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Key Points:

- Equilibrium SOC varies greatly depending on cropping and management practices
- Fractional factorial design can help attribute contributions of driving forces
- Residue management deserves a balance for carbon sink and biofuel production

Supporting Information:

- Readme
- Figure S1
- Figure S1 caption

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Quantitative attribution of major driving forces on soil organic carbon dynamics

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Abstract Soil organic carbon (SOC) storage plays a major role in the global carbon cycle and is affected by many factors including land use/management changes (e.g., biofuel production-oriented changes). However, the contributions of various factors to SOC changes are not well understood and quantified. This study was designed to investigate the impacts of changing farming practices, initial SOC levels, and biological enhancement of grain production on SOC dynamics and to attribute the relative contributions of major driving forces (CO_2 enrichment and farming practices) using a fractional factorial modeling design. The case study at a crop site in Iowa in the United States demonstrated that the traditional corn-soybean (CS) rotation could still accumulate SOC over this century (from 4.2 to 6.8 kg C/m^2) under the current condition; whereas the continuous-corn (CC) system might have a higher SOC sequestration potential than CS. In either case, however, residue removal could reduce the sink potential substantially. Long-term simulation results also suggested that the equilibrium SOC level may vary greatly ($\sim$5.7 to $\sim$11 kg C/m^2) depending on cropping systems and management practices, and projected growth enhancement could make the magnitudes higher ($\sim$7.8 to $\sim$13 kg C/m^2). Importantly, the factorial design analysis indicated that residue management had the most significant impact (contributing 49.4%) on SOC changes, followed by CO_2 Enrichment (37%), Tillage (6.2%), the combination of CO_2 Enrichment-Residue removal (5.8%), and Fertilization (1.6%). In brief, this study is valuable for understanding the major forces driving SOC dynamics of agro-ecosystems and informative for decision-makers when seeking the enhancement of SOC sequestration potential and sustainability of biofuel production, especially in the Corn Belt region of the United States.

1. Introduction

The terrestrial ecosystems might make a significant contribution to offsetting carbon dioxide (CO_2) emissions from human activities [*Gurney et al*., 2002; *Heimann and Reichstein*, 2008; *Hurtt et al*., 2002; *Le Quéré et al*., 2013; *Pan et al*., 2011; *Schimel*, 1995; *Zhu and Reed*, 2014]. The amount of carbon accumulated in soil is usually greater than that in living vegetation [*Post and Kwon*, 2000], with soil organic carbon (SOC) accounting for about 62% of global soil carbon [*Lal*, 2004]. The huge storage and the sink/source potential of SOC can affect the global carbon budget and thus has prompted considerable interest in SOC dynamics [*Baker et al*., 2007; *Batjes*, 1996; *Bellamy et al*., 2005; *Schlesinger and Andrews*, 2000].

The conversion from natural (forests and grasslands) to agricultural ecosystems (agroecosystems) usually leads to the loss of SOC [*Buyanovsky and Wagner*, 1998a, 1998b; *Harden et al*., 1999; *Kucharik et al*., 2001; *Liu et al*., 2003; *Paul et al*., 1997], which may degrade soil quality, reduce biomass productivity, and adversely impact water quality [*Lal*, 2004]. However, long-term agricultural practices on croplands may result in different directions and rates of temporal changes of SOC (a carbon sink or source and the magnitude), depending on factors such as climate, magnitudes of initial SOC contents, crop species and rotations, genetic technology, farming practices (e.g., fertilization, tillage, drainage), and residue management [*Bellamy et al*., 2005; *Jenny*, 1980; *Kucharik et al*., 2001; *Lal*, 2004; *Lark et al*., 2006; *Tan and Liu*, 2013; *Tan et al*., 2005; *Z. X. Tan etal*. 2009; *Zhu and Reed*, 2014]. Since SOC plays a vital role in soil fertility maintenance [*Bationo et al*., 2007], increasing SOC storage (soil carbon sequestration) in farmlands cannot only enhance crop yield production, but also mitigate fossil-fuel emissions [*Lal*, 2004]—a win-win strategy for agroecosystems. From the perspective of agricultural sustainability and environmental protection, it is important to investigate the potential influencing factors and identify the major driving forces that dictate the evolution of SOC and the CO_2 exchange between the farmlands and the atmosphere [*Bationo et al*., 2007; *Liebig and Varvel*, 2003; *Paul et al*., 1997].

In a previous study, we reported an overall mild reduction of SOC for a 35 year (1972–2007) historical period [*Liu et al*., 2011] in the Midwest Corn Belt state of Iowa, in the United States, which is dominated by the corn and soybean cropping system [*Liebig and Varvel*, 2003; *Wright and Wimberly*, 2013]. However, the future temporal change of SOC is still uncertain considering the potential positive and negative impacts of farming practices and land-cover or crop-rotation changes. In particular, due to the Energy Independence and Security Act (EISA) of 2007, ethanol was expected to be the primary fuel to reduce U.S. dependence on foreign oil. Thus expansion of corn ethanol would intensify corn production, causing an increase in corn acreage use and a decrease in crop rotation for soybeans [*Committee on Water Implications of Biofuels Production (CWIBP)*, 2008; *Simpson et al*., 2008; *Thomas et al*., 2009; *Zhang et al*., 2010]. Further, grain-ethanol capacity may be limited due to the competition in feed and food; crop residues (corn stover), and perennial grasses are being considered as second generation cellulosic feedstock for biofuel production [*Oliver et al*., 2009], leading to potential reduction of SOC in the future [*Gaiser et al*., 2009]. Therefore, both increased corn growth frequency (e.g., from corn-soybean to continuous-corn) and residue harvest (stover or staw removal) may cause adverse environmental impacts such as increased nutrient loads to the Gulf of Mexico and a net release of CO_2 to the atmosphere from Corn Belt regions [*Gelfand et al*., 2013; *Tan et al*., 2012; *Wright and Wimberly*, 2013; *Wu et al*., 2012].

In addition, SOC has a potential to change towards or remain at an appropriate equilibrium level, which is dependent on the soil texture, climate, input of organic material and its decomposition rate, and SOC mineralization rate [*Johnston et al*., 2009; *Lardy et al*., 2011; *Wutzler and Reichstein*, 2007]. Thus, the changes of farming practices (e.g., induced by the biofuel production) could alter the equilibrium level and thus affect the potential magnitude of a carbon sink or source. Further, initial SOC contents may influence the temporal changes of SOC when it is approaching its equilibrium level. Clearly, it is important to investigate the relationship between initial SOC contents and its change over time and to estimate the potential SOC equilibrium values under different cropping systems and management practices.

The objective of this study is to evaluate SOC dynamics of the current primary cropping system (corn-soybean) and the anticipated increased corn production system (for corn ethanol production) using a process-based biogeochemical model at a crop site in Tama County in Iowa. We also assessed the impacts of residue management (i.e., returning residue to the soil or harvesting residue for biofuel production), bioimprovement of production, and initial SOC contents on carbon dynamics and the equilibrium level. More importantly, we used the fractional factorial design to guide multiple model simulations for attributing the contributions of major driving forces to the SOC dynamics of agroecosystems.

