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Incorporating Agricultural Management Practices into the Assessment of Soil Carbon Change and Life-Cycle Greenhouse Gas Emissions of Corn Stover Ethanol Production

Energy Systems Division

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by
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NOTES

The GREET^{TM} model and its CCLUB module discussed in this document are both available at: https://greet.es.anl.gov/. A CCLUB user's manual is also available at: https://greet.es.anl.gov/publication-cclub-manual.

NOTATION

AEZ	agro-ecological zone
CCLUB	Carbon Calculator for Land Use change from Biofuels production (model)
CT	conventional tillage
GHG	greenhouse gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation (model)
HWSD	Harmonized World Soil Database
LCA	life cycle assessment
LHV	lower heating value
LMC	land management change
OM	organic matter
NT	no tillage
RT	reduced tillage
SOC	soil organic carbon
WTW	well-to-wheels
ARMS	Agricultural Resource Management Survey
ASAE	American Society of Agricultural Engineers
IPCC	Intergovernmental Panel on Climate Change
NOAA	National Oceanic and Atmospheric Administration
SARE	Sustainable Agriculture Research and Education Program
U.S.	The United States
USDA	U.S. Department of Agriculture
US DOE	U.S. Department of Energy
US EPA	U.S. Environmental Protection Agency
C	carbon
CO_2	carbon dioxide

CO_2eq	carbon dioxide equivalent of CO_2, CH_4, and N_2O
N	nitrogen
N_2O	Nitrous oxide
NH_3	Ammonia
NO_x	Nitrogen oxide
P	phosphorus
P_2O_5	phosphorus pentoxide
SOC_r	SOC sequestration rate (*in equation*)
T	time horizon (*in equation*)
ac	acre(s)
Btu	British thermal unit(s)
g	gram(s)
gal	gallon(s)
ha	hectare
J	joule(s)
kg	kilogram(s)
L	liter(s)
Mg	megagram(s)
lb	pound(s)
mi	mile(s)
MJ	megajoule(s)
t	(short) ton(s)
yr	year(s)

INCORPORATING AGRICULTURAL MANAGEMENT PRACTICES INTO THE ASSESSMENT OF SOIL CARBON CHANGE AND LIFE-CYCLE GREENHOUSE GAS EMISSIONS OF CORN STOVER ETHANOL PRODUCTION

by

Zhangcai Qin, Christina Canter, Jennifer B. Dunn, Steffen Mueller, Ho-young Kwon, Jeongwoo Han, Michelle Wander, and Michael Wang

ABSTRACT

Land management practices such as cover crop adoption or manure application that can increase soil organic carbon (SOC) may provide a way to counter SOC loss upon removal of stover from corn fields for use as a biofuel feedstock. This report documents the data, methodology, and assumptions behind the incorporation of land management practices into corn-soybean systems that dominate U.S. grain production using varying levels of stover removal in the GREET™ (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model and its CCLUB (Carbon Calculator for Land Use change from Biofuels production) module. Tillage (i.e., conventional, reduced and no tillage), corn stover removal (i.e., at 0, 30% and 60% removal rate), and organic matter input techniques (i.e., cover crop and manure application) are included in the analysis as major land management practices. Soil carbon changes associated with land management changes were modeled with a surrogate CENTURY model. The resulting SOC changes were incorporated into CCLUB while GREET was expanded to include energy and material consumption associated with cover crop adoption and manure application. Life-cycle greenhouse gas (GHG) emissions of stover ethanol were estimated using a marginal approach (all burdens and benefits assigned to corn stover ethanol) and an energy allocation approach (burdens and benefits divided between grain and stover ethanol). In the latter case, we considered corn grain and corn stover ethanol to be produced at an integrated facility. Life-cycle GHG emissions of corn stover ethanol are dependent upon the analysis approach selected (marginal versus allocation) and the land management techniques applied. The expansion of CCLUB and GREET to accommodate land

management techniques can produce a wide range of results because users can select from multiple scenario options such as choosing tillage levels, stover removal rates, and whether crop yields increase annually or remain constant. In a scenario with conventional tillage and a 30% stover removal rate, life-cycle GHG emissions for a combined gallon of corn grain and stover ethanol without cover crop adoption or manure application are 50 g CO_2eq MJ^{-1}, in comparison with 91 g CO_2eq MJ^{-1} for petroleum gasoline. Adopting a cover crop or applying manure reduces the former ethanol life-cycle GHG emissions by 4% and 6%, respectively. We considered two different life cycle analysis approaches to develop estimates of life-cycle GHG emissions for corn stover ethanol, marginal analysis and energy allocation. In the same scenario, this fuel has GHG emissions of 12 – 17 g CO_2eq MJ^{-1} (for manure and cover crop application, respectively) and 46 – 49 g CO_2eq MJ^{-1} with the marginal approach and the energy allocation approach, respectively.

1. INTRODUCTION

Corn stover is considered to be a major feedstock for advanced biofuel production (U.S. Department of Energy (US DOE), 2011; Karlen & Johnson, 2014). Stover accounts for about half of the total corn aboveground biomass production (Kwon *et al.*, 2013). One potential drawback of removing stover from corn fields as a biofuel feedstock is the effect of this removal on soil organic carbon (SOC) stocks (Karlen & Johnson, 2014; Liska *et al.*, 2014). Early studies of the sustainability of stover removal focused mostly on the importance of avoiding soil erosion (e.g., water and wind erosion), but failed to consider SOC as a major environmental factor (Karlen & Johnson, 2014). Recent reports found that removing a large quantity of corn stover from the field can reduce SOC, leading to a conclusion that the biomass removed should be constrained to levels that maintain SOC (Blanco-Canqui & Lal, 2007; Johnson *et al.*, 2014). In some extreme cases, if corn stover is completely removed without any additional organic matter (OM) inputs, the SOC level may decrease significantly compared with situations where no stover is removed. This drop in SOC is especially pronounced if SOC levels after stover removal over a period of time are compared to SOC levels that would have been achieved if all stover were left on the field. For example, Liska *et al.* (2014) reported that in such a scenario, the decline in SOC, translated into CO_2 emissions for ethanol production, caused the life-cycle GHG emissions of stover ethanol to be so high that this fuel did not achieve the 60% GHG reduction threshold US Congress (2007) established for cellulosic biofuels in the Renewable Fuel Standard.

To counter SOC losses, many studies suggest use of improved land management practices (e.g., applying cover crops, manure, compost and biochar) to augment SOC levels, possibly restoring them to those that would be experienced if all stover were left on the field (Liska *et al.*, 2014; Warren Raffa *et al.*, 2015). In experimental studies conducted near East Lansing, Michigan (Fronning *et al.*, 2008; Thelen *et al.*, 2010), scientists found that the SOC gains achieved from adopting cover crops or applying a soil amendment (manure or compost) exceeded the GHG emissions associated with the activities required to implement these land management practices. Although these techniques (e.g., cover crop adoption and manure application) hold potential to increase SOC levels, their effect on SOC will likely vary depending on spatially explicit factors such as soil type, crop yield, and climate. Furthermore, the implementation of these practices (for example, spreading of manure) consumes energy. The degree of SOC change and the amount of energy consumed during practice implementation will influence the life-cycle GHG emissions of biofuels produced from feedstocks grown on lands where practices are applied (Schlesinger, 1999).

We investigated these issues in this study with three objectives: (1) to quantify spatially-explicit (county-level) SOC changes under conventional and improved land management practices on lands that experience stover removal; (2) to evaluate energy use in different land management systems; and (3) to estimate life-cycle GHG emissions from stover ethanol production under different land management scenarios.

In this report, we document background information about the land management techniques that we consider and the system boundary of our analysis (Section 2). In Section 3, we describe our approach to SOC modeling that leads to estimates of SOC changes under these land management techniques. Section 4 reviews the data and methodology behind the energy and GHG intensity of the agricultural activities associated with cover crop adoption and manure application. In Section 5, we discuss life cycle analysis (LCA) methodology considerations associated with this analysis. A brief description regarding the use of GREET™ (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) to evaluate life-cycle GHG emissions of corn grain or stover ethanol incorporating land management practices is provided in Section 6. Finally section 7 presents the results of our analysis.

2. AGRICULTURAL MANAGEMENT PRACTICES

2.1 Land Management Types

This modeling effort concentrated on the rotation systems of corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.]which are the dominant crops in the U.S., accounting for 89 and 85 million planted acres in 2015, respectively (U.S. Department of Agriculture (USDA), 2015). Corn-soybean rotation is one of the most common cropping systems in the U.S., occurring on over 50% of planted corn areas and over 60% of soybean areas (USDA, 2012). This study evaluated the effects of three important management practices (tillage, stover removal and OM addition) within corn-soybean production systems that are used for stover ethanol production.

2.1.1 Tillage

Tillage involves different types of mechanical agitation for the purpose of agricultural preparation of soil for crop production. It loosens and dries the top soil, facilitates planting, mixes residues, and destroys weeds. However, because of the mechanical disturbance of soil, it may also cause soil nutrient loss, soil organic matter reduction, and enhanced erosion. For example, conventional agricultural practices that were dominant up until the last decade required extensive tillage using a moldboard plow to incorporate residues into the soil; this aggressive tillage consumes time and energy, and leaves soil unprotected from wind or water erosion. Conservation tillage has been increasingly adopted as an alternative to conventional tillage (e.g., moldboard or other disruptive primary tillage method) (USDA, 1994, 2012). Conservation tillage is a soil conservation practice that leaves part of the previous year's crop residue (e.g., corn stover) on field surfaces before and after planting the next crop. To reduce soil erosion and runoff, it is normally suggested that at least 30% of the soil surface must be covered with residues after planting the next crop (USDA, 2006). Reduced till (with no less than 20% residue biomass left) and no till (the soil is left undisturbed from harvest to planting) are considered in this study as conservation tillage practices.

Numerous studies have explored the effects of various tillage practices on SOC and generally accepted that compared with conventional tillage, less intensive tillage can sequester more soil organic carbon (SOC) (Lal *et al*.2003; Powlson *et al.*, 2012) and the degree to which this occurs is site and cropping-system specific (Baker *et al.*, 2007). Use of reduced tillage practices can also lower farm energy consumption (USDA, 1996, 2003; Hanna *et al.*, 2012). Compared to conventional tillage, reduced tillage is a practice that does not use a moldboard plow (USDA, 1996) and has less trips over the field (USDA, 1996, 2003). Even though the farming energy input is decreased, more fertilizers may be required (USDA, 1996), which can affect the GHG emissions (West & Marland, 2002). In this study, we include three major tillage types (i.e., conventional, reduced and no tillage) to represent different tillage intensities. At this time, as a result of limited data concerning the share of farming energy intensity associated with tilling, we do not consider the changes to farming energy or fertilizer requirements due to change in tillage.

