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Key Points:
- Eddy covariance shows a decrease in ecosystem C after 11 yr of corn-soybean production
- Soil inorganic C decreased in 90–120 cm, and organic C decreased in 0–15 cm after 11 yr
- DayCENT simulations suggest current conventional corn-soybean rotations decrease all SOC pools in topsoil layer

Supporting Information:
- Supporting Information S1
- Figure S1

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Measured and Simulated Carbon Dynamics in Midwestern U.S. Corn-Soybean Rotations

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Abstract Corn (*Zea mays* L.) and soybean (*Glycine max* [L.] Merr.) production dominate Midwestern U.S. agriculture and impact the regional carbon and nitrogen cycles. Sustaining soil carbon is important for corn-soybean production (CS); however, quantifying soil carbon changes requires long-term field measurements and/or model simulations. In this study, changes in soil organic (SOC), inorganic (SIC), and total (TC) carbon; pH; total nitrogen (TN); and net ecosystem production (NEP) were measured in a conventional corn-soybean rotation in central Iowa. Soil samples (n = 42; 0–120 cm depth) were collected from two adjacent fields in 2005 and 2016. Eddy-flux stations set up in the fields continuously monitored NEP from 2005–2016, and net biome production (NBP) was calculated using yield records. The DayCENT model was used to simulate the effects of conventional management practices on soil carbon and calibrated with field-measured NEP and SOC. Measured soil TC (0–120 cm) decreased by -14.19 ± 6.25 Mg ha^{-1}, with highest reductions in SOC and SIC ($p < 0.05$) at 0–15 and 90–120 cm, respectively. Measured TN decreased by -0.7 ± 0.29 Mg ha^{-1} with N-accumulation at 60–90 cm ($p < 0.05$). Eddy-flux NBP decreased by -13.19 ± 0.05 Mg ha^{-1}. Soil and eddy-flux records show a carbon reduction by -1.14 ± 0.63 and -1.20 ± 0.06 Mg ha^{-1} yr^{-1}, respectively. The validated DayCENT model suggests that all SOC pools declined. We postulate that conventional CS production has adverse effects on C and N dynamics in Midwestern United States.

1. Introduction

Corn (*Zea mays* L.) and soybean (*Glycine max* [L.] Merr.) production dominate Midwestern U.S. agriculture, and both crops are important commercial commodities. The total harvested area of corn and soybean fields in 2018 was approximately 14.9 and 17.5 million ha, respectively, in the Corn Belt States of Indiana, Illinois, Iowa, Nebraska, and Kansas (USDA-NASS, 2019). The production of corn and soybeans on vast land areas affects Gross Primary Production (GPP) in the Midwestern U.S. region (Guanter et al., 2014). Crop and soil management greatly influence soil C dynamics, and optimizing corn and soybean production in the Midwestern United States while sustaining C stocks remains an active research topic (e.g., Basche et al., 2016; Bernacchi et al., 2005; Dold et al., 2019; Ogle et al., 2012; Poffenbarger et al., 2017; Verma et al., 2005; Yu et al., 2018). The underlying line of reasoning is that small beneficial changes in crop and soil management may have substantial regional impact on C dynamics in corn-soybean production systems (CS) (Bernacchi et al., 2005). Sustaining or increasing C stocks is important to maintain essential soil chemical and physical properties for crop production and mitigation of climate change effects. Agricultural soils are possible sinks of atmospheric C, thus capable of ameliorating anthropogenic carbon emissions (Chenu et al., 2019; Lal, 2016; Minasny et al., 2017; Rumpel et al., 2020). However, there is an ongoing debate and criticism of its feasibility (Amundson & Biardeau, 2018; Baveye et al., 2018; Baveye & White, 2020; de Vries, 2018; Minasny et al., 2018; Poulton et al., 2018).

The potential of increasing soil C sequestration depends on the inherent soil biophysical characteristics, climate, land use, and soil management, among others (Chenu et al., 2019). A comprehensive assessment of the C storage potential and measures to reach this potential is still incomplete (Chenu et al., 2019; Rumpel et al., 2020). Estimates of storage potential range from 45–98 Tg C yr^{-1} for U.S. Croplands (Chambers et al., 2016; Sperow, 2016). However, agricultural activity has resulted in soil C depletion (DeLuca & Zabinski, 2011). Yu et al. (2018) estimated that 4.5 Pg of soil organic C (SOC) was lost due to land use change in the Midwestern United States since 1850. An earlier study estimated a loss of 25–40 Mg C ha^{-1} by the conversion of natural prairie to cropland (Lal, 2002). These regional estimates are not possible without field studies, which are the backbone for meta-analysis and modeling approaches. Several field studies assessed the impact of CS production in the Midwestern United States. Al-Kaisi and Yin (2005) found that soil C increased and soil respiration decreased with decreasing tillage intensity. In a 3-yr study in Nebraska, Verma et al. (2005) reported declined soil C under conventional CS, however, with high soil C variability. Unfortunately, the high spatial variability of soil C impedes short-term assessments of changes with classical soil sampling (Baker & Griffis, 2005). Therefore, long-term monitoring of soil C under different crop and soil management focused on how soil and crop management impact soil C storage are required. A 30-yr assessment of soil C under continuous corn production found that plowing increases respiration and inhibits soil C increase from crop residues (Reicosky et al., 2002). Similarly, soil C declined in CS after 23 yr of ridge and disk tillage (Moorman et al., 2004). Many studies emphasized soil conversation practices to reach soil C storage potential in U.S. croplands (e.g., Bernacchi et al., 2005; Chambers et al., 2016; Lal, 2002; Rumpel et al., 2020; Sperow, 2016). Ogle et al. (2012) stated that no till can reduce crop productivity and C inputs from residues, while also reducing C mineralization rates. However, Baker et al. (2007) postulated that tillage might only affect soil C distribution and not absolute C concentration; tillage incorporates C-rich material into deeper soil layers while C accumulates in the topsoil layer in no-till systems. Hence, the requirement to analyze the subsoil for soil C (Baker et al., 2007; Chenu et al., 2019). In addition, many studies have focused on the organic C fraction, yet inorganic C contributes to the global carbon cycle, and organic and inorganic C pools are interlinked (Kindler et al., 2011).