2. Materials and Methods

2.1. EDCM Description

Erosion and Deposition Carbon Model (EDCM) is a process-based biogeochemical model used to simulate carbon and nitrogen cycles in diverse ecosystems at a monthly time step and take into account the impacts of land management and disturbances [*Liu et al*., 2003; Z. *Tan et al*., 2009]. EDCM [*Liu et al*., 2003] is a modified version of CENTURY (version IV) [*Parton et al*., 1987, 1994], but the former uses up to 10 soil layers to simulate the SOC dynamics in the whole soil profile. This carbon pool model (EDCM) focuses on tracking the dynamics of carbon storage in each pool. EDCM was updated to include a generic autocalibration package (Shuffled Complex Evolution (SCE) [*Duan et al*., 1992] and R-based Flexible Modeling Environment (FME) [*Soetaert and Petzoldt*, 2010] for site and regional model calibration, and known as EDCM-Auto [*Wu et al*., 2014a, 2014b]. Driven by its interface—General Ensemble Modeling System (GEMS), EDCM-Auto has been used to assess the carbon stocks and fluxes under changing climate and land covers for the baseline and projection periods across the conterminous United States [*Liu et al*., 2012; *Zhu*, 2011].

2.2. Study Site and Model Setup

We used a crop site (250×250 m^2) as the case study, which is located in the center of Tama County, Iowa, in the United States (42°10′N, 92°35′W, elevation 200m) (see supporting information Figure S1). Corn was planted at this site for a 19 year (1992–2010) period, except for years 1993, 1994, 1999, 2000, 2004, 2005, and 2009 when soybean was cultivated. From our national soil data layers which were derived from Soil Survey Geographic database (SSURGO) [*Zhu*, 2011; *Zhu and Reed*, 2012], soil texture data indicate this site is 11% sand, 66% silt, and 23% clay, with a bulk density of 1.3 g/cm^3. The manure application rate for corn growth was 64 g C/m^2; disk tillage was applied prior to corn/soybean planting; and grain was harvested only with residue being left on the field.

The initial SOC content in the top 20 cm layer at this site was about 4.2 kg C/m^2, as obtained from the national data layers of soil carbon, which were built based on the SSURGO soil database but can provide the allocated carbon amount between different pools (e.g., active and slow) for 1992 [*Zhu*, 2011; *Zhu and Reed*, 2012]. For the current site simulation, we used the same starting year (1992) and initial conditions as we did for the national assessment.

The annual average precipitation at the study site is about 885 mm; the annual average air temperature is about 9.1°C, and ranges from an average minimum of −11°C in January to an average maximum of 29°C in July. Monthly time series of precipitation and minimum and maximum air temperatures from the *Parameter-elevation Regressions on Independent Slopes Model (PRISM) Climate Group* [2012] were used as the climate input for EDCM, covering the 19 year (1992–2010) historical period. This set of historical climate data was used (by repetition) to fill in the remaining 90 years (2011–2100) of the entire simulation period—109 years (1992–2100) for the current study. We did not use projection data by General Circulation Models for the future climate because we were attempting to exclude the climate-change impact (changes of precipitation and air temperature are not the focus of the study).

2.3. Model Calibration and Validation

Although process-based models are used to represent the natural systems and examine the dynamics of carbon, water, and other elements, they usually contain parameters that need to be calibrated by model inversion for reasons such as the lack of field measurements, mismatch between measurement and modeling scales, and heterogeneity of the physical environment for regional modeling [Beven, 2001; *Foglia et al*., 2009; *Nandakumar and Mein*, 1997; *Tang and Zhuang*, 2008; *Wu et al*., 2014a].

In EDCM and CENTURY, potential primary productivity of a given ecosystem is the foremost parameter (named as PRDX) used to calibrate the plant production for different species, environments, and varieties [*U.S. Department of Agriculture* (*USDA)*, 1993]. Thus, PRDX was calibrated to constrain EDCM's ecosystem production against the observed grain yield data of corn and soybean for Tama County.

We used the R package FME (using the modFit function with the PseudoOptim algorithm) included in EDCM-Auto to constrain the model using 10 years (1992–2001) of observed grain yield. The subsequent 9 years (2002–2010) of observations were used as the independent data to validate the model performance. To evaluate the model performance for the calibration and validation periods, a group of criteria was used, including Percent Bias (PB), Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970), r^2 (squared correlation coefficient) [*Krause et al*., 2005], and Root Mean Square Error (RMSE)—observation Standard deviation Ratio (RSR), which is the ratio of RMSE to observation standard deviation [*Moriasi et al*., 2007; *Singh et al*., 2005].

2.4. Fractional Factorial Design

Hypothetical factorial experiment design has been commonly used to investigate the behaviors of independent variables [*Box et al*., 2005; *Groemping*, 2014; *Hembree et al*., 2012]. A full factorial design contains all possible combinations of a set of factors, and a design with 2 level factors is one with all input factors set at two levels (e.g., "high" and "low," "on," and "off," "1," and "0") [*Box et al*., 2005]. For example, if there are *n* factors, each at 2 levels, a full factorial design has 2^n runs. A fractional factorial design is a carefully chosen subset (fraction) of a full factorial design [*Box et al*., 2005], exploiting the sparsity-of-effects principle to expose information about the most important features of the problem studied while using a fraction of the effort of a full factorial design in terms of experimental runs and resources [*Box et al*., 2005; *Hembree et al*., 2012]. For example, if there are *n* factors (each at 2 levels), a fractional factorial design has 2^{n-k} runs (*k* is the size of the fraction of the full factorial used). A full factorial design is the most conservative and costly among all the design types [*JMP Software Team*, 2014], and thus it is not recommended for five factors or more [*Hembree et al*., 2012].

An important property of a fractional factorial design is its resolution or ability to separate main effects and low-order interactions from one another. The most useful fractional designs are those of resolution III, IV, and V because resolutions below III may not be useful and resolutions above V may be wasteful because the expanded experimentation may have no practical benefit in most cases [*Hembree et al*., 2012; *Vaughn et al*., 2000]. Resolution III is useful for economical screening, resolution IV may be adequate, but as others have noted, resolution V is excellent and highly recommended because it can estimate the main effects and two-factor interaction effects

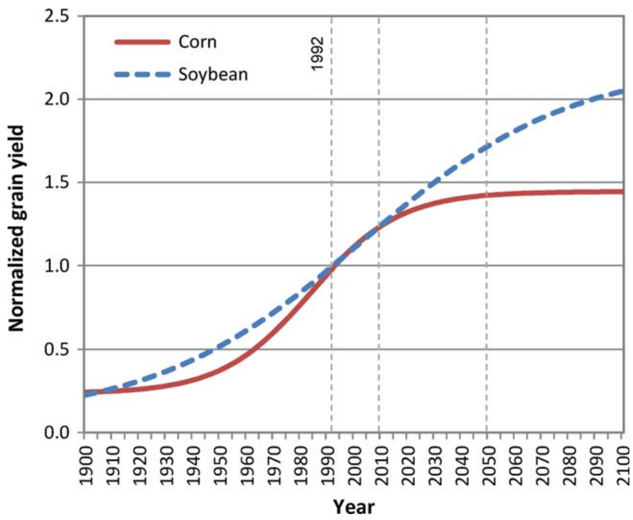

Figure 1. Normalized growth curves (annual grain yield) for corn and soybean in the United States.