2.1.2 Corn stover removal

After corn grain harvest, the stover, including stalks, leaves, cobs, husks and tassels, is generally left in the field. These residues either fully integrate into the soil or can be partially harvested as a livestock feed. Alternatively, they can be harvested as a biofuel feedstock. With stover removal, the carbon and other nutrients (e.g., nitrogen, phosphorus and potassium) that the stover contains are also removed from the field, which to some extent, can reduce SOC and affect subsequent crop productivity. It has generally therefore been advised to remove only a limited amount of stover to maintain SOC (Wilhelm *et al.*, 2007). The amount of stover that can be removed sustainably has been subject to analysis and is spatially-dependent. For example, Muth Jr. *et al*., (2013) assessed the sustainable residue removal quantity by utilizing integrated multi-factor environmental process modeling that took into account spatially explicit factors like soils, climate, crop yields, and land management.

In this study, aside from the scenario in which no stover is removed, we include two additional scenarios with a stover removal rate at 30% and 60% (of total dry mass). A 30% removal rate is generally the acceptable amount of stover that can be removed from corn fields without negatively impacting the soil (Lal, 2005; Johnson *et al.*, 2014). It is important to note that a stover removal rate that maintains SOC will vary even within a single farm field (Muth *et al.*, 2013; Johnson *et al.*, 2014). This analysis, however, aims to assess the influence of agricultural management practices on SOC more broadly and so we consider only two stover removal rates in modeling county-level SOC changes.

2.1.3 Organic matter inputs

Whether corn stover can be removed from a production system without decreasing SOC content and associated soil fertility and productivity is determined in large part by the amount and character of OM inputs returned to the field (Powlson *et al.*, 2012; Johnson *et al.*, 2014). Crop residues, for example, root matter, corn stover and soybean residue that remain after corn and soybean harvest, are the main sources of soil carbon inputs within corn-soybean production systems. Accordingly, OM inputs are positively related to crop productivity and so sustainable stover removal rates can be expected to increase along with yield. To increase sustainable stover removal rates, land management techniques that add carbon and nutrients to agricultural soils can be adopted. Two practices that can be incorporated into corn-soybean production systems include cover crops and manure application.

Cover crops maintain soil and ecosystem quality (e.g., erosion reduction, SOC increase, nutrient retention, biodiversity enhancement), and can be grown either within or outside the growing season of regular crops (Midwest Cover Crops Council, 2015). A recent survey to gauge cover crop use reported that cover crop adoption has been increasing rapidly. Between 2010 and 2012, cover crop acreage had increased by about 30% each year among surveyed cover crop users (Sustainable Agriculture Research and Education Program (SARE), 2014). In the U.S., corn (for grain) is mostly planted in April and May. This crop is harvested in September and October. On the other hand, most farmers plant soybeans in May and June, harvesting this crop in October and November. The actual planting and harvesting date varies among locations (USDA, 2010). In corn-soybean rotation systems, winter rye (*Secale cereale* L.) is often planted as a cover crop after corn harvest. This cover crop provides winter cover, builds soil structure and scavenges nitrogen from previous crop (Hoorman *et al.*, 2009; SARE, 2015). Accordingly, winter rye was included in our analysis of cover crop influences on SOC. As described later in Section 4.1, we also consider the energy and materials consumed when cover crops are incorporated into the cropping system when we calculate life-cycle GHG emissions of corn stover ethanol produced from biomass grown on lands that incorporate winter rye as a cover crop.

Animal manure can be used as an organic fertilizer in agriculture. It can improve soil fertility by adding organic matter and nutrients to soil. Anaerobic digestion of manure can be used to produce biogas, but to date this practice uses a relatively small share of available manure

(USDA, 2009b). In the U.S., about 5% of cropland is manured; nearly 60% of the acreage is planted with corn. It is reported that manure application can help maintain and even improve SOC levels (Fronning *et al.*, 2008; Thelen *et al.*, 2010). In this analysis, we consider the energy consumed in applying manure (e.g., dairy cow, beef cattle, swine, and poultry), the impacts of manure application on SOC dynamics, and the influence of the manure nutrient content on reducing application of conventional fertilizers.

2.2 System Boundary of the Analysis

Figure 1 illustrates the system boundary for the production of stover ethanol and incorporates the two land management scenarios we considered in this study. In the case of cover crops, energy is consumed during planting and herbicides are consumed to kill the cover crop prior to the next planting cycle. While the cover crop consumes soil nutrients as it grows, these nutrients are essentially returned to the soil as the cover crop degrades. We assume that soil N, P, and K content does not change as a result of winter rye adoption (note that the leguminous cover crops, e.g., clover, can affect soil N pools). Furthermore, the cover crops do not require fertilizer, nor does their adoption change overall fertilization rates for the production of corn or soybeans. The decay of the cover crop, however, is a source of N_2O emissions.

On the other hand, applying manure consumes energy as does transporting manure to the farm field (see Section 4.2 for a more detailed discussion of our treatment of the system boundary for manure production and use). Manure provides nutrients (N, P, and K) to the soil. We use a nutrient balance to estimate the reduction 1) in supplemental fertilizer that would be used to supply the nutrients in the stover removed from the field and, 2) in conventional fertilizer that must be applied when corn is planted per typical agricultural practice. We consider N_2O emissions from the N content of manure and conventional fertilizer using the methods described in section 4.2.5.

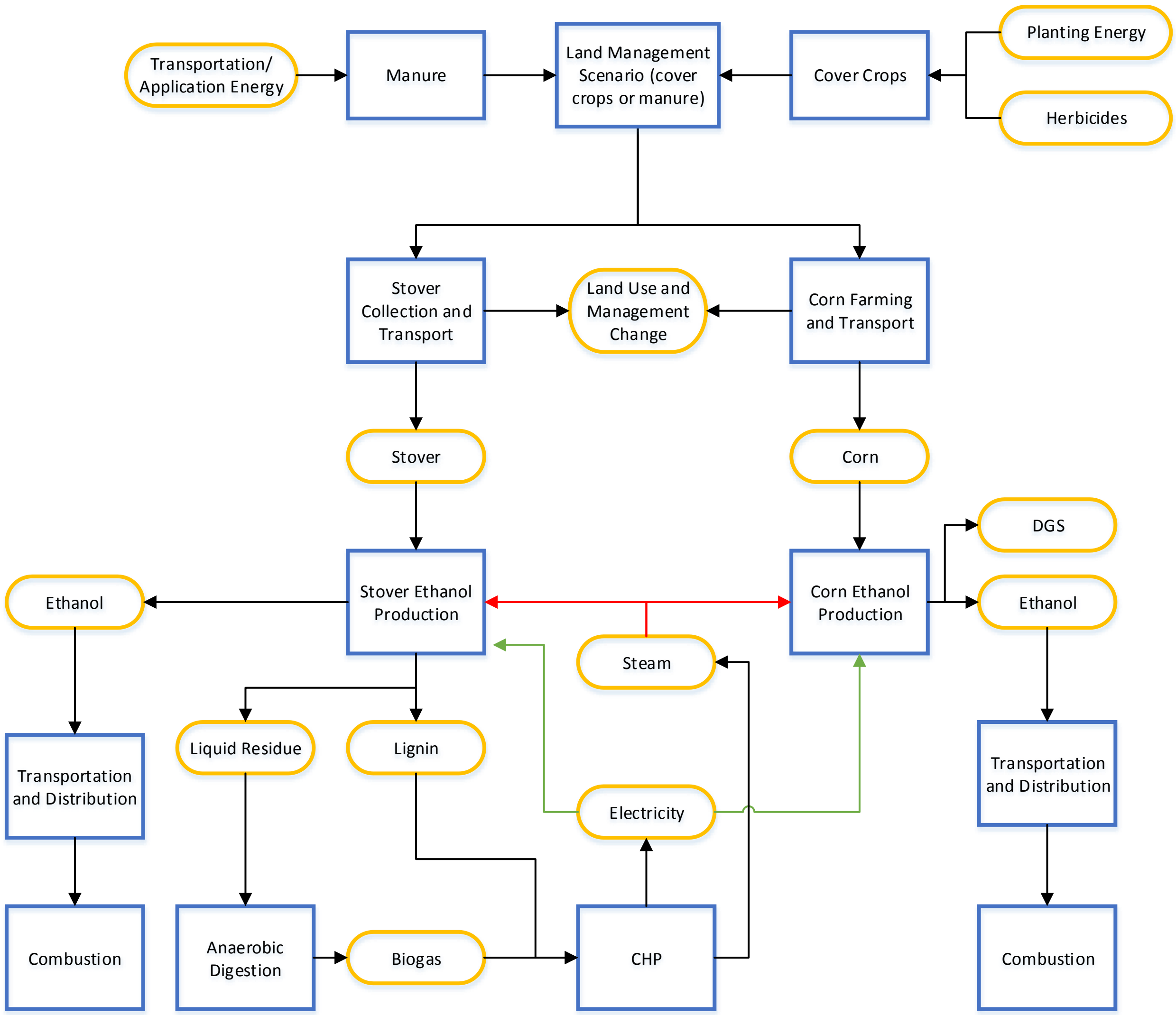

Figure 1. System boundary for ethanol production from corn grain and corn stover using either cover crops or manure. Processes are presented in blue and material and energy flows in yellow. The red and green arrows represent heat and electricity flows, respectively.