Changes in soil C with classic soil sample analysis require long-term monitoring of CS systems. A short-term quantification of C dynamics can be achieved with the eddy covariance (EC) method, where the carbon flux (F_c) is calculated as the mean covariance of atmospheric CO_2 density and the vertical wind scalar (Burba, 2013). The annual sum of F_c is the net ecosystem production (NEP), that is, the sum of assimilated and respired carbon within the footprint of the EC system. With the additional knowledge of residue and grain C removal and organic fertilizer input, the net biome production (NBP) is calculated, which is a measure of the "apparent" change in soil C (Baker & Griffis, 2005). Several studies have analyzed NEP and NBP in corn-soybean systems. Corn-years have been identified as either C neutral or C source, while soybean-years are a C source under conventional crop management in the Midwestern United States (Dold et al., 2017; Verma et al., 2005). There is little impact of irrigation on NEP, while ecosystem respiration increases with irrigation (Verma et al., 2005). Reduced-till cover-crop systems had substantially higher NEP during the off-season, probably owing to reduced mineralization of crop residues (Dold et al., 2019). However, Baker and Griffis (2005) found small differences in NEP in strip till compared to conventional CS. While the EC method has been widely used in studying carbon dynamics, the method depends on several preconditions. This can affect the quality of F_c measurements, for example, by the underestimation of nighttime fluxes (Burba, 2013). Yet only a few studies have assessed C dynamics using a combination of several methods, for example, deep-core soil analysis and EC flux measurements (Abraha et al., 2016; Curtis et al., 2002; Ferster et al., 2015; Leifeld et al., 2011; Skinner & Dell, 2015; Stahl et al., 2017; Vaccari et al., 2012; Verma et al., 2005). Verma et al. (2005) found similar trends with both EC measurements and topsoil sampling in CS, but the study period was too short for a comprehensive analysis and did not include the subsoil. Abraha et al. (2016) compared CS in Michigan with both deep-core sampling and the EC method in a 6-yr study. Zenone et al. (2011) reported both significant and not significant relationships between NEE and soil C, depending on season and crop. Other studies focused on other cropping systems and biomes and comparison to CS is limited.

Model simulations require field data for evaluation and calibration of model parameters and output. Process-based, biogeochemical models such as DayCENT can simulate the impact of crop and soil management on the C dynamics in agroecosystems (Cheng et al., 2014; Del Grosso et al., 2016; Parton et al., 1998). The DayCENT model has shown good agreement with measured soil C fluxes in CS under conventional and no-till soil management (Chang et al., 2013). Ogle et al. (2010) estimated SOC stocks in U.S. croplands with the Century model (i.e., the monthly version of DayCENT), and Ogle et al. (2012) assessed the impact of no till with Century. The greenhouse gas emission estimates from agriculture for the U.S. Inventory of Greenhouse Gas Emissions and Sinks are also based on DayCENT simulations (EPA, 2017). In addition, the soil C submodel and tillage mineralization rates were also included into other models (Lawrence et al., 2019; Levis et al., 2014). The DayCENT model can give regional estimates or predictions of C and N dynamics but requires location-specific climate, soil, and management data for calibration (Rafique et al., 2014), which can be derived from soil sampling and ancillary EC data.

Combined long-term soil C, EC, and crop observation are important data sets to quantify soil C stocks and model the impact of crop and soil management. In this study, EC flux towers measured F_c and soil sample analysis quantified soil C and N dynamics between 2005 and 2016 in a conventional CS rotation in central Iowa. The field data-calibrated DayCENT model simulated how soil C stocks changed in the studied fields. The objective of this study was to assess the effect of conventional CS impacts on soil C dynamics by using a multimethodological approach. The combined approach of long-term field data analysis and modeling contributes to the ongoing debate on how to grow crops sustainably in one of the most productive agricultural regions.