[*Hembree et al*., 2012; *Vaughn et al*., 2000]. The main effects of a specific factor (e.g., *a*) are the difference between two averages: average response of experiments with factor *a* being "on" and average response with factor *a* being "off" [*Box et al*., 2005], with a positive sign referring to a positive effect and a negative sign referring to a negative effect. The effects of a two-factor interaction are a coupled influence on the response beyond main effects, a measure of the difference between factor *a* main effects at the "on" and "off" levels of factor *b* [*Box et al*., 2005].

Based on the results from the main effects or two-factor effects on the response variable (e.g., SOC storage in this study), we can rank the significance of the examined factors or factor combinations. Further, the contribution of each factor to the response variable can be quantified by defining the relative contribution (f_i) of factor (i) as the ratio of its absolute effect (x_i) to the sum of all the absolute effects (i.e., $f_i = |x_i| / \sum |x_i|$). Taking the absolute calculation avoids the offset of positive or negative effects of different factors.

2.5. Biological Enhancement of Crop Growth

Crop yield has experienced continuous improvement over the past century and this trend is likely to continue into the future due to genetic engineering. In a previous national-scale study [*Zhu and Reed*, 2014], we analyzed the temporal trends of yield from 1866 to 2009 for the major crops based on the census data of the U.S. Department of Agriculture at the county and state level [*USDA*, 2011]. The reported yields for several crops were averaged across the country and normalized to that in 1992 for deriving the overall temporal changes through 2050 (the end year of the national assessment). Additionally, the projected yield changes from Integrated Model to Assess the Global Environment (IMAGE) [*Integrated Model to Assess the Global Environment Team*, 2001; *Strengers et al*., 2004] for various crops were used to constrain the future paths and potentials of these crops. Details can be found in a USGS publication [*Zhu and Reed*, 2014], which showed the regressed growth curves from 1900 through 2050. In the current study, we used these normalized annual yields for corn and soybean (growth curves) from 1992 through the end of the century, as shown in Figure 1. These annual growth curves were embedded into the EDCM model to represent the biological improvement (denoted as "bio-improvement" in this paper) of grain production over time.

2.6. Scenario Setting

Two representative crop rotation schemes were selected to evaluate the impacts of cropping systems: the traditional corn-soybean (CS) rotation and continuous-corn (CC) production (i.e., reflecting the increased corn growth frequency). For each cropping system, we set two different residue management practices (i.e., with and without residue removal) under two hypotheses of bioimprovement of grain production (i.e., with and without bio-improvement). Therefore, there are eight modeling scenarios covering the above three proposed factors—cropping system, residue management, and bio-improvement (i.e., eight combinations for the first six terms shown in Table 1).

The initial SOC content is also a factor influencing SOC dynamics, and the real initial SOC content at this study site was about 4.2 kg C/m^2 (as stated in subsection 2.2). To investigate the effects of initial SOC levels, we used eight scenarios (one real value plus seven hypothetical values) with SOC contents being 2.2, 4.2, 6.2, 8.2, 10.3, 12.3, 14.3, and 16.3 kg C/m^2. For easy description, we used whole numbers ($\sim$2 to $\sim$16) to represent these eight scenarios (see Table 1); this range can cover the primary magnitudes of spatial distributions of SOC in Iowa [*Liu et al*., 2011]. In addition to soil type and climate, the equilibrium SOC level

Table 1. Definition of Scenario Terms Used in This Study

No.	Scenario Term	Description
1	Corn-soybean (CS)	Corn and soybean rotation (traditional cropping system)
2	Continuous-corn (CC)	Continuous corn production (reflecting increased corn growth frequency)
3	Without residue removal	Grain harvest only
4	With residue removal	50% of residue (corn stover or soybean straw) is removed in addition to gain harvest
5	With bioimprovement[a]	Considering temporal improvement of grain production due to genetic technology for years after 2010
6	Without bioimprovement	No considering biological improvement of grain production for the future period: using grain yield in 2010 (current) for simulations afterwards
7	Initial SOC levels	One real initial SOC content (~4 kg C/m^2) plus seven more hypothetical levels (~2, ~6, ~8, ~10, ~12, ~14, and ~16 kg C/m^2), representing the primary SOC contents in Iowa

[a]See details about "bio-improvement" in subsection 2.5.

depends on farming systems [*Johnston et al*., 2009], so we implemented these scenarios under each crop rotation, each residue management practice, and each bio-improvement option to estimate the variation of equilibrium SOC content—resulting in a total of 64 modeling scenarios.

Crop growth and SOC dynamics could be simultaneously affected by multiple driving forces such as farming practices based on previous studies [*Baker et al*., 2007; *Barbera et al*., 2012; *Bationo et al*., 2007; *Lobell and Field*, 2008; *McGrath and Lobell*, 2013; *Post and Kwon*, 2000; *Stewart et al*., 2007]. We selected five potentially important factors—CO_2 Enrichment, Fertilization, Tillage, Drainage, and Residue Removal—to conduct a fractional factorial design with two levels per each factor (see Table 2). Using the R package FrF2 [*Groemping*, 2014], we produced a design with 16 model runs for resolution V, and the statuses of the five factors in each model run are summarized in Table 3. This design was then implemented under two crop rotation schemes, respectively—a total of 32 model runs involved in this experimental design.

3. Results and Discussion

3.1. Model Evaluation

We partitioned the 19 year historical period (1992–2010) into a 10 year (1992–2001) calibration period and a 9 year (2002–2010) validation period. With the model calibration function of the EDCM-Auto, the derived optimal values of the production parameter (PRDX) are 685.7 and 216.9 for corn and soybean, respectively. The simulated annual grain yields against those observed during the 10 year calibration and the 9 year validation periods are presented in Figure 2, suggesting a general agreement between simulations and observations. The statistical measures (PB, NSE, r^2, RSR) used to scale the model performance are listed in Table 4. During the calibration period, the PB was about -6.0%, indicating a little underestimation. The NSE and r^2 values were as high as 0.87 and 0.92, respectively, and RSR was 0.35. For validation, these statistical terms had similar values, demonstrating that the simulation matched well with the observation for the two periods. If we reference the performance ratings by *Moriasi et al*. [2007], this simulation can be evaluated as "very good" (NSE $>$ 0.75 and $|PB| < 10\%$) for both calibration and validation. Therefore, the model performance can be considered acceptable for this study.

Table 2. Definition of Five Factors Involved in the Fractional Factorial Design

No.	Factor Code	Factor Description	No. of Levels	Status	Details
1	CO2Enr	CO_2 enrichment	2	On	Use projected atmospheric CO_2 concentrations under the A1B scenario
				Off	No CO_2 enrichment
2	Fert	Fertilization	2	On	Use automatic fertilization algorithm
				Off	No fertilization
3	Till	Tillage	2	On	Use disk-till
				Off	No-till
4	Drain	Tile drainage	2	On	Use tile drainage
				Off	No tile drainage
5	ResRem	Residue removal	2	On	50% of residue is removed in addition to gain harvest
				Off	No residue removal (grain harvest only)

Table 3. The Fractional Factorial Design With Five 2 Level Factors and Resolution V[a]

Factor	1	2	3	4	5
Model Run	CO2Enr	Fert	Till	Drain	ResRem
1	0	0	0	0	1
2	1	0	0	0	0
3	0	1	0	0	0
4	1	1	0	0	1
5	0	0	1	0	0
6	1	0	1	0	1
7	0	1	1	0	1
8	1	1	1	0	0
9	0	0	0	1	0
10	1	0	0	1	1
11	0	1	0	1	1
12	1	1	0	1	0
13	0	0	1	1	1
14	1	0	1	1	0
15	0	1	1	1	0
16	1	1	1	1	1

[a]Note: Please see Table 2 for description of the five factors; values 1 and 0 refer to statuses "On" and "Off," respectively, of factors.