Beyond the feedstock production stage, the system boundary also includes ethanol production, ethanol transportation and distribution, and ethanol combustion in a vehicle. We consider integrated production of corn grain and corn stover ethanol. The methodology behind this approach, including the treatment of co-produced heat and power from lignin combustion, is described in Canter *et al.* (2015). We consider land use change (LUC) GHG emissions as described in Qin *et al.* (2015) in this analysis, including both domestic and international LUC GHG emissions. That is, a value of 2.1 to 9.3 g CO_2eq MJ^{-1} (corn ethanol), as estimated in

CCLUB, is included in this study for the integrated ethanol production (Qin *et al.,* 2015). In our separate estimates of GHG emissions of grain and stover ethanol, we attributed all LUC GHG emissions to corn ethanol because LUC GHG emissions associated with corn stover ethanol are essentially negligible (-0.5 g CO_2eq MJ^{-1}) (Qin *et al.*, 2015). It is important to note that the LUC GHG emissions included in the total life-cycle GHG emissions has some drawbacks in that the direct LUC GHG emissions included in total LUC GHG emissions estimates already include SOC changes on corn fields associated with corn production. Additionally, the SOC emission factors in CCLUB that are used in calculating LUC GHG emissions are based on modeling corn agriculture as a corn-corn rather than corn-soybean rotation. Nevertheless, given the concern regarding indirect effects of corn ethanol production, including LUC GHG emissions in the results from this analysis is an inclusive and conservative approach.

It should be noted that GREET estimates life-cycle GHG emissions at the national level, while the SOC modeling of both LUC and LMC impacts is conducted at the county-level and the SOC change results are aggregated to the national level.

3. MODELING LMC IMPACTS ON SOIL ORGANIC CARBON

In this section, we describe our use of the surrogate CENTURY model (Kwon & Hudson, 2010) to estimate SOC changes upon implementation of the different land management techniques we consider herein. In Section 3.1, we describe this model and the scenarios we ran. In Section 3.2, we explain model inputs and in Section 3.3 we summarize SOC modeling results.

3.1 The Surrogate CENTURY Model

The surrogate CENTURY model is used in this study to simulate SOC dynamics. The model was developed based on CENTURY (version 4.0)'s soil organic carbon (SOC) dynamics sub-model (Kwon & Hudson, 2010). It utilizes recorded or observed crop yields instead of simulating crop growth and subsequent yield (Kwon *et al.*, 2013). The model has been validated and used to simulate SOC change under various types of land uses (Kwon & Hudson, 2010; Kwon *et al.*, 2013; Qin *et al.*, 2015). It is capable of modeling SOC changes in both top (0-30cm) soils and deeper soils (30-100cm) at a county level (Qin *et al.*, 2015). For detailed information on model development, please refer to earlier publications (Kwon & Hudson, 2010; Kwon *et al.*, 2013; Qin *et al.*, 2015).

In this study, the land use history and LMC scenarios are established for a corn-soybean rotation, and the SOC change under LMC is simulated for 0-100cm soils. The land use history is constructed by dividing the entire simulation into three major periods: pristine prior to 1881 (grasslands), 1881-1950 (croplands), and 1951-2010 (croplands).The historical croplands were mainly planted with corn, soybean and wheat (*Triticum aestivum* L.). The LMC period (2011-2040) is designated for biofuel feedstock production. In corn-soybean rotation systems, various management practices (**Figure 2**) are introduced to simulate LMC impacts on SOC dynamics. These practices include: three tillage types (i.e., CT, RT and NT), three corn stover removal rates (i.e., 0—no removal, 30% and 60% of stover dry matter), and two major organic matter (OM) input practices, cover crop adoption or manure application. In particular, for cover crop application, winter rye is planted between the corn and soybean growing seasons; it is terminated (mainly by herbicide, see Section 4) in the spring before soybean planting. Manure is applied every four years during the corn season (**Figure 2**). A total of 21 LMC combinations are included in the SOC modeling (**Table 1**).

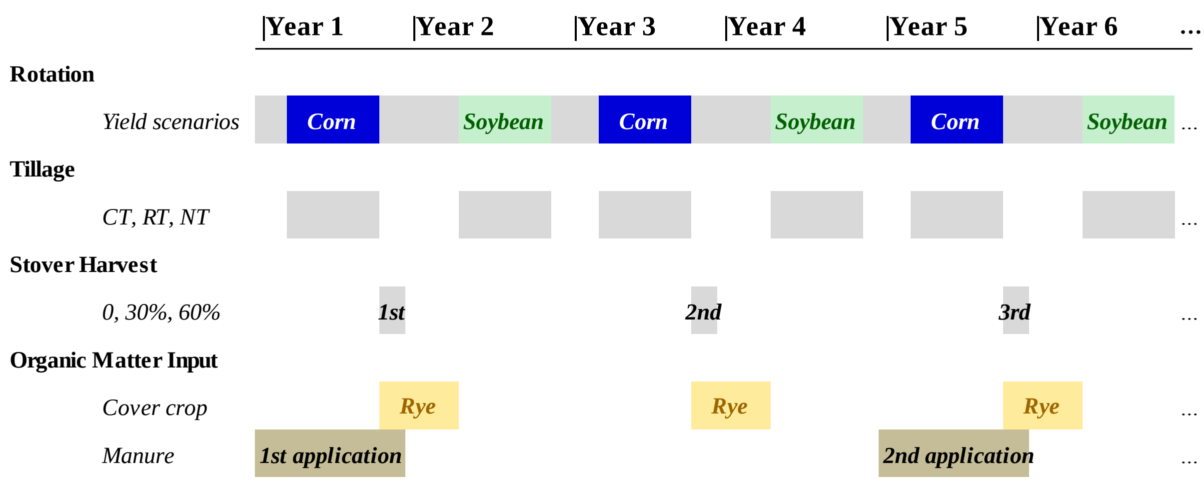

Figure 2. SOC modeling timetable for a corn-soybean rotation system with land management practices. Two yield scenarios, constant and increasing yield, are also included. CT, RT and NT indicate conventional, reduced and no tillage, respectively.

Table 1. Land management scenarios included in the SOC modeling for each yield scenario.

Scenario #	Tillage*	Stover removal rate (dry matter) (%)	OM inputs
1	CT	0	none
2	CT	30	none
3	CT	30	cover crop
4	CT	30	manure
5	CT	60	none
6	CT	60	cover crop
7	CT	60	manure
8	RT	0	none
9	RT	30	none
10	RT	30	cover crop
11	RT	30	manure
12	RT	60	none
13	RT	60	cover crop
14	RT	60	manure
15	NT	0	none
16	NT	30	none
17	NT	30	cover crop
18	NT	30	manure
19	NT	60	none
20	NT	60	cover crop
21	NT	60	manure

*CT, RT and NT indicate conventional, reduced and no tillage practices, respectively.

3.2 Modeling Data Inputs

The model is run at a county level for counties with both corn and soybean production in the conterminous U.S. For the historical period, corn and soybean yields are based on USDA data (USDA, 2015). For future LMC scenarios (2011-2040), constant and increasing yield scenarios are considered for corn and soybeans. In the yield increase scenario, the county-level crop yields are projected using historical yield data (Kwon *et al.*, 2013). When yields are held constant, the average yield between 1991 and 2010 is used for each crop.

For the cover crop land management technique, the key model input is the rye cover crop yield. These model input data are based on county-level cover crop (i.e., rye) yields modeled with a plant–soil–atmosphere model (Feyereisen *et al.*, 2013). In this study, we choose county-level yields of rye in a corn-soybean rotation harvested 14 days before soybean planting as the data basis, and assume that 50% of the rye yield can be achieved when the cover crop is killed early to minimize nitrogen tie-up and conserve soil moisture (Personal communication with Dr. Gary W. Feyereisen of USDA, 2015). In the yield increase scenario, we assume the rye yield increases by 1% annually.

In the case of the manure application land management technique, the key SOC model input is the manure application rate. The USDA Agricultural Resource Management Survey (ARMS) Farm Financial and Crop Production Practices database provided state-level manure use data including manure type and application rate (USDA, 2014). The total carbon input is calculated according to the dry matter content and carbon content of each manure type (American Society of Agricultural Engineers (ASAE), 2005; University of California Cooperative Extension, 2009). Due to limited data available in the USDA database, the manure application rate is not available for all states, so we aggregated the application rates from the state level to the agro-ecological zone (AEZ) level (**Figure 3**) to better represent regional distribution. The yields for corn (**Figure 4a**), soybean (**Figure 4b**) and rye (**Figure 4c**) are at county-level, and the manure application is at AEZ level (**Figure 4d**).

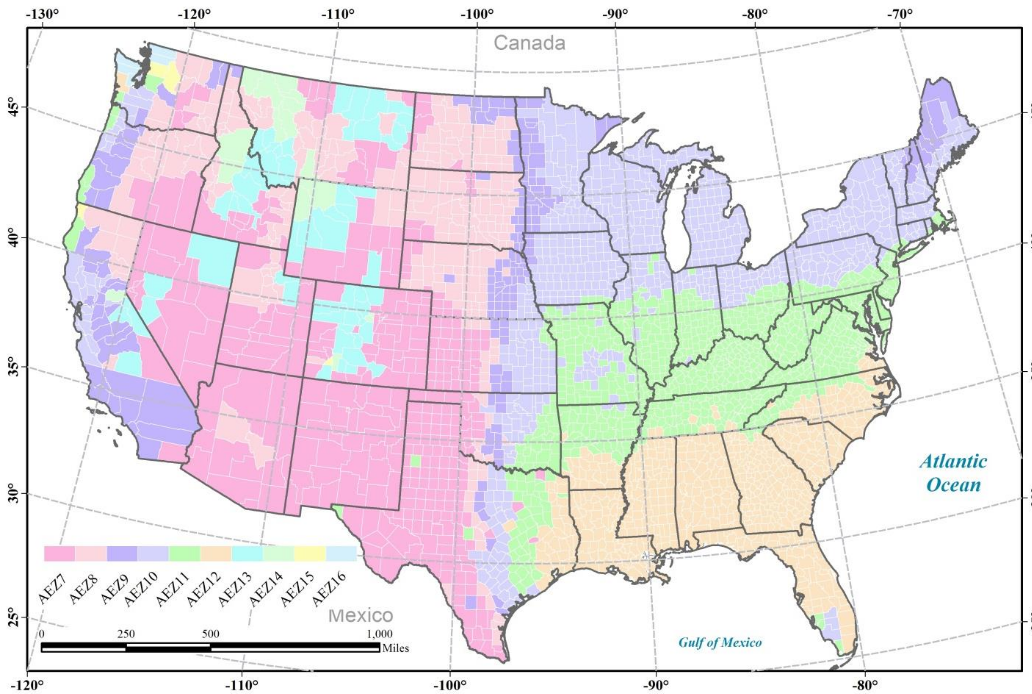

Figure 3. The modeling spatial boundaries in the conterminous U.S., with resolution at county-, state-, AEZ- and national levels.