2. Materials and Methods

2.1. Site Description

The study was conducted on two adjacent farmer-managed fields in Story County, Iowa, planted with a corn-soybean annual rotation for >20 yr (Figure 1). The east field (41.975°N, 93.691°W) has a size of 31.5 ha, and the west field (41.975°N, 93.694°W) a size of 25.8 ha, with both at 315 m above sea level. The east field was planted with corn in odd years and with soybean in even years, and vice versa for the west field. The crops are rainfed, and planting and harvest are weather dependent. Planting and harvesting of soybeans are late April (late June in 2013) and mid-September to mid-October, respectively. The mean ± standard deviation (SD) of days after planting (DAP) was 172 ± 19. Corn is generally planted from mid-April to mid-May with harvest occurring between mid-September and early November (144 ± 16 DAP).

The crops were produced under conventional soil and fertilizer management practices. Prior to corn planting, 168 kg N ha^{-1} of anhydrous ammonia was injected into the soil of the soybean fields. The farm manager tills the soil with a field cultivator prior to planting, and again to a depth of approximately 30 cm after corn harvest using a chisel plow. This incorporates the remaining corn residues after harvest into the soil. After the soybean harvest, P_2O_5 and K_2O were applied according to soil fertility tests with a field cultivator. There were no cover crops planted during the off season. Table 1 summarizes important site-specific data.

2.2. Soils, Soil Sampling, and Processing

The soils of the sampled fields belong to the Clarion-Webster-Nicollet association and are located on the Des Moines lobe (Table 1). The soil classifications (USDA) are mesic Typic Hapludolls, mesic Aquic Hapludolls, and mesic Typic Endoaquolls (Hernandez-Ramirez et al., 2010). These soils originate from glacial till under the influence of the former prairie vegetation and relief (DeWitt, 1984). The soils are generally poorly drained (DeWitt, 1984), which required the installation of a subsoil tile drainage system to reduce water logging conditions in the spring.

The first soil sampling occurred in October 2005 (Anex et al., 2011), after harvest and prior to fall tillage, where 42 locations in a 50 m × 50 m grid were identified in each field (Figure 1). Soil cores 116 ± 8 cm length (±SD) and 38.2 mm diameter were taken ($n = 84$) at each location using a truck-mounted hydraulic deep soil core sampling system (Giddings Inc., Windsor, CO, USA). The second field sampling was in October 2016 after harvest and prior to fall tillage. The same grid and sampling methods as in 2005 was used, where soil cores of mean length 105 ± 15 cm and a diameter of 38.2 mm were extracted.

All cores were cut into segments of 0–15, 15–30, 30–60, 60–90, and 90–120 cm. Note that at 12 locations in 2016, there were no soil segments from 90–120 cm extracted. The extracted soil core segments were weighed field moist and then air dried. Air-dried soil was sieved to <2 mm, and coarse materials (>2 mm) were separated and weighed. A subsample was weighed fresh and oven dried at 105°C for 24 hr.

2.3. Chemical Soil Analysis

A core-segment subsample was fine ground (<0.25 mm) with a roller mill for total carbon (TC) and nitrogen (TN) and soil inorganic carbon (SIC) analysis. TC and TN concentration were measured with a C-N Analyzer using the dry combustion method (2005: Fison NA 15000 Elemental Analyzer, ThermoQuest Corp., Austin, TX; 2016: Flash 1112, Thermo Finnigan, San Jose, CA; reagents: silvered cobaltous oxide and chromium oxide, copper granules, and magnesium perchlorate). A 5-to-30-mg sample is weighed into tin capsules,