3.2. Impacts of Crop Rotations and Residue Management

The simulated annual SOC (in the top 20 cm layer) under cropping systems and residue management scenarios are shown in Figure 3; Figure 3a shows SOC without considering the impact of bio-improvement and Figure 3b shows SOC considering the impact of bio-improvement (see explanations in Table 1). Without residue removal (Figure 3a), the traditional CS rotation indicated a SOC carbon sequestration rate of 54.1 g C/m^2/yr in the first 20 years of the simulation period (1992–2011, denoted as "early 20 years" hereafter). This rate decreased gradually along time and reached as low as 5.7 g C/m^2/yr in the latter 20 years of the century (2081–2100, denoted as "late 20 years" hereafter), which was about 10.6% of the initial accumulation rate. In contrast, the CC cropping scheme showed a somewhat higher SOC sequestration potential (Figure 3a), with the rate ranging from 74.4 g C/m^2/yr (in the early 20 years) to 7.8 g C/m^2/yr (in the late 20 years). By the end of the century, the SOC storage could reach to 6.8 and 7.8 kg C/m^2, respectively, for the CS and CC cropping systems without residue removal (relative increases of 60.2% and 85.7%, respectively, during the 109 years). With residue removal, however, the carbon sink potential could reduce significantly, with a rate varying from 19.1 g C/m^2/yr (in the early 20 years) to 2 g C/m^2/yr (in the late 20 years) for the CS system and a higher rate changing from 38 g C/m^2/yr (in the early 20 years) to 3.5 g C/m^2/yr (the late 20 years) for CC. Figure 3a shows that, under residue removal, the relative changes of SOC during the 109 years were 23% and 44% for CS and CC, respectively.

Following these scenarios without bioimprovement, we implemented similar modeling scenarios under the hypothesis of bioimprovement of grain production for the future period (2011–2100). The corresponding simulated annual changes of SOC are shown in Figure 3b. It is clear that bioimprovement produced a higher SOC sequestration potential. For example, CS and CC with no residue removal resulted in SOC accumulation rates of 20.6 and 17.3 g C/m^2/yr in the late 20 years of the century, respectively, which are 260% and 122% higher than those without bioimprovement. The simulated SOC content by the end of this century was also higher than those without bioimprovement, with values at 8.2 and 8.7 kg C/m^2 for CS and CC, with no residue removal as shown in Figure 3b. Under the implementation of residue removal, CS made the soil a weaker carbon sink—13.1 g C/m^2/yr for the late 20 years of the century, while CC caused a SOC accumulation rate of 9.4 g C/m^2/yr, a noticeable enhancement compared to those without bioimprovement of crop growth.

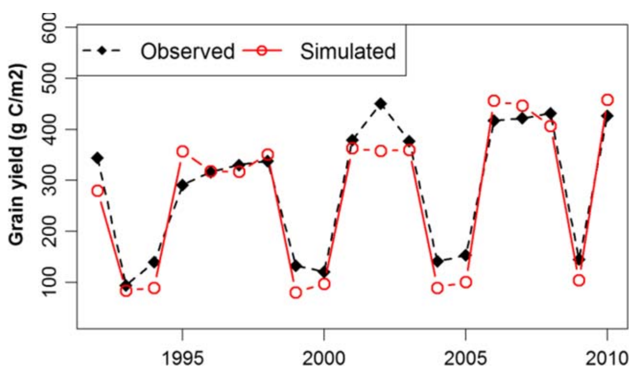

Figure 2. Simulated grain yields versus observations during the 10 year (1992–2001) calibration and 9 year (2002–2010) validation period for the study site in Tama County, Iowa. The crop species grown on this site was corn except for years 1993, 1994, 1999, 2000, 2004, 2005, and 2009 when soybean was grown.

The results for "without bioimprovement" showed that increased corn production is helpful for enhancing SOC accumulation because corn has a higher net primary production than soybean. Under the hypothesis of bio-improvement, CS rotation showed a lower SOC sequestration potential (i.e., 19.2 g C/m^2/yr) than CC (i.e., 38.1 g C/m^2/yr) in the early simulation period and reversed in the late period (i.e.,

Table 4. Evaluation of Model Performance in Grain Yield Simulation During the 10 Year (1992–2001) Calibration and 9 Year (2002–2010) Validation Periods

Period	PB (%)[a]	NSE[b]	r^{2c}	RSR[d]
Calibration	−6.0	0.87	0.92	0.35
Validation	−6.2	0.87	0.94	0.34

[a]PB: percent bias (%).
[b]NSE: Nash-Sutcliffe Efficiency [*Nash and Sutcliffe*, 1970].
[c]r^2 squared correlation coefficient [*Krause et al.*, 2005].
[d]RSR: Root Mean Square Error (RMSE)—observation Standard deviation Ratio, which is a ratio of RMSE to observation standard deviation [*Moriasi et al.*, 2007, *Singh et al.*, 2005].

13.1 g C/m^2/yr for CS and 9.4 g C/m^2/yr for CC). This reverse can be partly attributed to the continued bioimprovement of grain production for soybean through this century and the relatively stable production for corn after the mid century (see Figure 1). Also, a relatively larger amount of residue removed from corn fields might be another reason for the reverse.

It is clear that residue management played a pivotal role in the dynamics of SOC in farmlands. "Residue return to the soil" can result in a significant carbon sink; whereas "residue removal" may cause great reduction of the sink potential, depending on the crop rotation schemes and consideration of bioimprovement. Therefore, it is important to consider a trade-off between harvesting for cellulosic biofuel production and returning residue to soil for maintaining/enhancing the soil fertility and carbon sequestration. In addition, we recognize that the qualitative and quantitative results presented here are dependent on the conditions of the study site, especially the magnitudes of initial SOC contents, which may affect the temporal changes of SOC [*Bellamy et al.*, 2005; *Tan and Liu*, 2013], as described in the next section.