Spatially explicit data describing soil types and climate are also important SOC model inputs. Soil texture data from the Harmonized World Soil Database (HWSD) (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012) and climate data (e.g. temperature and precipitation) based on National Oceanic and Atmospheric Administration (NOAA) data (NOAA, 2015) are organized at county-level. More information on model inputs can also be found in Kwon *et al*. (2013) and Qin *et al*. (2015).

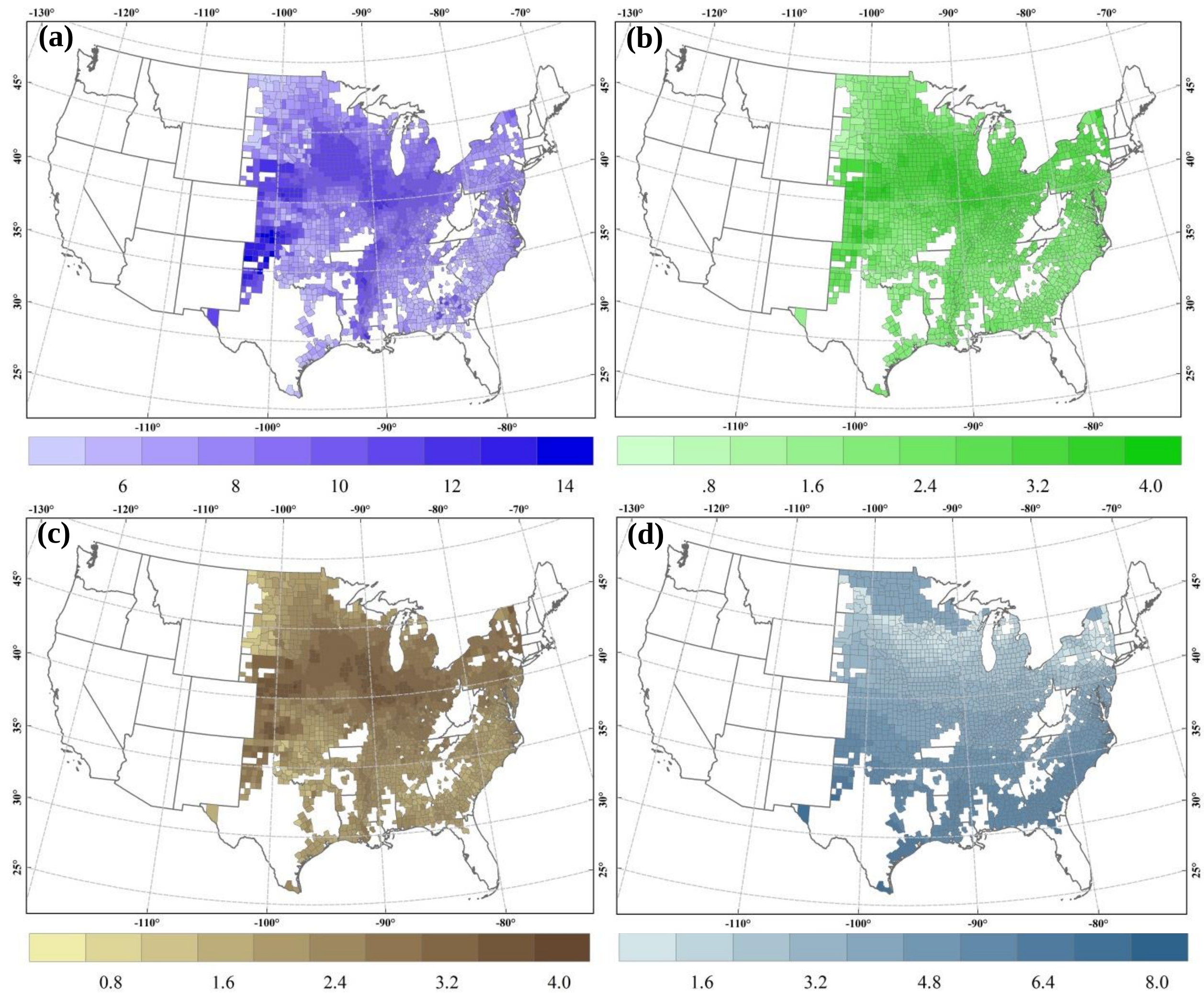

Figure 4. Spatially explicit data inputs of (a) corn yield, (b) soybean yield, (c) rye yield and (d) manure application. The county-level yields (t ha^{-1}) for corn, soybean and rye are for year 2011, and the manure application rates (t C ha^{-1}) are averaged data at AEZ level.

3.3 SOC Sequestration Rate

In total, 42 scenarios (21 LMC × 2 yield scenarios) are included in the model runs for each county. For each scenario, the SOC sequestration rate (SOC_r, t C ha^{-1} yr^{-1}) is calculated as the annual SOC change over the LMC period (2011-2040), that is the difference between the final (2040) and initial SOC content (2011) divided by the 30-year time period (T) (**Equation 1**). Particularly, for scenarios with manure application, the final and initial SOC content is averaged over four years (2037-2040 vs. 2008-2011) to account for the variance of SOC changes over manure application cycle.

$$SOC_r(t\ C\ ha^{-1}yr^{-1}) = {(SOC_{final} - SOC_{initial})}\Big/{T}$$

(**Equation 1**)

Note that SOC emissions ((Mg C ha^{-1} yr^{-1}), indicating CO_2 emission due to SOC change, is calculated as the opposite of SOC_r which suggests CO_2 being sequestered in soil. Example cases are provided in Section 7 for demonstration.

In general, the national level SOC change results suggest that the application of cover crop and manure in the systems with 30% stover removal could maintain or even increase the SOC to the levels where no stover is removed, regardless of tillage practices. If more corn stover is removed (60%), the SOC level may decrease relative to corresponding cases with 30% removal. Even at this higher removal rate, SOC can be maintained in some scenarios, such as those with cover crop adoption and those with manure application under no till.

4. EXPANSION OF GREET TO INCLUDE ENERGY AND GHG BURDETS ASSOCIATED WITH LAND MANAGEMENT PRACTICES

This section describes the second element of estimating life-cycle GHG emissions of biofuels produced from corn grain and corn stover with cover crops or manure application and the energy and GHG intensity of the two agricultural practices. Section 4.1 describes the development of these parameters for cover crops; Section 4.2 covers this topic for manure application.

4.1 Cover Crops

For this analysis, cover crops are planted after the corn phase of the rotation. The amount of seed used depends on the application method (i.e. grain drilled or broadcast). Rye can be planted with a grain-drill or by broadcasting. For broadcasting, seed requirements range from 20 – 160 lb ac^{-1} (SARE, 2012), while grain-drilled seeding is 10 – 120 lb ac^{-1} (SARE, 2012; Plumer *et al.*, 2013). Energy consumed during seed production was excluded from this analysis because it has been shown elsewhere to be a minor contributor to biofuel life-cycle GHG emissions (Landis *et al.*, 2007).

Broadcasting can be used if there is adequate moisture because rye needs rain for germination (University of Vermont Extension, 2006; Plumer *et al.*, 2013). Using a grain-drill for planting makes successful germination much more likely (Plumer *et al.*, 2013). For this analysis, diesel consumption comes from a study that investigated planting rye cover crops with a grain drill (Hanna, 2014). Hanna (2014) developed four different estimates of diesel consumption during cover crop planting (**Table 2**) based on information about the planting equipment including the engine gear ratio and whether the tractor front wheel drive was engaged during planting. We adopted the average of these four estimates (0.47 gal ac^{-1} at 128,540 Btu gal^{-1} of diesel) as the basis of the rye planting energy intensity in GREET. We assumed the cover crop does not consume any fertilizer and does not alter the N, P, or K content of the soil.

In this land management scenario, there is no intention to harvest the rye cover crop. It should be killed 10 – 14 days before planting the soybean crop (Kaspar *et al.*, 2007). If it is terminated too close to the planting date, crop yields can be affected (SARE, 2012). The rye can be killed by mowing or through herbicide application. The latter technique is recommended because it is less expensive (SARE, 2012) and so we have adopted it. In GREET, we use the average of typical herbicide application rates of 1.2 – 1.5 lb of glyphosate ac^{-1} (Plumer *et al.*, 2013), at 1.35 lb of glyphosate ac^{-1}. GREET does not have energy and material flow information for glyphosate; instead we use GREET material and energy intensity data for herbicides applied for corn production. For corn, a 31.2%, 28.1%, 23.6%, and 17.1% mixture of atrazine, metolachlor, acetochlor, and cyanazine are applied, respectively. We assume the same mix percentage for rye cover crops.

Table 2. Diesel consumption for planting rye cover crop based on varying engine gear ratio and whether the front wheel drive was engaged (Hanna, 2014)

Seeding type	Diesel consumption (gal ac^{-1})	Comments
Grain-drill	0.56	Gear/engine rpm B4/2150
Grain-drill	0.39	Gear/engine rpm C2/1900
Grain-drill	0.49	Front wheel drive disengaged
Grain-drill	0.46	Front wheel drive engaged

An important issue to consider in this analysis is how the addition of the cover crop will affect overall N_2O emissions from the agricultural system. No nitrogen-containing fertilizer is added to the soil to promote cover crop growth so there are no additional N_2O emissions from fertilizer. The cover crop will uptake N from the soil as it grows and will emit N_2O as it decays. The influence of this cycle on N_2O emissions is unclear, especially if temporal considerations are taken into account. For example, the literature suggests that soil emits an N_2O emissions pulse during the spring thaw (Wagner-Riddle & Thurtell, 1998; Wagner-Riddle *et al.*, 2007). These emissions depend on numerous factors, including soil temperature, soil water content, and mineral nitrogen content (Wagner-Riddle *et al.*, 2007). The rye cover crop’s nitrogen uptake may lower the N_2O emissions pulse. This effect could offset some or all of N_2O emissions from the cover crop’s decay. Rye cover crops, however, may not affect the total net N_2O emissions from a field at all (Parkin & Kaspar, 2006; Jarecki *et al.*, 2009). For our analysis, we conservatively assume that the rye cover crop’s nitrogen uptake does not reduce the spring N_2O pulse and include N_2O emissions from the cover crop’s decay. N_2O emissions associated with cover crop adoption are then estimated using the GREET default N_2O conversion rate of 1.525% of the N in the cover crop as determined in Wang *et al.* (2012). This rate includes both direct and indirect

N_2O emissions and is dependent upon the nitrogen content of the rye cover crop, which was calculated as the sum of the above- and below-ground nitrogen contents of 0.005 and 0.011 t N t^{-1} dry cover crop (de Klein *et al.*, 2006), respectively. Further, we use a rye cover crop yield of 3 dry t ha^{-1} based on the CCLUB national-level average yield, which is determined from county-level yields (Feyereisen *et al.*, 2013).