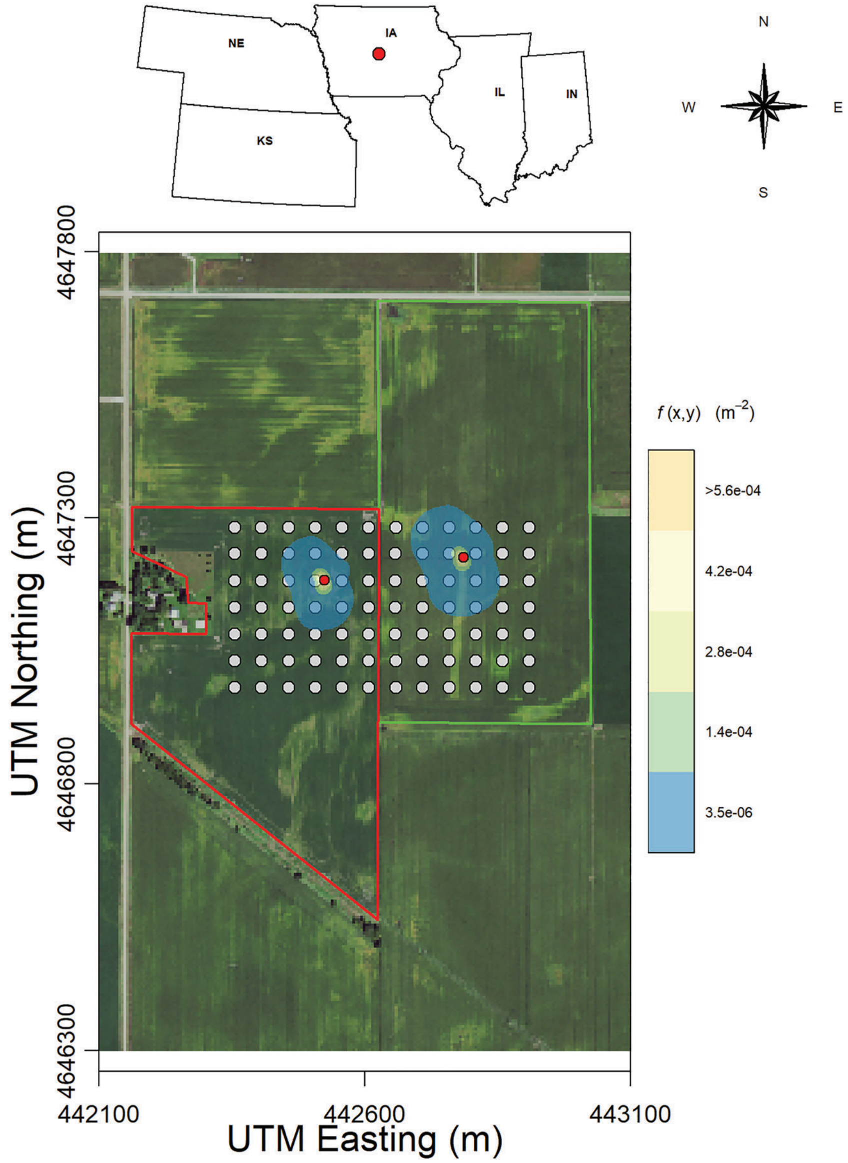

Figure 1. Map of the study area with the east (green border) and west field (red border) with corn and soybean production. The red circles show the position of the eddy flux stations with its 80% footprint climatology $f(x/y)$ (m^{-2}) in 2015 (Kljun et al., 2015), and the gray circles show the 50 × 50 m soil sampling grid in 2005 and 2016. Imagery from growing season 2015 (USDA-FSA-APFO, 2017). Small map above shows the Midwestern States of Iowa (IA), Nebraska (NE), Kansas (KS), Indiana (IN), and Illinois (IL) with the site location marked with a red circle.

and the samples are flash combusted. A first-order calibration curve was established using five atropine standards ($R^2 >= 0.999$ accepted), and five additional soil, plant, and acetanilide standards were run for quality control prior to analysis. SOC concentration was calculated as the difference between TC and SIC, of which the latter was measured with pressure calcimetry (Sherrod et al., 2002). The pressure increase from CO_2 evolution is measured after adding 2 ml of 50% hydrochloric acid with 3% ferrous chloride to 1 g of soil sample. The pressure is measured using a pressure transducer (Setra Systems, Boxborough, MA, USA), which converts pressure into an electrical signal, and a voltmeter (ECM Industries, LLC, New Berlin, WI, USA) to read the voltage. A linear calibration curve derived from 11 standards of known $CaCO_3$ content is used ($R^2 >= 0.995$ accepted) to convert voltage into SIC content. Blanks, standards, and duplicate samples are run with the samples for quality control. The samples are allowed to react for 6 hr prior to measurement. The soil pH in 0–15 cm soil depth was measured on 20 g of soil (<2 mm) in a 1:1

Table 1
Site Specifics (Location, Soils, Crop Management)

Variable	West field	East field
Latitude, Longitude (dec. °)	41.975, −93.694	41.975, −93.691
Field size (ha)	31.5	25.8
Soil type	Canisteo, Harps, Okoboji, loam-clay loam	Canisteo, Harps, Okoboji, loam-clay loam
Soil texture % (clay, silt, sand)	27, 34, 38	29, 37, 34
Bulk Density (g cm^{-3})	1.25	1.25
Cropping system	Corn-soybean rotation	Corn-soybean rotation
No. corn years 2005–2016	5	6
No. soybean years 2005–2016	6	5
Tillage	Spring, fall after corn harvest	Spring, fall after corn harvest
Fertilizer N rate (kg N ha^{-1} yr^{-1})	Anhydrous-N: 168 (corn-years only)	Anhydrous-N: 168 (corn-years only)
Mean density (plants ha^{-1})	Corn: 82,700 Soybean: 295,000	Corn: 84,200 Soybean: 333,000
Range planting—harvest DOY	Corn: 107–309 Soybean: 112–292	Corn: 104–310 Soybean: 120–282

soil-water suspension using a calibrated pH meter. Twenty milliliters of double-distilled water was added to the air-dry soil sample, and the suspension was mixed for 30 min on a horizontal shaker (120 cycles per minute). The pH electrode was placed into the suspension, and pH measured after the reading became stable. Double readings were taken, and the mean value was used for further analysis.