3.3. Impacts of Initial Soil Organic Carbon Levels

The simulated annual changes of SOC for the two cropping systems (CS and CC) and two residue management practices under eight different initial SOC levels are shown in Figures 4a and 4b; Figures 4c and 4d show similar simulations but with the hypothesis of bioimprovement of grain production for the future period (2011–2100). For the traditional CS rotation without residue removal (see the four black lines and four blue lines in Figure 4a), initial levels ranging from ~2 to ~8 kg C/m^2 demonstrated a carbon sink: the higher the initial contents, the lower the carbon sequestration potential. Conversely, the initial SOC levels varying from ~10 to ~16 kg C/m^2 behaved like a carbon source: the higher the initial contents, the greater the carbon emission rate. For the two scenarios with the initial SOC contents of ~8 and ~10 kg C/m^2, the annual change of SOC in the late 20 years changed very slowly and stood at 1.0 and −1.4 g C/m^2/yr, respectively. The SOC storage as of 2100 could be 8.7 and 9.6 kg C/m^2, respectively, indicating that the equilibrium (or steady state) SOC level under the CS rotation without residue removal may be somewhere between these two values (i.e., ~9 kg C/m^2). For the CC system (see the

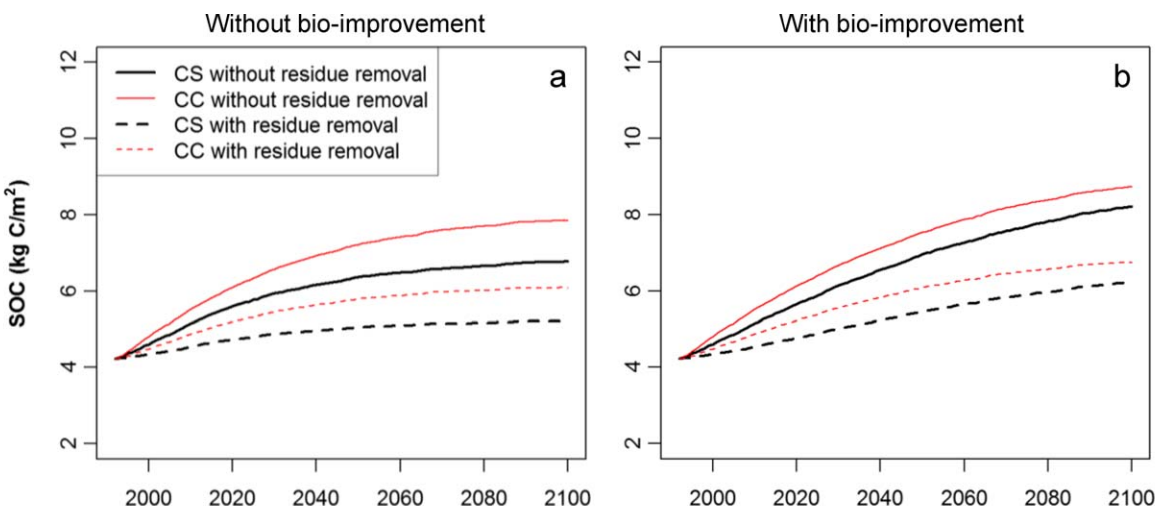

Figure 3. Annual changes of soil organic carbon (SOC) in the top 20 cm soil layer during 109 years (1992–2100) under different scenarios—various combinations of rotation systems (corn-soybean (CS) and continuous-corn (CC)), residue management practices (residue removal), and bio-improvement of grain production—at the study site (with real initial SOC content). See Table 1 for the explanations of the terms presented in this figure.

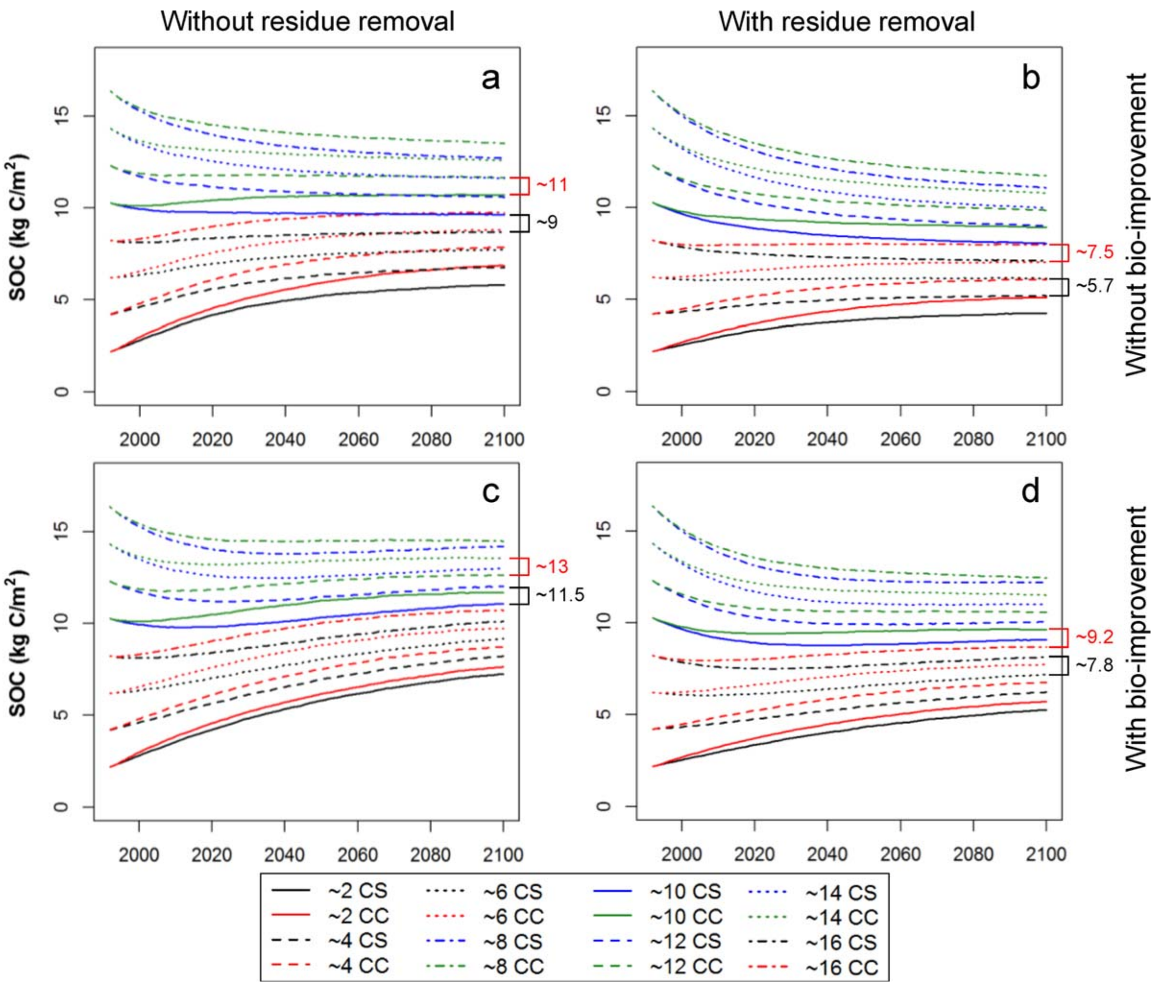

Figure 4. Annual changes of soil organic carbon (SOC) in the top 20 cm soil layer during 109 years (1992–2100) under different scenarios—various combinations of rotation systems (corn-soybean (CS) and continuous-corn (CC)), residue management practices (residue removal), bio-improvement of grain production, and different initial SOC contents (~2, ~4, ~6, ~8, ~10, ~12, ~14, ~16 kg C/m^2). The legend of each line indicates the combination of initial SOC content and the cropping system (e.g., "~2 CS" refers to initial SOC content of ~2 kg C/m^2 with CS rotation). The estimated potential equilibrium SOC levels were marked with black for CS and red for CC at the right side of each plot, and they are independent of initial SOC levels. See Table 1 for the explanations of the terms presented in this figure.

red lines in Figure 4a), the equilibrium SOC level may be between 10.7 and 11.6 kg C/m^2 (i.e., ~11 kg C/m^2), corresponding to the two scenarios with the initial SOC contents of ~12 and ~10 kg C/m^2, respectively. Therefore, CC cropping may help some in accumulating SOC, although it requires the larger amount of fertilizer than CS and thus may have a greater impact on water quality. With the implementation of residue removal (Figure 4b), the predicted equilibrium SOC level may be between 5.2 and 6.2 kg C/m^2 (i.e., ~5.7 kg C/m^2) for CS and range from 7.0 to 8.0 kg C/m^2 (i.e., ~7.5 kg C/m^2) for CC. A comparison between Figures 4a and 4b indicated that the residue removal may reduce SOC sequestration potential by 37% for CS and 32% for CC.