4.2 Animal Manure

Determining the material and energy inputs for animal manure is more complex than determining these parameters for cover crops. Manure is only applied every other corn planting season and as a result, energy consumption and nutrient application values are divided by two. In the following subsections, we also consider the boundary of our analysis and which unit operations for manure management to consider, the amount of nutrients applied to the soil, energy consumption for manure utilization, and N_2O emissions from application.

4.2.1 Scope of analysis

An important consideration for animal manure is the boundary for life-cycle modeling. To determine this boundary, we consider all the unit operations involved in manure management. The method to manage this waste is dependent on the consistency of the manure (USDA, 1992). It can be a liquid, slurry, or a solid, defined by a solids content of <10%, 10 – 20%, or >20%, respectively. The type of animal and their diet will determine into which manure categories the animal's manure fits. Processes for dealing with solid waste have low equipment costs, but require more labor, while liquid waste management can be automated. There are four main unit operations for manure management – collection, storage, and treatment/utilization. The first operation, collection, removes the manure from the ground. Solid manure can be collected with a scraper or front end loader, while liquid and slurry manure can be pumped. Once the manure is collected, it can be stored, allowing the waste to be dealt with at a desired time (USDA, 1992). Solids are stored in ponds or buildings. Liquid and slurry manure is pumped through pipelines into a storage ponds, lagoons or tanks (USDA, 2009a).

After the manure is collected, it can either undergo treatment or utilization. The aim of treatment is to reduce levels of nutrients, pathogens, and other pollutants and contaminants in mature (USDA, 1992). Primary treatment involves dewatering, solid/liquid separation, and settling basins (USDA, 2009a). Secondary treatment technologies that further reduce levels of nutrients, pathogens, and other manure components are lagoons (aerobic or anaerobic) and compositing. Manure can be used as a soil amendment either on or off the farm. Using the manure near the point of generation reduces transportation costs (USDA, 2009a). Depending on the type of waste, tank wagons, dump trucks or box/open spreaders can transport manure off-site (Laguë & Roberge, 2005; USDA, 2009a).

As an alternative to manure treatment, manure can be put to beneficial use. For example, manure can be used as a soil amendment to add carbon, nitrogen, and other nutrients to soils. Manure can also be anaerobically digested to produce biogas, a source of energy, although this use is less common (USDA, 1992, 2009), but with increased interest. Manure can be applied to land by broadcasting, injection or spraying through irrigation systems (USDA, 1992; Laguë & Roberge, 2005; Lupis *et al.*, 2012). During broadcasting, the animal waste is spread on the surface of the field. The manure can also be injected into the soil through tilling (Laguë & Roberge, 2005), which reduces surface runoff (Lupis *et al.*, 2012). Injection is more expensive than broadcasting, but because the manure is put directly into the soil, there is a lower nutrient loss due to runoff or volatilization (Lupis *et al.*, 2012). The application of manure can reduce the demand for conventional fertilizers in cropping systems. Application rates on corn fields are higher than on fields producing other crops because corn has a high nitrogen demand, which is the limiting factor for the application rate (USDA, 2009a). Conversely, manure application rates to fields producing soybeans are determined by the phosphorus requirements of this crop.

The unit operations for managing manure through land application are summarized in **Figure 5**. Activities can be classified as on or off the corn-producing farm. For our analysis, the system boundary starts at the animal farm gate, meaning we do not consider off-corn-producing farm activities but consider only the energy consumed in transporting and applying the manure. One underlying reason for this choice is that the manure will be generated and handled in a manner consistent with existing practice regardless of use of manure as a soil amendment. In our analysis, we also consider the benefits of manure application in nutrient reduction for corn production and stover management. Currently, we do not take into account what direct farming energy consumption and emissions would be if manure were not applied to corn fields but treated or used in other applications.

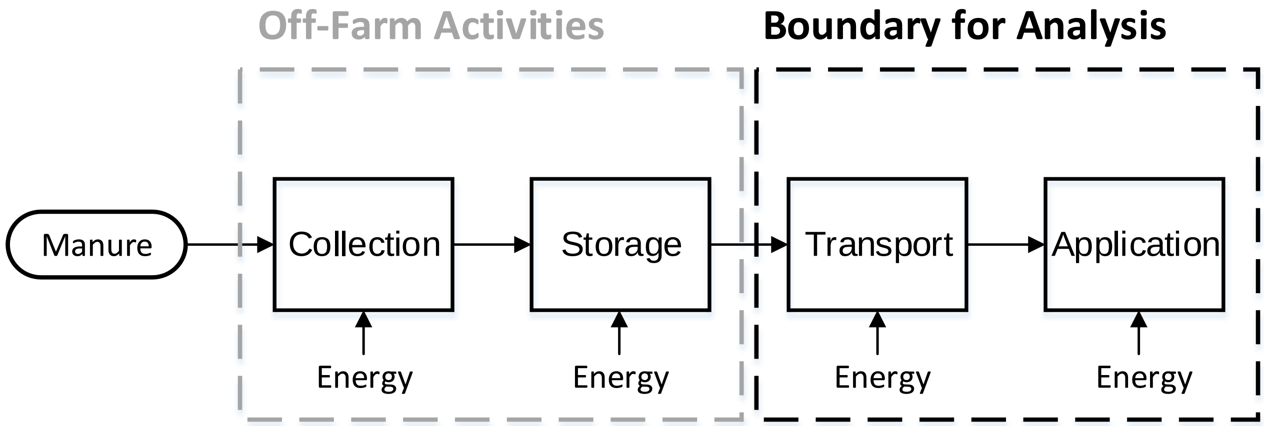

Figure 5. Boundary diagram for manure application in farms.

4.2.2 Application mass and nutrients

The USDA ARMS Farm Financial and Crop Production Practices Database contains manure usage data that informed our modeling of manure application (USDA, 2014). The database contains data for manure applied to various commodity crops, but we used data for manure application in corn agriculture because we are evaluating corn growth and the manure may be spread before or after this growth. The survey contains both state and national level survey information on the type of manure applied, application amounts, and application methods. Although we used AEZ-level manure application rates in soil carbon modeling, we use the national average rate in GREET, which is typically used for national level analyses. It is possible for users to enter a specific manure application rate to investigate the influence of this parameter on results. The manure application rate affects the nitrogen balance of the analysis, influencing nitrogen fertilizer demand and N_2O emissions. The latest survey year available in the database is 2010. In that year, the national level-manure application rate was 15.7 t ac^{-1}. We divide this value by two when entering it into GREET for subsequent calculations because manure is only applied every other corn planting during the 30 year modeling horizon. The share of manure application by animal type is presented in **Table 3**. Also available in the table is the amount of nitrogen and phosphorus that the manure contains that is available for crops (Kellogg *et al.*, 2000). These values are not the amount of nutrients excreted from the animals, but rather the amount that would remain in the manure after collection, storage, treatment and transfer. Although manure also contains potassium, we were unable to locate similar quality data for the potassium content of manure or the amount of potassium in manure that is available at the time of manure application on the field. We used breeding hog manure composition data from Kellogg et al. (2000) for swine manure in GREET. Similarly, milk cow data were adopted for dairy cow manure, fattened cattle data for beef cattle manure, and broiler chicken data for chicken manure. The nutrient values for each animal waste were then multiplied by the share of application. These values were summed for each nutrient to arrive at 1,218 and 1,446 g t^{-1} manure of N and P_2O_5, respectively.

Table 3: Shares of manure used for corn farming (USDA, 2014) and the amount of nutrients available at farms (Kellogg *et al.*, 2000)

Manure type	Share of application	Available nitrogen content (g N t^{-1} manure)	Available phosphorus content (g P_2O_5 t^{-1} manure)
Swine	24.3%	640	1,456
Dairy cow	42.3%	975	857
Beef cattle	21.6%	996	1,486
Chicken	11.9%	3,651	3,436

4.2.3 Transportation energy

Manure transportation distances were taken from the ARMS database (USDA, 2014). This resource provides values for transportation onsite and offsite animal farms, as well as a total travel distance. The total travel distance of 0.367 miles was used. Because this value includes offsite transport, we assume manure is transported by trucks, as is common practice (USDA, 2009a, p. 10). The diesel consumed during transportation was determined from two sources (Lopez-Ridaura *et al.*, 2009; Lenkaitis, 2012). Lopez-Ridaura *et al.* (2009) reported that 2.49 L diesel was needed to transport a cubic meter of manure a distance of 39.2 km. This value was converted to an energy per mile basis by using a swine manure density of a 8.3 lb gal^{-1} (Schmitt & Rehm, 2002) and the lower heating value (LHV) of diesel for non-road engines at 128,450 Btu gal^{-1} in GREET. The transportation energy per mile was 3,164 Btu t^{-1} manure mi^{-1}. Lenkaitis (2012) presented information on dairy manure transportation by truck over a distance of 5,000 ft based on manufacturer specifications. Over the course of a day, 72,000 gal of manure was transported and 40.7 gal of diesel was consumed. This value was also converted to an energy per mile basis using a dairy manure density of 8.7 lb gal^{-1} (Houlbrooke *et al.*, 2011) and the LHV of diesel. The transportation energy was 17,669 Btu t^{-1} manure mi^{-1}. The average of these two values, was adopted as the energy intensity of manure transportation, 10,000 Btu t^{-1} manure mi^{-1} and adopted for all manure types.

4.2.4 Application energy

The energy consumed in applying the manure to the field is dependent on the application method. Farmers apply manure to fields with several application methods including broadcast (spreading) with or without incorporation with tillage, direct injection, or irrigation spraying. The ARMS database contains data about which of these methods were used to apply manure to corn fields in 2010 (**Table 4**). Broadcasting is the most common application method, followed by direct injection. The share of manure applied through spraying with irrigation water was so small that we excluded this technique. We assume that when manure is applied via broadcasting with incorporation, the farmer is applying the manure before corn planting. The tilling associated with the manure incorporation would essentially serve as the tillage step in a conventional till scenario. The energy consumption associated with corn agriculture is based on survey data that reports the amounts and types of energy farmers use in corn farming (Wang *et al.*, 2014). The data does not break out energy consumption by activity type, so we are unable to decrease the total energy consumption in a no-till scenario. Rather, we hold constant the farming energy intensity regardless of tillage scenario. For this reason, even in a no-till scenario, the energy associated with manure application is implicitly accounted for in our analysis. We will continue to seek reliable data on energy consumed during tillage. With the broadcast percentages summed together and the irrigation percentage neglected, we arrive at broadcasting and direct injection percentages of 73.7% and 26.3%, respectively.