2.4. Equivalent Soil Mass

The TC, TN, SOC, and SIC content (in Mg ha^{-1}) were calculated using the equivalent soil mass calculation (Wendt & Hauser, 2013). The classic volume-based calculation with bulk density (BD) is susceptible to errors, because BD changes during the season, over long time periods, owing to soil management, and differs among sampling methods (Dold et al., 2018; Folegatti et al., 2001; Wuest, 2009). The equivalent soil mass approach calculates the C and N content of soil (referred to as TN_m, TC_m, SOC_m, and SIC_m, respectively) without using BD (Wendt & Hauser, 2013):

$$x_m = \frac{S_m * \%x}{100}, \tag{1}$$

where x_m = mass-based TC_m, SOC_m, and TN_m (Mg ha^{-1}); S_m = soil mass (Mg ha^{-1}); and $\%x$ = TC, SOC, and TN concentration.

The S_m of each soil core segment is calculated as

$$S_m = \frac{(DW_t - DW_c)}{(A_t * n)} * 10,000, \tag{2}$$

where DW_c = coarse fragment DW (g); A_t = sampling area (here 1,146 mm^2); and n = number of composite samples (here 1).

A cubic function was fitted with cumulative x_m as dependent and cumulative S_m as independent variable (cumulated by depth) (Figure 2). The fitting parameters of the cubic functions are then used to calculate TC_m, SOC_m, and TN_m at a reference soil mass of interest (m_{ref}). The SIC_m was calculated as the difference between TC_m and SOC_m. Note that TC_m, SOC_m, and TN_m refer to soil mass and not soil depth. A reference soil depth which corresponds to m_{ref} is used throughout, which was calculated as a cubic fit with soil depth (cm) as dependent and S_m as independent variable (Figure 2d). The m_{ref} was set to 2,060, 4,400, 8,900, 13,600, and 17,800 Mg ha^{-1}, which corresponds to similar soil core segment depths of 15, 31, 61, 91, and 116 cm, respectively (Figure 2d). The applied cubic functions were prone to calculate erroneous TC_m, SOC_m, and TN_m when extrapolated (that is, m_{ref} beyond minimum and maximum cumulative S_m). In this study, TC_m, SOC_m, and TN_m were not calculated, when m_{ref} undercut or exceeded cumulative S_m by factor 0.01 and 1.15, respectively (Figure 2).

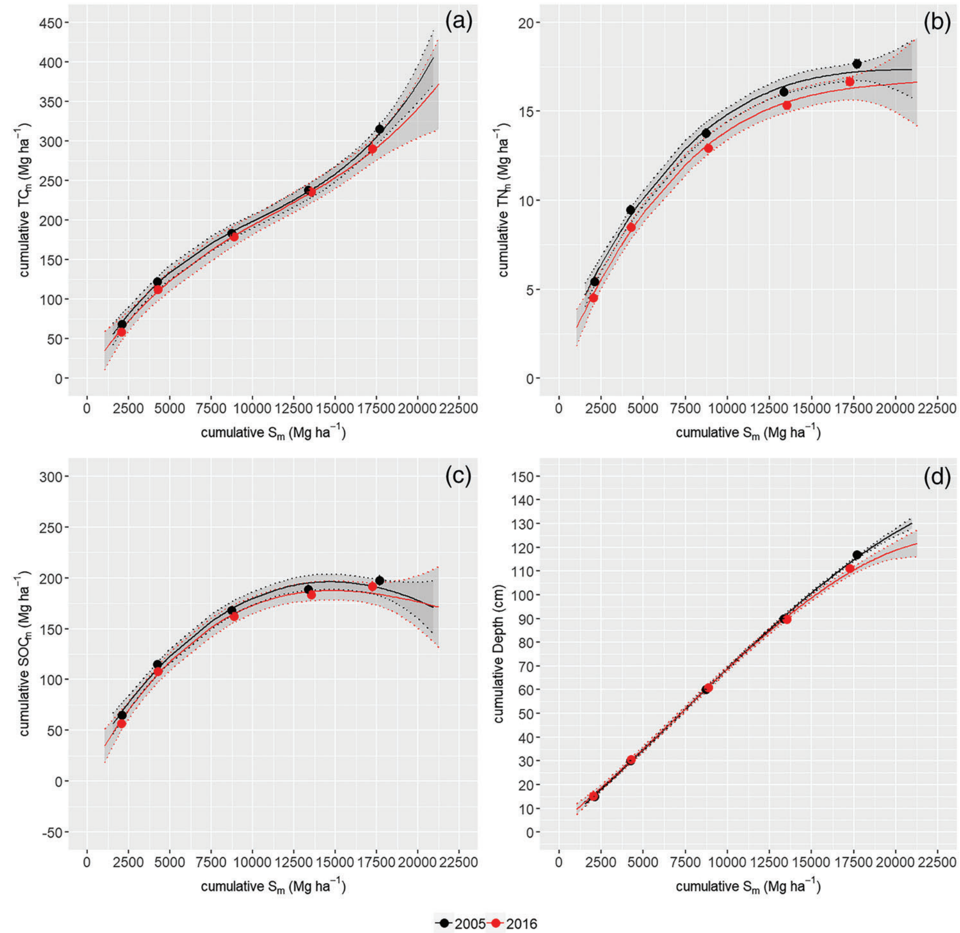

Figure 2. Cubic function with cumulative S_m (mg ha^{-1}) as independent and cumulative TC_m, TN_m, and SOC_m (all in mg ha^{-1}) (a–c) and reference soil depth (cm) (d) in 2005 (black) and 2016 (red). The solid line shows the mean fit among all cores, and the dotted line and enclosed gray area shows the 95% confidence bands. The functions are used to calculate the equivalent soil mass with m_{ref} (Wendt & Hauser, 2013).