We also implemented similar modeling scenarios under the hypothesis of bioimprovement of grain production for the future period (2011–2100), and the corresponding simulated annual time series of SOC are shown in Figures 4c and 4d. The predicted equilibrium SOC level could be elevated to 11.1–12.0 kg C/m^2 (~11.5 kg C/m^2) for CS and 12.6–13.5 kg C/m^2 (~13 kg C/m^2) for CC without residue removal owing to the bioimprovement of crop growth. However, residue removal implementation reduced this level to 7.2–8.1 kg C/m^2 (~7.8 kg C/m^2) and 8.7–9.6 kg C/m^2 (~9.2 kg C/m^2) for CS and CC, respectively. In other words, the bioimprovement enhanced equilibrium SOC levels by 27.8% for CS and 18.2% for CC (see Figures 4a and 4c), with returning residue to soil; whereas these relative changes with harvesting residue could be 36.8% and 22.7% (see Figures 4b and 4d), respectively.

Johnston et al. [2009] stated that for a given site/area (with specific climate and soil type), the equilibrium SOC level is primarily appropriate to the farming system (crop type and practices). Our study results agreed with that their statements and indicated that the equilibrium SOC level may vary greatly (from ~5.7 to ~11 kg C/m^2) depending on cropping system and management practices under the current growth assumption. Further, the bioimprovement of crop production may lead to a higher anticipated steady state (~7.8 to ~13 kg C/m^2). The estimated equilibrium SOC levels (as shown in Figure 4) for the study site (i.e., a given soil and climate conditions) depend on the farming practices instead of initial SOC levels, which impacts just the time period for reaching the final steady state. Therefore, these estimated equilibrium SOC levels are informative because croplands with a higher or lower SOC content than the equilibrium level may demonstrate a potential carbon source or sink, respectively, under the similar climate and farming practices described in this study. We can also see that the further the SOC content is from the equilibrium value, the higher the carbon sink/source potential, and the longer the time period could be for reaching the final steady state. The relationship between the initial SOC level and its change over time is consistent with a previous study based on soil survey data across England and Wales [*Bellamy et al*., 2005]. The relationship between the initial SOC level and its change over time may be of intrinsic interest when monitoring the soil and may be of practical value when using it to resample sites for soil monitoring [*Lark et al*., 2006]. Additionally, the derived equilibrium SOC levels may help the preliminary identification of potential carbon sink or source areas in Iowa and the Corn Belt region (assuming similar climate and cropping systems) by comparing the current and equilibrium SOC levels. The impacts of residue management and cropping systems on equilibrium SOC level may also inform decision makers of better management practices for enhancing the carbon sequestration potential of farmlands.

3.4. Importance of Driving Forces

We used a 2-level fractional factorial design with resolution V, as described in subsection 2.6, to investigate the main effects and two-factor interactions of five potentially important factors—CO_2 Enrichment, Fertilization, Tillage, Drainage, and Residue Removal. There were 16 model runs for this design with each cropping system (CS and CC) under the current growth assumption (for 2010). The main effects of the five factors on SOC storage are shown in Figure 5, visualizing the different SOC responses to factor levels under the CS (Figure 5a) and CC (Figure 5b) cropping systems. It is clear that residue management (ResRem) has the largest effect, causing variation of SOC storage of −1.22 (from an average of 6.45 at "off" to an average of 5.23 at "on") kg C/m^2. The second largest effect is CO_2 Enrichment (about 0.91 kg C/m^2), followed by Tillage (about −0.14 kg C/m^2), and fertilization (about 0.03 kg C/m^2), while drainage had little effects on SOC storage at this site. The small effect of fertilization was not surprising considering the manure application for corn growth. Using the simple approach for attributing contributions of each factor, as described in Section 2.6, we quantified the relative contributions of the significant individual factors to the SOC storage: 52.9% for Residue Removal, 39.2% for CO_2 Enrichment, and 6% for Tillage (1.4% for Fertilization, and 0.5% for Drainage). Comparison of Figures 5a and 5b illustrated that the relative main effect of each factor and the effect ranking did not change, but the absolute magnitude seemed larger for CC than those for CS.

The interaction plot matrix (Figure 6) demonstrated the average responses (SOC storage) to the level combinations of every two factors (e.g., CO2Enr and ResRem = (0,0), (0,1), (1,0), and (1,1) at the lower left corner of the figure) with CS and CC cropping systems. The plot for CS (Figure 6, left) shows that the interaction of "ResRem=1" with any of the other four factors would cause strong negative effects on SOC storage irrespective of the status of its partner-factor, indicating the relatively larger effect of residue removal. The interaction of "CO2Enr=1" with any of the other four would have a positive effect except for its interaction with "ResRem=1" which indicated a lower SOC storage than the interaction of "CO2Enr=0" with "ResRem=0" because of the off-set by the relatively larger negative effect of residue removal. The interaction of "Till=1" with Fertilization and Drainage can result in a negative effect on SOC storage irrespective the status of the other two factors, but its interaction with "CO2Enr=1" or "ResRem=0" would change the situation because they both (CO2Enr and ResRem) had a relatively larger effect than Tillage. Neither "Fert" nor "Drain" made a clear difference because neither of them was the predominant factor among all the interactions with other factors. The above analysis results did not change as noted in the interaction plot with the CC cropping system (Figure 6, right), which indicated that crop rotations may not impact quantifying the effects of these factors to a noticeable degree.

The plots of normal and half-normal effects under the CS rotation are shown in Figures 7a and 7b, respectively; those effects that are significant at a specified level ($\alpha = 0.025$) are labeled. For the CS rotation system, the most significant factor with positive effects on SOC storage is CO_2 Enrichment (A), followed by

