO_2e MJ^{-1} for the national average case and −14 and −11 g CO_2e MJ^{-1} for Wichita County and Kossuth County cases, respectively. The nitrogen application rate is proportional to the LMC N_2O emissions, with the national average case having the highest nitrogen application rate at −22.2 kg N ha^{-1} $yr^{-1}$and highest LMC N_2O emissions at 24 g CO_2e MJ^{-1}. Fertilizer application rates in Kossuth County were the lowest of the cases considered at −14.1 kg N ha^{-1} yr^{-1}. This case also exhibited the lowest LMC N_2O emissions at 17 g CO_2e MJ^{-1}. The Wichita County case sees the highest LMC SOC sequestration at −64 g CO_2e MJ^{-1} due to the manure type applied, even though other cases had higher mass of manure applied per acre. In fact, the national average manure application rate is higher than the Wichita County rate, but only sees 8.9 g CO_2e MJ^{-1} associated with SOC changes. This is because the carbon content of the manure, on a per area basis, is highest at 7.6 tonne ha^{-1}, which is due to the type of manure utilized. Kossuth County has the lowest LMC SOC carbon sequestration rate at −4.2 g CO_2e MJ^{-1} due to the lowest manure application rate of the three locations and a carbon content of the manure than Wichita County.

Limitations and future needs

This study explored different LMC, and the impacts of LMC on spatially explicit SOC change and life cycle GHG emissions associated with corn and corn stover ethanol. However, our understanding of LMC influences on SOC change and subsequent effect on biofuel GHG emissions are still limited in several ways. The SOC model used in an analysis is one of the most important tools determining SOC changes associated with LMC across the nation. However, with LMC becoming increasingly complex and interest in exploring land management practices such as cover crop and manure application, SOC models need to be further expanded and validated across the major corn-producing regions to improve site-specific SOC estimates (Robertson *et al*., 2014; Wu *et al*., 2015). A SOC database collecting nationwide experimental observation data (especially long-term) could be of great value to identify SOC changes associated with LMC and validate SOC models simulating changes of stover removal, rotation, tillage, soil organic matter input, irrigation, among other possible management practices.

A corn–soybean rotation was specifically modeled in this study, but other rotation systems may also become applicable for crop residue harvest. For instance, corn–corn systems produce a significant amount of stover which can be used as a biofuel feedstock or for other purposes. Future work should further explore other rotations (e.g., corn–corn), multiple products (e.g., corn ethanol and soybean biodiesel from corn–soybean rotation) and possible rotation changes (e.g., corn–soybean to corn–corn) (e.g., Kim & Dale, 2005; Kendall & Chang, 2009; Chen *et al*., 2017). In our study, we looked at one LMC factor (cover crop, manure, tillage, and removal rate, among others) at a time. However, in actual farming practice, multiple management practices may occur simultaneously. For example, a cover crop may be grown with less intensive tillage, and the crop rotation shifts from corn–soy to corn–corn and therefore stover could be harvested annually. Also, farming practice in reality is also affected by culture and farmers' beliefs

(Burton *et al*., 2008). Specific LMCs may be recommended to famers to maintain soil health such as harvest frequency and collection method. As aforementioned, RT and NT may also occur in the baseline scenario as conservation tillage is increasingly adopted; LCA should further evaluate different tillage change scenarios and their impact on stover ethanol life cycle GHG emissions. Even though it is unlikely LCA can capture every possible LMC change that could happen in farming systems with stover collection, LCA can be improved if a nationwide LMC database becomes available to inform not only national scale LMC trends (e.g., direction of change) but also spatial variations of LMC differences (e.g., tillage intensity, rotation system).

In the LCA we conducted, manure entered the system starting from manure transportation, any upstream processes or counterfactual uses were treated as out of the system boundary (Fig. S2). This was based on the assumption that manure collection/storage processes are a result of animal farming, and that manure could become available to corn farming without competing with other uses (e.g., energy generation, existing application on cropland) [USDA (US Department of Agriculture), 2009; Potter *et al*., 2010; Zhang *et al*., 2017]. Future work may consider counterfactual uses to evaluate alternative ways to make use of current manure production, for example, landfill, energy generation, and fertilizer production (Thygesen & Johnsen, 2012; Lee *et al*., 2017). In addition, this analysis focused on GHG emissions. In the future, analyses could be expanded to include additional environmental effects of LMC including air and water pollutant emissions that could lead to, for example, increased eutrophication due to excessive phosphorus application.

In summary, analysis of manure and rye cover crop as carbon inputs in corn–soybean systems shows that life cycle GHG emissions are dependent upon corn stover removal rate, the land management techniques applied, and the life cycle analysis approach selected (marginal vs. energy allocation). Stover removal can reduce SOC spatially, with higher stover removal resulting in more SOC loss. Reducing tillage intensity and/or applying a cover crop after corn harvest or manure before corn growth can reduce or negate the SOC loss due to stover removal. The allocation method used for agricultural and land management inputs affects the GHG emissions results for grain and stover ethanol, with energy allocation having higher emissions than marginal allocation for stover ethanol in both the cover crop and manure scenarios. The opposite trend is seen for grain ethanol. However, it should be noted that more efforts are needed to further assess the life cycle GHG emissions associated with fuels produced from corn stover. SOC modeling needs to be extensively validated against field observations to guarantee its accuracy and spatial representativeness. LCA needs to identify representative land management baseline(s) and practical LMC(s) that reflect large-scale farming practices under new systems with stover removal.