Table 4. Share of manure application method at the national level for corn determined by (USDA, 2014).

Application method	Share of application
Broadcast (no incorporation with tillage)	42.8%
Broadcast (incorporation with tillage)	30.7%
Direct injection	26.2%
Irrigation spray	0.4%

We used data from several studies to estimate energy consumed during manure application for the broadcasting and direct injection techniques. For broadcasting, four different studies (that did not consider incorporation) provided application energies (McLaughlin, 1997; Wiens *et al.*, 2008; Hamelin *et al.*, 2011; Aguirre-Villegas *et al.*, 2014). All energy intensity values were put on a per area basis. Wiens *et al.* (2008) estimated the energy consumed in applying swine manure either once or twice a year, and by drag hose or slurry wagon. The energy consumption for once a year application by drag hose and slurry wagon were 2,048 and 2,138 MJ diesel ha^{-1}, respectively. For biannual application, the energy consumption by drag hose and slurry wagon were 2,498 and 2,162 MJ diesel ha^{-1}, respectively. Aguirre-Villegas *et al.* (2014) estimated the energy required to broadcast dairy cow manure based on an economic model for applying liquid manure (Hadrich *et al.*, 2010). Their application energy intensity of 1.42 kg diesel t^{-1} manure was converted to an energy-per-area basis by using the density and LHV for diesel of 128,450 Btu gal^{-1} in GREET, as well as the manure application rate used for our calculations (see section 4.2.2). McLaughlin (1997) determined the energy consumed in both manure broadcasting and direct injection based on field studies. Two types of equipment were used, a 7,000 L Husky tanker and an 11,400 L Houle tanker. McLaughlin considered two manure application speeds, 4.5 and 6.3 km hr^{-1} for two different brands of equipment, Husky and Houle. The energy consumed in applying manure was measured as 11.4, 7.8, 16.3, and 10.6 L ha^{-1} for the Husky 4.5, Husky 6.3, Houle 4.5 and Houle 6.3 spreaders, respectively. Hamelin *et al.* (2011) reported the energy consumed in applying swine and dairy waste at 0.34 kg diesel t^{-1} manure based on communication with industry. The density and LHV of diesel, as well as the manure application rate, were used to convert this value to an energy per area basis. The manure application energy consumption values in *Btu diesel* ac^{-1} from all four studies are summarized in **Table 5**.

For direct injection, three different studies were used to determine the application energy (McLaughlin, 1997; Lopez-Ridaura *et al.*, 2009; Griffing *et al.*, 2014). McLaughlin (1997) investigated two types of direct injection equipment (called conventional and modified), along with the same type of equipment and speeds as for broadcasting. Griffing *et al.* (2014) determined the energy requirement for swine manure injection during a field study. They reported the energy required to pump and inject the manure as 9 and 23 L diesel ha^{-1}. The final study (Lopez-Ridaura *et al.*, 2009) reported that 0.8 L diesel m^{-3} manure was consumed in the application of swine manure based on information in a trade publication. This value was converted to an energy-per-area basis using a swine manure density of 8.3 lb gal^{-1} (Schmitt & Rehm, 2002) and the LHV of diesel.

To calculate the energy intensity of each manure application technique, we first halved all energy consumption values to account for the rotation. Then, we averaged these values. GREET parameters for energy consumed in manure broadcasting and direct injection is 221,366 and 120,435 Btu ac^{-1}, respectively.

Table 5. Energy consumed during manure application broadcasting and direct injection.

Animal type	Application energy (Btu diesel ac^{-1})	Data source	Comments
Broadcast			
Swine	785,586	(Wiens *et al.*, 2008)	Drag hose – once yearly application
Swine	958,230	(Wiens *et al.*, 2008)	Drag hose - twice yearly application
Swine	820,222	(Wiens *et al.*, 2008)	Slurry wagon – once yearly application
Swine	829,274	(Wiens *et al.*, 2008)	Slurry wagon – twice yearly application
Dairy cow	904,681	(Aguirre-Villegas *et al.*, 2014)	Estimation based on economic model by (Hadrich *et al.*, 2010)
Not specified	156,547	(McLaughlin, 1997)	Husky – broadcasting at 4.5 km hr^{-1}
Not specified	107,111	(McLaughlin, 1997)	Husky – broadcasting at 6.3 km hr^{-1}
Not specified	223,834	(McLaughlin, 1997)	Houle – broadcasting at 4.5 km hr^{-1}
Not specified	145,561	(McLaughlin, 1997)	Houle – broadcasting at 6.3 km hr^{-1}
Swine and dairy Cow	216,614	(Hamelin *et al.*, 2011)	Industry communication
Direct injection			
Swine	439,429	(Griffing *et al.*, 2014)	Fuel consumption from a field study (includes pumping)
Swine	388,953	(Lopez-Ridaura *et al.*, 2009)	Literature value for land application
Not specified	177,145	(McLaughlin, 1997)	Husky – conventional injector at 4.5 km hr^{-1}
Not specified	129,082	(McLaughlin, 1997)	Husky – conventional injector at 6.3 km hr^{-1}
Not specified	185,384	(McLaughlin, 1997)	Husky – modified injector at 4.5 km hr^{-1}
Not specified	134,575	(McLaughlin, 1997)	Husky – modified injector at 6.3 km hr^{-1}
Not specified	276,016	(McLaughlin, 1997)	Houle – conventional injector at 4.5 km hr^{-1}
Not specified	196,370	(McLaughlin, 1997)	Houle – conventional injector at 6.3 km hr^{-1}

4.2.5 Nitrous oxide (N_2O) emissions

Nitrous oxide (N_2O) emissions are released from the soil when manure is applied to farm fields. Once applied, N_2O is released periodically throughout the year (Fronning *et al.*, 2008; Webb *et al.*, 2010). These emissions are dependent on manure application methods, soil moisture, animal type, and time of day and year applied (Velthof *et al.*, 2003; Webb *et al.*, 2010). Incorporation of the manure into the soil reduces N_2O emissions compared with surface spreading (Webb *et al.*, 2004, 2010). Liquid swine manure can have high emissions (up to 13.9% of the nitrogen lost as N_2O) partially due to a high inorganic nitrogen content (Velthof *et al.*, 2003). Comparatively, poultry and cattle emissions can see losses up to 1.9% and 3.0%, respectively. For our analysis we consider a mixture of manure types based on national data. The Intergovernmental Panel on Climate Change (IPCC) provides direct and indirect emission factors for animal manure (de Klein *et al.*, 2006). We used the default direct emission factor for manure from cattle, poultry, and swine applied to managed soils at 0.02 kg N_2O-N kg^{-1} N. The indirect emission factor considers the volatilization of N as NH_3 and NO_x, and leaching/runoff. The indirect emission factor due to volatilization was found by multiplying the fraction of manure lost (0.2 kg NH_3+NO_x kg^{-1} N) by the nitrogen volatilization and re-deposition emission factor of 0.01 kg N_2O-N/kg NH_3+NO_x. This gives a volatilization emission factor of 0.002 kg N_2O-N kg^{-1} N. For leaching/runoff, the emission factor is found by multiplying the fraction of manure lost (0.3 kg N kg^{-1} N) by the leaching/runoff emission factor at 0.0075 kg N_2O-N kg^{-1} N. This gives a value of 0.00225 kg N_2O-N kg^{-1} N. The sum of the direct and indirect emission factors give the total N_2O emission factor due to manure application at 0.02425 kg N_2O-N kg^{-1} N. This factor is multiplied by the nitrogen content of manure, which was determined in section 4.2.2. Total N_2O emissions from a farm field with manure applied depend both on the application rate of this OM input and the application rate of conventional fertilizer, which also produced direct and indirect N_2O emissions. Section 5.1 discusses how we account for reduced conventional fertilizer demand in scenarios with manure application.

5. LCA METHODOLOGY CONSIDERATIONS

In this section, we review the data and methodology that underpins the expansion of the GREET fuel cycle model (GREET1) to include the land management techniques of manure application and cover crop adoption. Both of these techniques require additional agricultural activities that consume energy and influence the life-cycle GHG emissions of biofuels produced from feedstocks grown on lands that experience these techniques. One key methodology choice is how we allocate the material and energy flows, as well as SOC changes, between corn grain and stover ethanol. We also discuss how we treat SOC changes while considering the current land management practice, as well as a new land management practice (cover crops or manure).

5.1 Allocation of Material and Energy Consumed in the Implementation of Land Management Practices

An important motivation of this study was the consideration that SOC levels will be lower in corn systems that experience stover removal than in systems that do not. Even if SOC levels are maintained, this loss of carbon compared to an alternative scenario in which no stover is removed could be considered a carbon debt. For this reason, the key result we seek to calculate is life-cycle GHG emissions of stover ethanol.

Two options exist for calculating these emissions. We can look at stover ethanol as an isolated product in which this fuel bears all the burdens and the benefits of using land management to boost SOC levels in what is called a marginal analysis approach. In this case, all energy consumed to implement the land management techniques are assigned to the stover (e.g. energy consumed in manure application). Additionally, gains in SOC attributable to the land management practice are also assigned to stover. Furthermore, when nitrogen levels in applied manure are sufficiently high to offset not only the demand for supplemental fertilizer required to replace nutrients in the removed corn stover but also the demand for conventional fertilizer, corn stover ethanol receives a credit for reduced fertilizer production and reduced fertilizer N_2O emissions. In a marginal analysis scenario, we calculate life-cycle GHG emissions of only stover ethanol; the emissions for corn ethanol will be unchanged from the GREET default values.

Marginal allocation is a logical approach to analyze adoption of cover crops as a land management technique because cover crops are planted after stover removal. However, manure can be applied at various times throughout the year and are can be used to reduce the conventional fertilizer demand (USDA, 1992). Moreover, a marginal analysis would be more relevant if corn stover removal caused more farmers to adopt manure application, tapping an excess of manure available from cattle, swine, and poultry farms. To assess the relevance of a marginal analysis approach for the manure application land management technique, we evaluated the amount of manure that is currently applied to crops, assessing whether a substantial amount of manure remains to be used as an OM input.