2.5. EC and Ancillary Data

The latent (LE) and sensible heat (H) fluxes and F_c were recorded continuously with two EC flux stations from October 2005 harvest to October 2016 harvest (Figure S1 in the supporting information). Note that EC data sets from 2005–2015 have previously been published (Dold et al., 2017; Hernandez-Ramirez et al., 2011), to investigate F_c among crops and agro-ecosystems. The EC approach had been described previously (Burba, 2013). Two EC stations were located inside the soil sample grid on each field, so that the EC footprint represented much of the sampled area (Kljun et al., 2015) (Figure 1). Both EC stations have an open-path, high-frequency infrared gas analyzer (IRGA LI-7500, LICOR Biosciences, Lincoln, NE, USA) and a 3-D sonic anemometer (CSAT, Campbell Scientific, Logan, UT, USA), of which the former measures water vapor and carbon dioxide densities and the latter measures wind speed components in three directions and sonic temperature. Each IRGA and sonic anemometer are installed at a height between approximately 1.5 and 5.5 m, depending on crop and season. All fluxes were computed as the mean covariance between carbon dioxide, water vapor density, and sonic temperature with vertical wind velocity. Sonic temperatures were transformed to actual air temperature using vapor pressure and air temperature from the Vaisala temperature humidity sensor. The fluxes were coordinate rotated (Tanner & Thurtell, 1969) and corrected for temperature and air density variations (Webb et al., 1980).

In addition, the EC stations were instrumented with a four-component net radiometer (CNR-1, Kipp and Zonen, Delft, the Netherlands), an air temperature and relative humidity probe (Vaisala HMP45c, Vaisala, Vantaa, Finland), and a tipping bucket for precipitation measurements (Texas Electronics TE 525,

Table 2
EC Station Instrumentation (Sonic, IRGA, and Radiation Specifics, Measurement Height, Measurement Frequency, and Sonic Direction)

Variable	West field	East field
Ameriflux code	US-Br1[a]	US-Br3[a]
IRGA model	LI-7500[b]	LI-7500[b]
3-D Sonic anemometer model	CSAT-3[c]	CSAT-3[c]
Range zm (cm)	150–530	150–530
Frequency (Hz)	10 (2005–2013)/20 (2013–2016)	10 (2005–2011)/20 (2011–2016)
Azimuth from North	180 (2005–2011)/270 (2012–2016)	180 (2005–2011)/270 (2012–2016)
Radiation sensor model	CNR-1[d]	CNR-1[d]

Note. Sonic = 3-D sonic anemometer; IRGA = infrared gas analyzer; z_m = measurement height.
[a]Retrieved from SSURGO database (USDA-NRCS, 2018). [b]LICOR Biosciences Inc., Lincoln, NE, USA. [c]Campbell Scientific, Inc., Logan, UT, USA. [d]Kipp & Zonen, Delft, the Netherlands.

Campbell Scientific, Logan, UT, USA). Other ancillary data at this station include measurements of soil heat flux, soil temperature, and soil moisture content, which are not subject of this study. The sampling rate of the sonic anemometer and IRGA changed from 10 to 20 Hz in 2013 on the west field and in 2011 on the east field. The ancillary instrumentation was sampled at 0.1 Hz. All data were stored on data loggers (CR5000 and CR3000, Campbell Scientific, Logan, UT, USA) as 15-min interval averages (Table 2).

The EC data set was screened for statistical outliers and sensor errors and thereafter interpolated. Outliers in the EC data set were defined by (1) empirically set thresholds and (2) exceeding a limit based on the interquartile range (IQR) as first/third quartile ± 3.5 * IQR. Rainfall events (Hernandez-Ramirez et al., 2011), periods of water condensation (Baker & Griffis, 2005), low wind turbulence intervals ($u^* < 0.1$ m s^{-1}) (Baker & Griffis, 2005), signals recorded at wind directions opposite to the sensor head (Hernandez-Ramirez et al., 2010), and periods flagged by the internal IRGA and CSAT warning systems were excluded. In addition, the Vaisala humidity probe was used to screen LE (Schmidt et al., 2012); an empirically derived difference of 10 g m^{-3} water vapor density between both sensors was used as a threshold level. Approximately 46–68% of the original 15-min F_c data was retained after gap screening. The EC data set was interpolated following an inverse-weighted time-average approach (Hernandez-Ramirez et al., 2010). Missing nighttime F_c was calculated using the exponential relationship between air temperature and F_c as described in Lloyd and Taylor (1994), and following the approach described in Reichstein et al. (2005), however, using a static 2-week time window. Missing daytime F_c was calculated with daily light response curves using a rectangular hyperbola (Gilmanov et al., 2007). A daily data set was generated by calculating daily averages and multiplying by the daily sample size. The annual NEP was calculated with daily mean F_c multiplied with the number of days per year. The NEP has negative values for fluxes from the surface to the atmosphere, and vice versa. Details on screening and interpolation as well as data uncertainty are described in literature (Dold et al., 2017). The mean annual energy balance closure for 2004–2007 was 0.807 and 0.873 for soybean and corn, respectively (Hernandez-Ramirez et al., 2010). Footprint analysis, outlier screening, and gap filling were done in R (R Core Team, 2019).