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References

Adler PR, Mitchell JG, Pourhashem G, Spatari S, Del Grosso SJ, Parton WJ (2015) Integrating biorefinery and farm biogeochemical cycles offsets fossil energy and mitigates soil carbon losses. *Ecological Applications*, **25**, 1142–1156.

Argonne National Laboratory (2015) The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model 2015. Available at: https://greet.es.anl.gov/ (accessed 5 December 2015).

ASAE (American Society of Agricultural Engineers) (2005) Manure production and characteristics (ASAE D384.2 MAR2005). Available at: http://extension.psu.edu/animals/dairy/nutrient-management/certified-dairy/tools/manure-prod-char-d384-2.pdf (accessed 5 December 2015).

Bentsen NS, Larsen S, Felby C (2014) CO2 emissions from crop residue-derived biofuels. *Nature Climate Change*, **4**, 932–934.

Burton RJF, Kuczera C, Schwarz G (2008) Exploring farmers' cultural resistance to voluntary agri-environmental schemes. *Sociologia Ruralis*, **48**, 16–37.

Canter CE, Dunn JB, Han J, Wang Z, Wang M (2015) Policy implications of allocation methods in the life cycle analysis of integrated corn and corn Stover ethanol production. *BioEnergy Research*, **9**, 1–11.

Chen R, Qin Z, Han J *et al*. (2017) Life cycle energy and greenhouse gas emission effects of biodiesel in the United States with induced land use change impacts. *Bioresource Technology*, **251**, 249–258.

Dunn JB, Mueller S, Kwon H, Wang MQ (2013) Land-use change and greenhouse gas emissions from corn and cellulosic ethanol. *Biotechnology for Biofuels*, **6**, 51.

EPA (U.S. Environmental Protection Agency) (2010) Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program; Final Rule. 40 CFR Part 80. Available at: http://www.gpo.gov/fdsys/pkg/FR-2010-03-26/pdf/2010-3851.pdf (accessed 15 May 2016).

Feyereisen GW, Camargo GGT, Baxter RE, Baker JM, Richard TL (2013) Cellulosic biofuel potential of a winter rye double crop across the U.S. Corn-Soybean Belt. *Agronomy Journal*, **105**, 631–642.

Fronning BE, Thelen KD, Min D-H (2008) Use of manure, compost, and cover crops to supplant crop residue carbon in corn Stover removed cropping systems. *Agronomy Journal*, **100**, 1703–1710.

Halpern MT, Whalen JK, Madramootoo CA (2010) Long-term tillage and residue management influences soil carbon and nitrogen dynamics. *Soil Science Society of America Journal*, **74**, 1211.

IPCC (Intergovernmental Panel on Climate Change) (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Prepared by the National Greenhouse Gas

Inventories Programme, (eds Eggleston HS, Buendia L, Miwa K, Ngara T and Tanabe K). Published: IGES, Japan.

Johnson JMF, Novak JM, Varvel GE *et al.* (2014) Crop residue mass needed to maintain soil organic carbon levels: can it be determined? *BioEnergy Research*, **7**, 481–490.

Kendall A, Chang B (2009) Estimating life cycle greenhouse gas emissions from corn–ethanol: a critical review of current U.S. practices. *Journal of Cleaner Production*, **17**, 1175–1182.

Kim S, Dale BE (2005) Life cycle assessment of various cropping systems utilized for producing biofuels: bioethanol and biodiesel. *Biomass and Bioenergy*, **29**, 426–439.

Kwon H-Y, Hudson RJM (2010) Quantifying management-driven changes in organic matter turnover in an agricultural soil: an inverse modeling approach using historical data and a surrogate CENTURY-type model. *Soil Biology and Biochemistry*, **42**, 2241–2253.

Kwon H-Y, Mueller S, Dunn JB, Wander MM (2013) Modeling state-level soil carbon emission factors under various scenarios for direct land use change associated with United States biofuel feedstock production. *Biomass and Bioenergy*, **55**, 299–310.

Kwon H, Ugarte CM, Ogle SM, Williams SA, Wander MM (2017) Use of inverse modeling to evaluate CENTURY-predictions for soil carbon sequestration in US rain-fed corn production systems. *PLoS ONE*, **12**, e0172861.

Lal R (2005) World crop residues production and implications of its use as a biofuel. *Environment International*, **31**, 575–584.

Lee U, Han J, Wang M (2017) Evaluation of landfill gas emissions from municipal solid waste landfills for the life-cycle analysis of waste-to-energy pathways. *Journal of Cleaner Production*, **166**, 335–342.

Liska AJ, Yang H, Milner M *et al.* (2014) Biofuels from crop residue can reduce soil carbon and increase CO2 emissions. *Nature Climate Change*, **4**, 398–401.