5.1.1 Current manure use and marginal allocation justification

The total dry mass of manure produced by broiler chickens, turkeys, layers, beef cattle, swine, and dairy cows for 2005 is summarized in Table 6 (Halden & Schwab, undated). The total dry mass produced was 84 million Mg. To arrive at a wet mass the dry mass was multiplied by the moisture content of that type of manure (ASAE , 2005). The total mass of wet manure produced was 766 million Mg, which converts to 840 wet tons.

Table 6. Manure produced in 2005.

Manure type	Dry mass* (dry Mg yr^{-1})	Moisture content† (%)	Wet mass (wet Mg yr^{-1})
Poultry	11,300,380	74%	43,463,000
Turkeys	1,824,982	74%	7,019,162
Layers	2,758,313	75%	11,033,252
Beef cattle	36,504,180	92%	456,302,250
Swine	2,343,470	90%	23,434,700
Dairy cows	29,171,691	87%	224,397,623

* Halden & Schwab (2008)

† ASAE (2005)

The amount of manure used for crops was taken from the ARMS database (USDA, 2014), **Table 7**. Each crop is surveyed in different years, so for this analysis the latest years (2003-2013) were used. It is assumed there would not be a large difference in the amount of manure applied between the years. The database provided the total crop planted area, the percent treated with manure, and the amount applied by area. These three values were multiplied together to arrive at the total manure application for each crop. The total mass applied was estimated at 240 million wet tons. Compared with the total amount of manure produced, only 28% of the manure was applied to crops. Of that, 83% went to corn.

Another use for manure is energy production (USDA, 2009a; Han *et al.*, 2011). As of 2008, 91 commercial dairy farms used anaerobic digesters, with 64 additional farms in planning stages for producing this type of energy (USDA, 2009a). There were also 17 hog farms with digesters. These facilities utilized manure from 2.9% and 0.5% of all dairy cows and hogs, respectively. As of March 2015, there were 247 digesters in operation, 202 of which were from dairy cows (EPA, 2015). The amount of hog manure digesters also increased to 39. Even though the spread of waste-to-energy projects may increase the use of digesters in the future, residues from anaerobic digesters will still be available as manure fertilizer, although digester residue carbon content is lower than that of manure carbon content. Overall, we determined that using manure as a soil amendment after stover removal would not compete with current manure use. Therefore marginal allocation is a justifiable analysis method.

Table 7.Manure applied to crops based on the latest survey years (USDA, 2014).

Crop	Survey year	Planted area(ac)	Treated area (%)	Application amount (t ac^{-1})	Total manure application (wet t yr^{-1})
Corn	2010	82,000,000	16	16	200,000,000
Soybean	2012	74,000,000	3.2	7.7	18,000,000
Cotton	2007	10,000,000	3.7	2.4	900,000
Rice	2013	2,500,000	1.8	1.9	84,000
Barley	2011	2,300,000	8.0	15	2,800,000
Spring wheat	2009	13,000,000	1.1	12	1,900,000
Winter wheat	2009	37,000,000	2.4	9.1	8,000,000
Durum wheat	2009	2,200,000	1.2	2.4	62,000
Sorghum	2011	5,000,000	2.6	7.7	1,000,000
Oats	2005	3,100,000	14	11	4,600,000
Peanuts	2013	993,000	8.3	1.7	140,000
Barley, feed	2003	1,100,000	11	13	1,700,000
Barley, malt	2003	3,700,000	2.0	7.1	520,000

5.1.2 Additional allocation methods

Furthermore, corn grain and corn stover are produced from the same land area and can be considered as an integrated system. For example, all the nutrients from manure are not immediately available to crops and later rotations of corn could benefit from the additional nitrogen and phosphorus available in the soil (Laguë & Roberge, 2005). Adopting an allocation approach to analyze this grain-stover system, we can divide the burdens and benefits of land management techniques between these two feedstock sources and final fuel yields on the basis of their energy (energy allocation, in terms of *g* CO_2*eq* MJ^{-1} *biomass*) or mass (mass allocation, in terms of *g* CO_2*eq* Mg^{-1} *dry biomass*) contents. For these allocation methods, energy and materials consumption are based on a previous GREET update (Wang *et al.*, 2014). In this integrated scenario, we produce life-cycle GHG emissions results for both fuels either separately or as a single gallon of ethanol.

5.2 SOC Changes Due to Land Management Practice

Another methodology issue concerns how to treat SOC changes. In our previous work looking at LUC GHG emissions, we adopted a technique in which we calculated a soil organic carbon emission factor based on the difference between the final and initial soil carbon stocks divided by the time horizon of the analysis (**Equation 1**). This approach was taken because the final land use distribution, as determined through economic modeling, was estimated only for the case in which the economy had experienced a biofuel shock and no alternative land use distribution was established as a baseline in which the economy did not experience this shock (Dunn *et al.*, 2014). In the present analysis considering changes in land management practices, the baseline scenario, the continuation of the current land management practice, is evident. For this reason, we calculate the SOC emission factor with (**Equation 2**) which accounts for the difference in SOC levels between a system that has experienced a transition in land management as compared to a system that has not.

$$\Delta SOC_r(Mg\ C\ ha^{-1}yr^{-1}) = SOC_{r,selected\ management} - SOC_{r,conventional\ management}$$

(**Equation 2**)

6. CCLUB AND GREET CONFIGURATION

This section discusses the changes that were made to CCLUB and GREET to address land management change scenarios.

6.1 CCLUB

6.1.1 CCLUB overview

CCLUB is a GREET module originally designed to calculate LUC GHG emissions for ethanol produced from corn grain ethanol and cellulosic ethanol from corn stover, *Miscanthus*, and switchgrass (*Panicum vigatum* L.) (Dunn *et al.*, 2014). The module combines LUC data produced from an economic model (the Global Trade Analysis Project, or GTAP, in particular), SOC emission factors developed with the surrogate CENTURY model (and international LUC emission factors from other sources), and other OM input yields (i.e., cover crop) or application rates (i.e., manure) to calculate domestic and international LUC GHG emissions. It enables users to choose a variety of ethanol pathways under different land use change scenarios (Dunn *et al.*, 2014).

CCLUB has been expanded to enable users to estimate SOC changes from the land management changes described in this report. In CCLUB, the LMC SOC modeling results are included in the "***C-Database***" tab, and the LMC GHG emissions calculation is located in the "***LMC Scenario & Results***" tab.

6.1.2 Estimating LMC GHG emissions

The SOC sequestration rates are first calculated at the county level, and then averaged (arithmetic mean) to either the AEZ or national level (**Figure 6**). Some AEZs have no counties with corn-soybean production. For these AEZs, the SOC sequestration rate is presented as "NA" or "not available". With SOC sequestration rates at county-, AEZ-, and national levels as inputs, CCLUB is capable of calculating the corresponding GHG emissions associated with SOC changes in each LMC scenario selected (**Table 8**). In general, the LMC GHG emissions are calculated as the SOC change per unit of biomass or energy over time T (**Equation 3**). The SOC change is the difference between the SOC sequestration rate in the selected land management scenario relative to a conventional management scenario (**Equation 2**). The conventional land management scenario varies based upon the spatial scale chosen (**Table 8**). In all cases, under the conventional scenario, no stover is harvested. At the national level, conventional tillage is defined as the conventional management scenario; even though the adoption of conservation tillage (in one form or another) has been increasing during the past two decades, the conventional tillage practice is still a common tillage technique in the 2000s(USDA, 2012). At the AEZ- and county level, three tillage practices (i.e., CT, RT, NT) are possible to select (**Table 8**). Two yield scenarios (i.e., yield increase and yield constant) are provided in CCLUB in accordance with the yield assumptions in SOC modeling. Calculations in CCLUB assign GHG emissions associated with LMC to corn stover ethanol or corn grain/stover ethanol using marginal or allocation approaches discussed in Section 5.

$$GHG\ emissions_{LMC}(g\ CO_2eq\ Mg^{-1}\ dry\ biomass\ or\ g\ CO_2eq\ MJ^{-1}\ Ethanol) = \left(\Delta SOC_r \times \frac{44}{12} \times T\right) \Big/ Biomass\ or\ energy\ production|\ T$$

(**Equation 3**)

where the change of SOC sequestration rate (ΔSOC_r) is calculated as in **Equation 2**.

Table 8. Land management practices for conventional and selected management scenarios at county-, AEZ- and national levels.

Spatial scale	Land management	Tillage*	Stover removal rate (%)†	OM inputs
National level				
	Conventional Management	CT	0	None
	Selected Management	CT, RT, NT	30, 60	None, cover crop, manure
AEZ or county level				
	Conventional Management	CT, RT, NT	0	None
	Selected Management	CT, RT, NT	30, 60	None, cover crop, manure

*CT, RT, NT indicate conventional, reduced and no tillage, respectively.

†by dry matter.