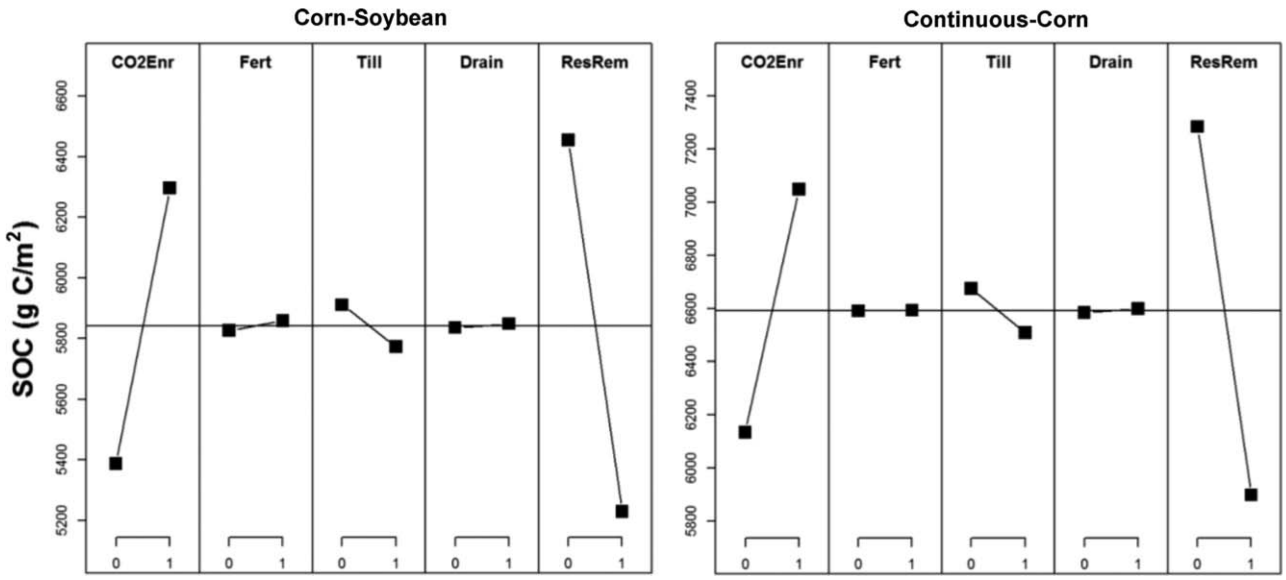

Figure 5. Main effects plot for soil organic carbon (SOC) in terms of the five factors—CO_2 Enrichment (CO2Enr), Fertilization (Fert), Tillage (Till), Drainage (Drain), and Residue Removal (ResRem)—involved in the fractional factorial design. The left (a) and right (b) plots are for corn-soybean and continuous-corn rotation systems, respectively. See Table 1 and Table 2 for the explanations of the terms presented in this figure.

Fertilization (B) (Figure 7a). The most significant factor with negative effects on SOC storage is Residue Removal (E), followed by Tillage (C), CO_2 Enrichment-Residue Removal (AE) (Figure 7a). In contrast, the half-normal plot (Figure 7b) ranked the above factors irrespective of the direction, indicating that Residue Removal (E) is most significant, followed by CO_2 enrichment (A), Tillage (C), CO_2 Enrichment-Residue Removal (AE), and Fertilization (B). Similar to estimating the relative contributions of individual factors, we can derive the quantitative relative contributions of these significant factors or factor combinations: 49.4% for Residue Removal (E), 37% for CO_2 Enrichment (A), 6.2% for Tillage (C), 5.8% for CO_2 Enrichment-Residue Removal (AE), and 1.6% for Fertilization (B). For the CC cropping system, as shown in Figures 7c and 7d, the first four factors with the most significant effects were still the same except for a ranking switch between

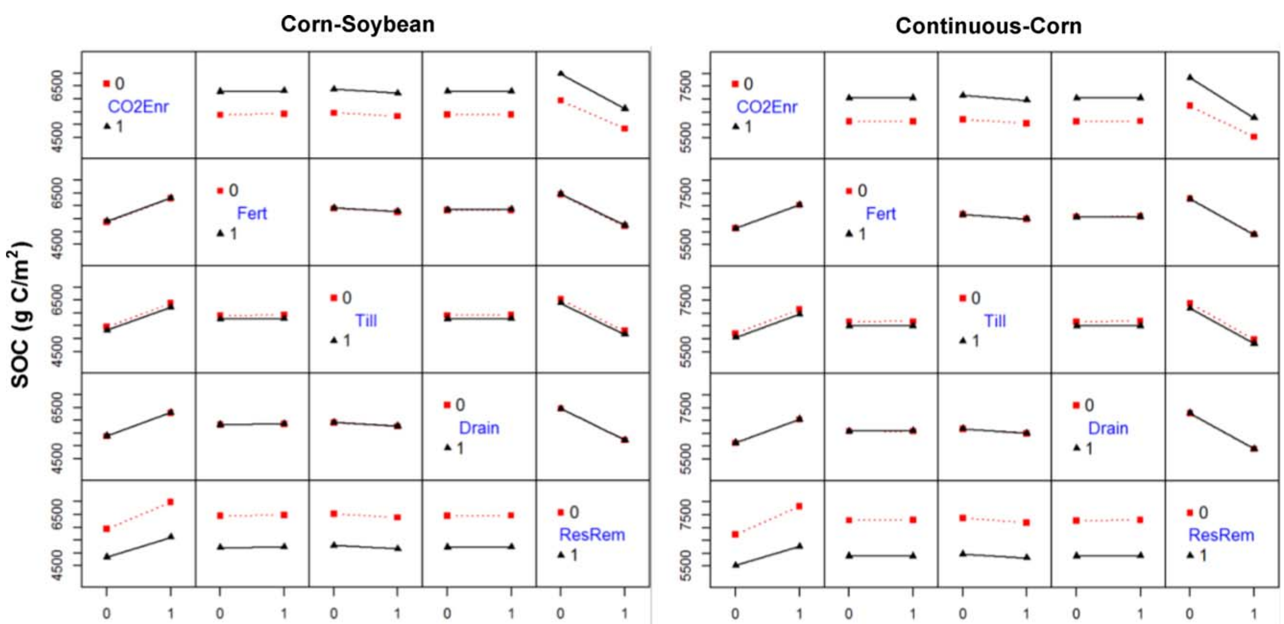

Figure 6. Interaction plot matrix for soil organic carbon in terms of the five factors—CO_2 Enrichment (CO2Enr), Fertilization (Fert), Tillage (Till), Drainage (Drain), and Residue Removal (ResRem)—involved in the fractional factorial design. The left (a) and right (b) plots are for corn-soybean and continuous-corn rotation systems, respectively. See Table 1 and Table 2 for the explanations of the terms presented in this figure.