Mann L, Tolbert V, Cushman J (2002) Potential environmental effects of corn (*Zea mays* L.) Stover removal with emphasis on soil organic matter and erosion. *Agriculture, Ecosystems and Environment*, **89**, 149–166.

Muth DJ, Bryden KM, Nelson RG (2013) Sustainable agricultural residue removal for bioenergy: a spatially comprehensive US national assessment. *Applied Energy*, **102**, 403–417.

Poeplau C, Don A (2015) Carbon sequestration in agricultural soils via cultivation of cover crops – A meta-analysis. *Agriculture, Ecosystems and Environment*, **200**, 33–41.

Potter P, Ramankutty N, Bennett EM, Donner SD (2010) Characterizing the spatial patterns of global fertilizer application and manure production. *Earth Interaction*, **14**, 1–22.

Qin Z, Canter C, Dunn JB *et al.* (2015) Incorporating agricultural management practices into the assessment of soil carbon change and life-cycle greenhouse gas emissions of corn stover ethanol production (No. ANL/ESD-15/26). Argonne National Laboratory, Argonne, IL. https://doi.org/10.2172/1221938.

Qin Z, Dunn JB, Kwon H, Mueller S, Wander MM (2016) Influence of spatially-dependent, modeled soil carbon emission factors on life-cycle greenhouse gas emissions of corn and cellulosic ethanol. *GCB Bioenergy*, **8**, 1136–1149.

Qin Z, Zhuang Q, Cai X *et al.* (2017) Biomass and biofuels in China: toward bioenergy resource potentials and their impacts on the environment. *Renewable and Sustainable Energy Reviews*, **82**, 2387–2400.

Robertson GP, Grace PR, Izaurralde RC, Parton WP, Zhang X (2014) CO2 emissions from crop residue-derived biofuels. *Nature Climate Change*, **4**, 933–934.

Schmer MR, Jin VL, Wienhold BJ, Varvel GE, Follett RF (2014) Tillage and residue management effects on soil carbon and nitrogen under irrigated continuous corn. *Soil Science Society of America Journal*, **78**, 1987–1996.

Sheehan J, Aden A, Paustian K, Killian K, Brenner J, Walsh M, Nelson R (2003) Energy and environmental aspects of using corn Stover for fuel ethanol. *Journal of Industrial Ecology*, **7**, 117–146.

Sheehan JJ, Adler PR, Del Grosso SJ, Easter M, Parton W, Paustian K, Williams S (2014) CO2 emissions from crop residue-derived biofuels. *Nature Climate Change*, **4**, 932–933.

Thygesen O, Johnsen T (2012) Manure-based energy generation and fertiliser production: determination of calorific value and ash characteristics. *Biosystems Engineering*, **113**, 166–172.

USDA (U.S. Department of Agriculture) (2009) *Manure Use for Fertilizer and for Energy, Report to Congress*. Available at: http://www.ers.usda.gov/publications/ap-administrative-publication/ap-037.aspx (accessed 5 December 2015).

USDA (U.S. Department of Agriculture) (2012) Agricultural Resources and Environmental Indicators, 2012 Edition. U.S. Department of Agriculture, Available at: http://www.ers.usda.gov/publications/eib-economic-information-bulletin/eib98.aspx (accessed 5 December 2015).

USDOE (U.S. Department of Energy) (2016) 2016 Billion-Ton Report: advancing domestic resources for a thriving bioeconomy, Volume 2: environmental sustainability effects of select scenarios from Volume 1 (2017). (eds Efroymson RA, Langholtz MH, Johnson KE, Stokes BJ), ORNL/TM-2016/727. Oak Ridge National Laboratory, Oak Ridge, TN. 642p. https://doi.org/10.2172/1338837.

Verma SB, Dobermann A, Cassman KG *et al.* (2005) Annual carbon dioxide exchange in irrigated and rainfed maize-based agroecosystems. *Agricultural and Forest Meteorology*, **131**, 77–96.

Wu Y, Liu S, Young CJ, Dahal D, Sohl TL, Davis B (2015) Projection of corn production and stover-harvesting impacts on soil organic carbon dynamics in the U.S. Temperate Prairies. *Scientific Reports*, **5**, 10830.

Zhang B, Tian H, Lu C, Dangal SRS, Yang J, Pan S (2017) Global manure nitrogen production and application in cropland during 1860–2014: a 5 arcmin gridded global dataset for Earth system modeling. *Earth System Science Data*, **9**, 667–678.

Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

Figure S1 Spatially explicit soil carbon modeling inputs of (a) corn yield, (b) soybean yield, (c) rye biomass yield and (d) manure application rate (in terms of carbon).
Figure S2 Boundary diagram for ethanol production from an integrated corn and corn stover production process.
Table S1 Land management change scenarios simulated in the analysis.
Table S2 Allocation of energy and materials based on marginal and energy allocation methods.
Table S3 GHG emissions and feed energy share for marginal and energy allocation in corn ethanol production.
Table S4 Crop, cover crop and manure information for the national average and two counties in the U.S.
Table S5 Fertilizer, manure and emission factor data for the national average and two counties in the U.S.

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