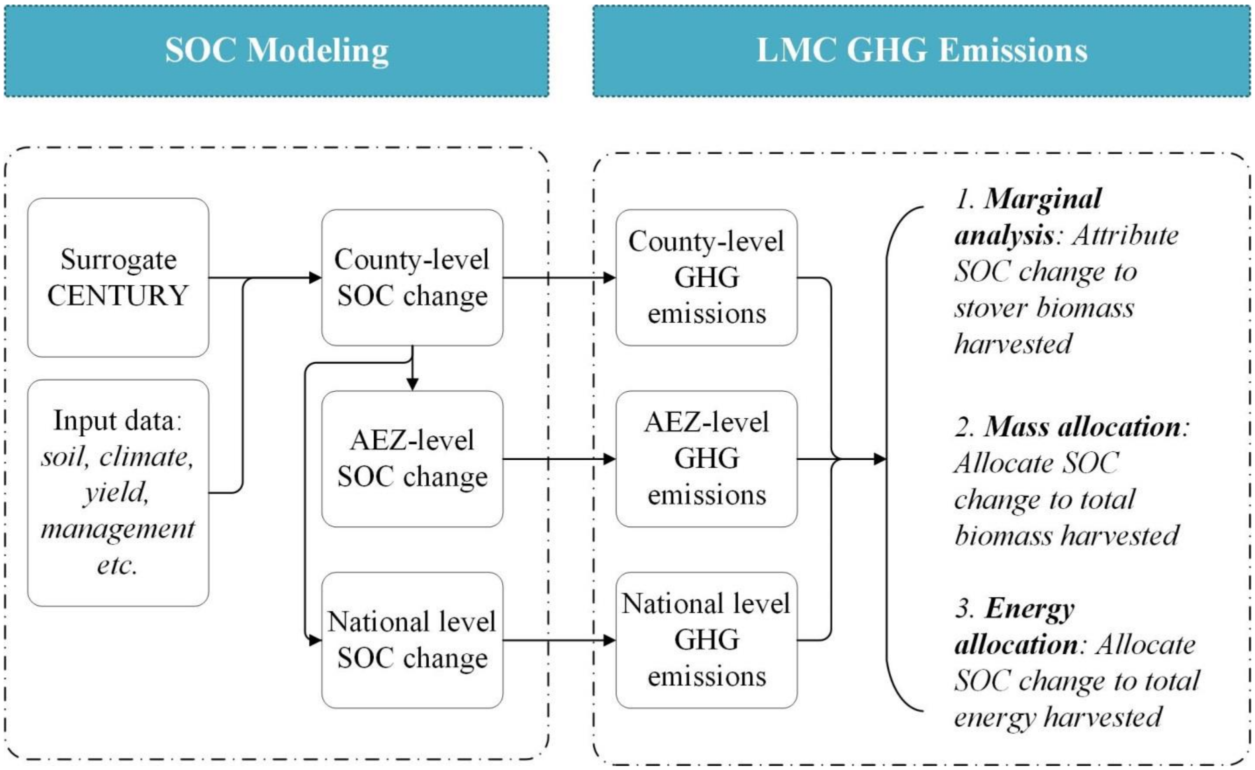

Figure 6. Flowchart of SOC modeling and LMC GHG emissions estimation. SOC is modeled at the county level and aggregated to AEZ- and national levels. Three spatial levels (i.e., county, AEZ and Nation) of GHG emissions are provided in CCLUB.

6.2 GREET

GREET is a life-cycle analysis tool that calculates the well-to-wheel (WTW) GHG emissions, water consumption, and energy inputs for various transportation fuels. GREET includes ethanol produced from corn grain and stover and provides users many analysis options to develop estimates of life-cycle GHG emissions for these fuels. For example, GREET includes different types of corn grain mills (dry and wet) and allows users to choose which types of process fuels are consumed at the mills. GREET includes an option that allows users to model grain and stover ethanol as being produced at an integrated facility that uses combined heat and power from stover ethanol production to reduce the energy requirements for corn ethanol production. This section describes how users can employ GREET to model life-cycle GHG emissions of corn stover and corn grain ethanol that have been grown on farmland that experiences cover crop adoption or manure application as land management techniques.

6.2.1 Inputs tab

A new section called "*8.3.d) Land Management Changes of Farming in Corn/Soy Rotations*" was added to the Inputs tab to accommodate the material and energy inputs associated with implementing the two new land management techniques, cover crop adoption and manure application. In this section, users can select five options for land management, which include the two land management scenarios, corn stover removal rate, yield modeling scenario, tillage type, and allocation method. When a cover crop or a manure LMC scenario is selected, the LUC values are set to zero for reasons explained in section 2.2.1. For cover crops, this section provides the farming energy, herbicide application rate, and relevant N_2O emission parameters. For manure, the application rate, transportation distance and energy, N_2O emission factor, and nutrient amounts are provided. As stated previously, all manure input parameters reflect application once every four years. Therefore application energies and nutrient amounts are halved. Also available in this new section are the national average LMC GHG emission factors as calculated in CCLUB. GREET selects the relevant LMC GHG emission factor based on the five options that users select.

6.2.2 ETOH tab

Energy consumed in cover crop planting or energy consumed in manure transportation and application are added to the corn farming and stover collection energies in the ***ETOH*** tab, while accounting for the allocation method chosen. Additionally, herbicide amounts are added to the calculation of energy consumption and emissions burdens associated with corn grain and corn stover. On this tab, a calculation is carried out to assess the amount by which conventional fertilizer application can be reduced as a result of manure application. Allocated manure nutrients are subtracted from the corn fertilizer and stover supplemental fertilizer requirements. In the case of marginal allocation where we assign all burdens and credits to stover, more nutrients are available in manure than the level of nutrients in fertilizer that would normally be applied to replenish the nutrient content of the removed stover. In some cases, there is an excess of nutrients that would reduce the future corn fertilizer requirement. Any future corn fertilizer reductions results in a credit for stover ethanol production during marginal allocation.

Also included in this tab are N_2O emissions calculations. These emissions are allocated between corn grain and stover, and assigned to the farming/collection N_2O emissions. The LMC GHG emission factors are added to the feedstock emissions for all plant types of corn ethanol, stover ethanol, and the integrated facility production. With all of these changes made to GREET, the user is able to determine the life-cycle impacts of producing ethanol from corn and stover with land management change scenarios.

7. RESULTS AND DISCUSSION

We have selected a few land management scenarios to highlight the effect management changes can have on LMC emissions and the life-cycle GHG emissions of corn grain and corn stover ethanol. We selected a 30% corn stover removal rate, annual crop yield increases, conventional tillage, and either cover crop adoption or manure application and report SOC change and LMC emissions results from CCLUB associated with each allocation method (**Table 9**). For example, in this case, the national level stover LMC emission is -2.3 g CO_2eq MJ^{-1} biomass if cover crop is applied and -0.7 g CO2eq MJ^{-1} biomass if manure is applied (**Table 9**). The LMC emission factors are further used in GREET to estimate life-cycle GHG emissions.

Table 9. Estimated national level SOC and LMC emissions for cases with cover crop or manure application by allocation methods.

Allocation method	SOC emissions (Mg C ha^{-1} yr^{-1}) *		LMC emissions	
	0†	30%‡	Value	Unit
Cover crop				
Marginal analysis	-0.12	-0.17	-198,000	*g CO_2eq Mg^{-1} dry biomass, stover*
Mass allocation	-0.12	-0.17	-42,000	*g CO_2eq Mg^{-1} dry biomass, stover and grain*
Energy allocation	-0.12	-0.17	-2.3	*g CO_2eq MJ^{-1} dry biomass, stover and grain*
Manure				
Marginal analysis	-0.12	-0.13	-61,000	*g CO_2eq Mg^{-1} dry biomass, stover*
Mass allocation	-0.12	-0.13	-13,000	*g CO_2eq Mg^{-1} dry biomass, stover and grain*
Energy allocation	-0.12	-0.13	-0.7	*g CO_2eq MJ^{-1} dry biomass, stover and grain*

*A positive value indicates net carbon loss while a negative value indicates carbon gain.

†Conventional management without corn stover removal.

‡Selected management with 30% corn stover removal.

The WTW GHG emission results for the scenarios in **Table 9** and a baseline scenario in which no land management technique is adopted are presented in **Table 10**. Furthermore, **Table 10** presents results for a combined gallon of ethanol, a gallon of stover ethanol, and a gallon of corn grain ethanol. In every case, we modeled corn grain and corn stover ethanol as being produced at an integrated facility (Canter *et al.*, 2015) to examine results on a per area of land basis. In an integrated facility, heat and electricity produced from lignin combustion in the stover ethanol portion of the facility is divided between grain and stover ethanol. For our analysis, we meet the stover energy demand during ethanol production first and any excess heat and electricity is then used during corn grain ethanol production. When ethanol is treated as a combined gallon, both cover crop adoption and manure application land management techniques reduce life-cycle GHG emissions compared to the baseline case when LUC GHG emissions are excluded.

In the marginal allocation approach while considering LUC, stover ethanol life-cycle GHG emissions decrease notably from 30 g CO_2eq MJ^{-1} g CO_2eq MJ^{-1} in the baseline case, to 17 and 12 g CO_2eq MJ^{-1} for cover crops and manure, respectively. When the energy allocation technique is applied, life-cycle GHG emissions for stover ethanol with LUC decrease from 50 g CO_2eq MJ^{-1} in the baseline case to 49 and 46 g CO_2eq MJ^{-1} for cover crops and manure, respectively. The same trend is also seen for grain ethanol with LUC with a reduction from 52 g CO_2eq MJ^{-1} from the baseline case to 50 g CO_2eq MJ^{-1} for both cover crops and manure. Life-cycle GHG emissions for stover ethanol are higher when energy allocation is applied because corn stover shares a portion of the corn grain farming energy. Correspondingly, the life-cycle GHG emissions for grain ethanol decrease. The influence of land management technique choice is more pronounced for stover ethanol under the marginal approach because the stover ethanol experiences the full benefit of SOC gains. The manure application scenario produces lower life-cycle GHG emissions because, although soil carbon gains are less substantial in this case (**Table 9**), reduced fertilizer demand cuts GHG emissions from the system. **Given the large number of choices available to GREET users to model land management techniques for corn-soybean systems, a wide range of results can be produced that will also vary spatially.** Further analyses will investigate these variations and their drivers and will be described in an upcoming manuscript.

Table 10. WTW GHG emissions for stover and grain ethanol at a 30% stover removal rate, with yield increase over the 30 year rotation, and under conventional tillage.

	LMC with LUC ($g\ CO_2eq\ MJ^{-1}$)			LMC without LUC ($g\ CO_2eq\ MJ^{-1}$)		
	Baseline	Cover crop	Manure	Baseline	Cover crop	Manure
Combined Gallon						
	50	48	47	44	42	42
Marginal Allocation						
Grain Ethanol	55	55	55	47	47	47
Stover Ethanol	30	17	12	31	18	12
Energy Allocation						
Grain Ethanol	52	50	50	44	41	42
Stover Ethanol	50	49	46	51	50	47

Results for cover crops and manure application in **Table 10** are also presented for the baseline and two land management techniques without LUC. For the combined gallon, the GHG emissions decrease by 5 to 6 g CO_2eq MJ^{-1}. Stover ethanol results are only slightly affected by not including LUC. Grain ethanol sees a decrease in the GHG emissions by not including LUC. For both marginal and energy allocation, this equates to 8 to 9 g CO_2eq MJ^{-1}.

Using cover crops and manure as a soil amendment in corn-soybean systems from which stover is removed provides a supplemental nutrient (including carbon) source to soils. As a result, even when accounting for the energy required to implement these land management techniques, grain and stover ethanol can be produced with lower GHG emissions than the baseline with no land management techniques in place.

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