2.6. Yield, Crop Residues, and NBP

Beans and kernels were weighed at yearly harvest with yield monitors. A moisture content of 15.5% and 13.0% for corn and soybean, respectively, was assumed, which are typical values for this region at harvest (Karlen et al., 2015). Yield C was estimated with a C concentration of 44.7% and 54% (Bernacchi et al., 2005). The NPB was calculated as the difference between annual NEP and Yield C. Crop residues were calculated as the difference between yields at 0% moisture and the estimated above-ground biomass. The above-ground biomass was estimated as yield divided by the Harvest Index of 0.50 and 0.57 for corn and soybean, respectively (Pedersen & Lauer, 2004). Residue C was estimated with 44.5% and 33.1% for corn and soybean, respectively (Al-Kaisi et al., 2005).

2.7. DayCENT Modeling

DayCENT has been widely used to simulate yield and greenhouse gases under a variety of agroecosystems and climate scenarios (Bista et al., 2016; Chang et al., 2013; Del Grosso et al., 2009; Rafique et al., 2013).

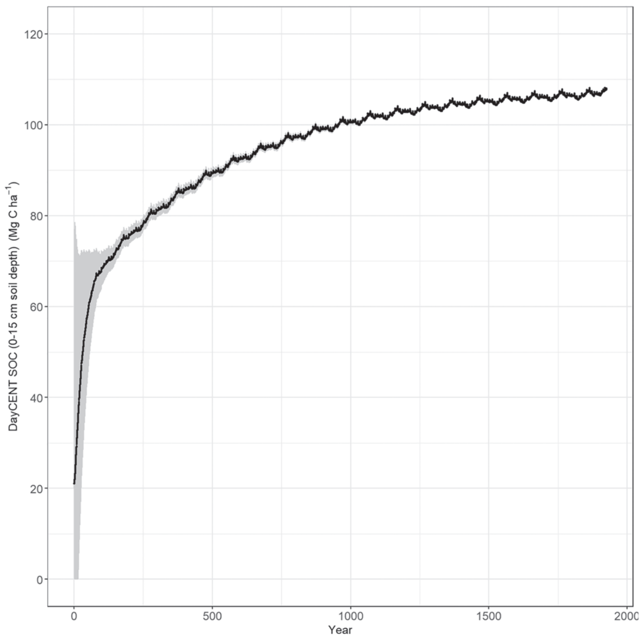

Figure 3. Time series plot of DayCENT model initialization for 1,925 yr as mean (±SE) SOC (mg ha^{-1}) in 0–15 cm soil depth, n = 2 fields.

DayCENT is documented broadly in terms of model descriptions, parameterization, and calibration procedures (Necpálová et al., 2015; Nocentini et al., 2015; Parton et al., 1998). In short, DayCENT is a process-based model that simulates the production and decay of organic matter through a collection of crop growth, water flow, and nutrient cycling submodels.

The model assumes three conceptual pools of soil C that vary based on turnover rates (active = annual, slow = decadal, and passive = centurial turnover). A 1,925-yr initialization period allowed these C pools to reach a state of pseudo-equilibrium (Figure 3). On-site soil properties were used to construct site files (Table 1). Stochastic daily climate data consisting of precipitation and min/max temperature using historic measurements at a nearby weather station were generated with the CLIGEN software (Nicks et al., 1995). During the 1,925-yr initialization period, the study fields were assumed to be under a perennial tall grass prairie (big bluestem; *Andropogon gerardii Vitman*), with light grazing and a fire frequency of 10 yr (Hart, 2001; Kaiser, 2011; Risser et al., 1981). The equilibrated soil C stocks in the top 15 cm were approximately 105 Mg C ha^{-1}, which agrees well with reported surface stocks in Midwestern native tallgrass prairie systems (Davidson & Ackerman, 1993; DeLuca & Zabinski, 2011; Mann, 1985).