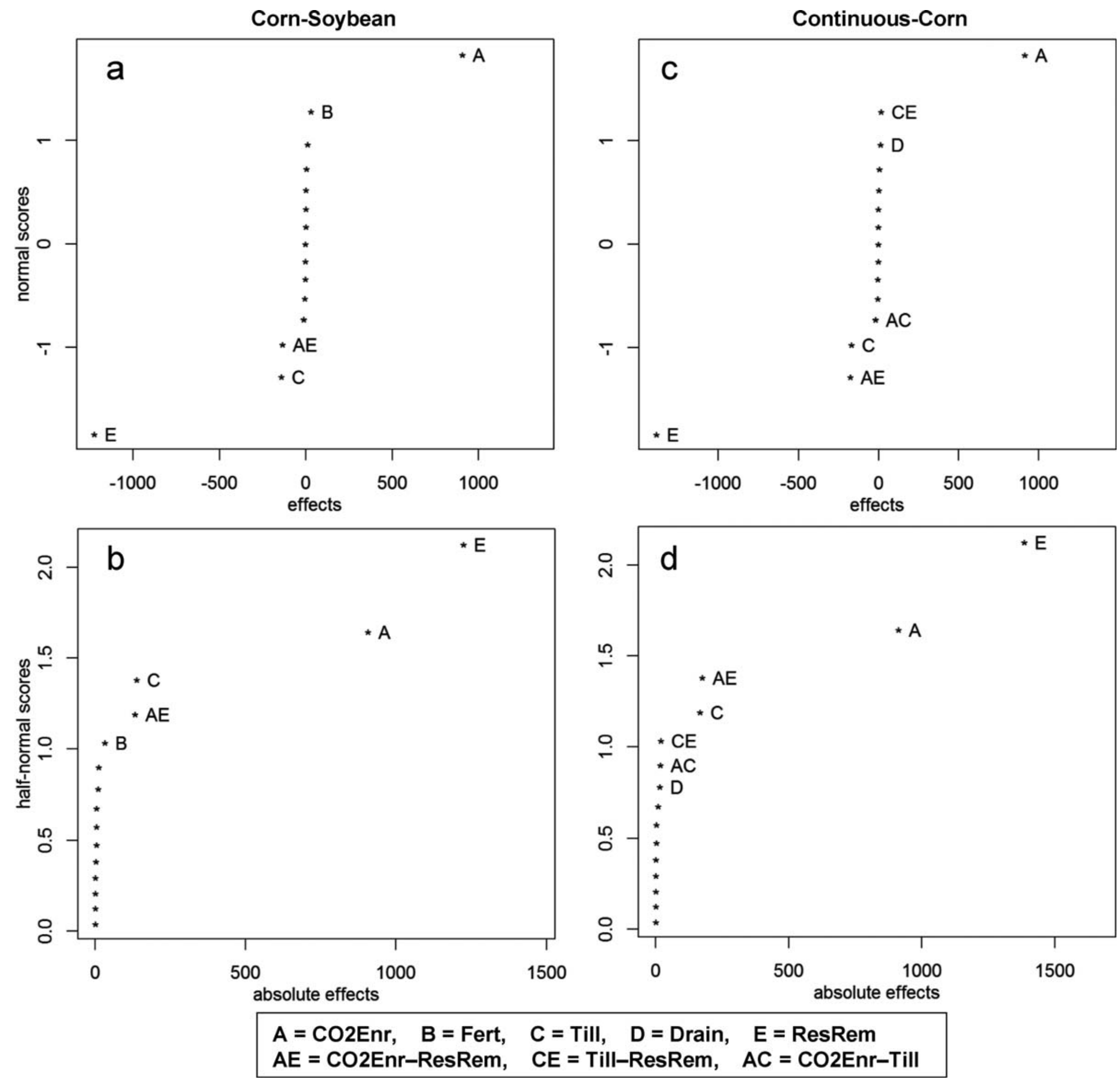

Figure 7. Normal and half-normal plots for soil organic carbon for the corn-soybean (a and b) and continuous-corn (c and d) cropping systems in terms of the five factors—CO_2 Enrichment (CO2Enr), Fertilization (Fert), Tillage (Till), Drainage (Drain), and Residue Removal (ResRem)—involved in the fractional factorial design. Factors with significant effects (alpha=0.025) were labeled only. See Table 1 and Table 2 for the explanations of the terms presented in this figure.

C and AE, while other factors or factor-interactions—D (positive), CE (positive), AC (negative), and D (positive)—have very little effects. This comparison illustrates that cropping system may not make a significant difference in identifying the most significant factors. We did not present the plots for those under the hypothesis of bioimprovement of crop production because the results are quite similar, especially in identifying the first four factors with the most significant effects.

3.5. Implications

Increasing corn growth frequency (e.g., from corn-soybean to corn-corn) is an option to meet the rising demand for corn kernel-based ethanol production without expanding the cropland acreage [*CWIBP*, 2008; *Simpson et al.*, 2008; *Thomas et al.*, 2009]. Out study indicated that this land management change could enhance the SOC sequestration, mitigating anthropogenic CO_2 emissions (see Sections 3.2 and 3.3). However, the intensified corn growth would decrease the water availability due to the higher water consumption by corn and likely worsen the hypoxia in the Gulf of Mexico because of the higher nutrient loads resulting from the higher fertilization rate for corn when compared to other small grains (e.g., soybean) [*CWIBP*, 2008; *Thomas et al.*, 2009; *Welch et al.*, 2010; *Wu et al.*, 2012]. Therefore, increasing corn growth frequency is still a double-edged sword strategy in terms of environmental protection, causing conflict in CO_2 mitigation and water resources protection.

In addition to corn kernels, corn stover is also considered as a candidate for the advanced biofuel feedstocks [*CWIBP*, 2008; *Wilhelm et al*., 2010], and thus harvesting stover may also contribute to the demands for biofuel production. However, our study illustrated that residue removal implementation had the maximum negative effect on SOC storage among a group of potential factors—reversing the potential carbon sequestration when returning residues into soil to carbon neutral, or a weak carbon sink/source (see subsections 3.2, 3.3, and 3.4). Residue removal could also have other adverse environmental impacts such as declined crop productivity [*Lal*, 2004], increased soil erosion due to reduced topsoil protection with no/less crop residues, and reduced soil fertility (nitrogen concentration), and the resulting increased fertilization rate [*Wu and Liu*, 2012]. Therefore, it is important to determine a proper rate of residue removal to get a reasonable trade-off between biofuel production development and sustainability of agroecosystems.

Additionally, we considered the continuing potential bioimprovement of crop production due to genetic technology in the future period (2011–2100). As described in subsection 2.5, this consideration of bioimprovement (growth curves for corn and soybean) was based on the regression of nationwide-averaged historical grain production [*Zhu and Reed*, 2014]. Therefore, we acknowledge that uncertainties exist in our results because nationwide-averaged regression may not represent the condition in a specific site or a state. Moreover, the further into the future we predict using this regression, the higher the uncertainties of the simulation results. Nevertheless, both "with and without bio-improvement" options that we adopted in this study can be useful to inform decision makers what the future outcomes might be in terms of SOC dynamics.

4. Conclusions

This study assessed the impacts of crop rotations, residue management, initial soil organic carbon (SOC) contents, and bioimprovement of grain production on SOC dynamics using a biogeochemical model approach. Our results show that the two representative cropping systems—corn-soybean (CS) and continuous-corn (CC)—can help accumulate SOC over this century considering the current conditions (climate, fertilization, drainage, no residue removal), but the CC system may have a higher accumulation rate owing to the higher net primary production of corn. However, residue (stover or straw) removal implementation can reverse this carbon sequestration potential to carbon neutral, or a small carbon sink/source. Therefore, biofuel production-oriented land management changes (e.g., increased corn growth frequency plus residue removal) may compromise the carbon sequestration potential of agroecosystems, even though the magnitude depends on how much residue would be removed. The derived equilibrium SOC levels without residue removal were ~9 and ~11 kg C/m^2 for CS and CC, respectively, but residue removal could lead to a decrease in the equilibrium SOC level by about 60% of the order of importance of the major forces driving SOC dynamics was identified as: Residue Removal, CO_2 Enrichment, Tillage, and CO2 Enrichment-Residue Removal. Overall, the results are valuable for understanding the impacts of farming practices including biofuel production alternatives on SOC dynamics, and can be used to help decision makers seek sustainable biofuel and food coexisting ecosystems, especially under the background of rising global CO_2 emissions.

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