After the initialization period, a sequence of historic management practices that were common of the study region were generated (Papanicolaou et al., 2015). Table 3 provides details on each rotation or time block. It was assumed that the tall grass prairie was plowed under beginning in 1925 to make way for crop production and implemented a diverse 5-yr rotation of corn-corn-oat-meadow-meadow (CCOMM). In Years 1 and 2 of the rotation, corn was planted with a moldboard plow used for both spring and fall tillage. In Year 3, oats (*Avena sativa*) were planted as a companion crop with alfalfa (*Medicago sativa*). Oat grain was harvested and baled for straw and in Years 4 and 5 of the rotation; the alfalfa was cut and baled for hay twice per year. Organic (manure) fertilizer was applied in both fall and spring. By 1950, the crop rotation shifted to a more intensely managed 3-yr rotation of corn-corn-soybeans (CCS), as organic (manure) applications began to be replaced by urea and the chisel plow was adopted for fall and spring tillage (Keeney & Hatfield, 2008). By 1970, the rotation switched to a conventional 2-yr corn-soybean rotation (CS) with inorganic fertilizer in the form of anhydrous N being applied after soybean harvest. The abovementioned management scenarios were simulated from 1900–2005 using measured daily climate data from a nearby weather station (Iowa Environmental Mesonet).

The plant production submodel in DayCENT was calibrated next to ensure accurate inputs of plant (organic) material were being supplied to the soil (Chapin et al., 2011). The management practices in Table 3 were used to construct a detailed schedule file. County-level grain yield averages of corn and soybeans from

Table 3
Summary of Historic Management Practices Used in Model Simulations

Time period	Management	Rotation (year)	Crop	Tillage	Fertilizer
1926–1950	CCOMM	1	Corn	MP	Organic (manure)
		2	Corn	MP	
		3	Oats	—	
		4	Alfalfa	—	
		5	Alfalfa	—	
1951–1970	CCS	1	Corn	CP	Organic (manure) urea
		2	Corn	CP	
		3	Soybean	CP	
1970–2005	CS	1	Corn		Inorganic
		2	Soybean		

Note. CCOMM = corn-corn-oats-meadow-meadow; CCS = corn-corn-soybean; CS = corn-soybean; MP = moldboard plow; CP = chisel plow.

Table 4
DayCENT Parameterization for Corn-Soybean Rotations

Site parameter		Units	Value
PRDX(1)	Potential production coefficient	—	CORN (0.7–1.00) SBYN: (0.25–0.75)
PPDF(1)	Optimal production temperature	°C	CORN (30) SBYN: (27)
PPDF(2)	Max production temperature	°C	CORN (45) SBYN: (40)
HIMAX	Max harvest index	—	CORN (0.5) SBYN: (0.57)
DEC1(2)	Max structural litter decay rate	yr^{-1}	1.00
DEC2(2)	Max metabolic litter decay rate	yr^{-1}	4.00
DEC3(2)	Max active soil carbon decay rate	yr^{-1}	3.00
DEC4(2)	Max passive soil carbon decay rate	yr^{-1}	0.048
DEC5(2)	Max slow soil carbon decay rate	yr^{-1}	0.162

1925–2005 were used in the calibration of the plant production (NASS, 2020). Because yields increased so dramatically over the span of 1925–2005, unique crop types of corn ($n = 6$) and soybeans ($n = 3$) were constructed by varying the potential production coefficient PRDX (1) of the plants. The optimal production temperature, PPDF (1), for all corn and soybean types were 30°C and 27°C, respectively. Likewise, the maximum temperature that production would occur, PPDF (2), was fixed at 45°C for corn and 40°C in soybeans. The yield data were corrected for seed moisture, and the yield C was estimated assuming a C concentration of 44.7% and 54% for corn and soybeans, respectively (Bernacchi et al., 2005). The maximum harvest index for corn and soybeans for all types was fixed at 0.5 and 0.57, respectively. The decay rates for the SOC and litter pools used for this study are found in Table 4.

The model was run, and an iterative scheme was performed changing the potential production of crops to match simulated (predicted) yield C with actual values. From 2006 to 2016, yield data from grain monitors in both fields were used (section 2.6). The study fields have been monitored extensively since 2005, which allowed a detailed schedule file to be built using documented management events and observations including planting, emergence, and fertilizer, tillage, and harvest dates (Table 1). Daily climate data from the EC stations provided climatic parameters including air temperature, wind speed, rain, and relative humidity for the modeling of the 2006–2016 period. Simulated NEP values were compared to measured values of NEP (section 2.5). Once the model was calibrated, the model was run to see how simulated SOC stocks compared with measured SOC_m (0–15 cm soil depth) in 2005 and 2016 (section 2.4).

2.8. Data Analysis

Changes in TC, SOC, SIC, and TN content and concentration in each soil layer were calculated as the difference between 2005 and 2016. The spatial autocorrelation of the differences was analyzed with Moran's *I* test ($p < 0.05$) (Moran, 1950). Where samples were spatially independent, changes in TC, SOC, SIC, and TN in each layer were statistically analyzed using two-sided one-sample *t* tests, tested against a true mean of zero (i.e., whether there is a significant difference to zero change at $p < 0.05$, $n = 84$ locations). The rate of change was calculated as cumulated ΔTC, ΔSOC, ΔSIC, and ΔTN to the soil layer of interest, divided by number of years (i.e., 11 yr).

Total NEP and NBP were summed from 2005–2016. The change of NBP over time was statistically analyzed with a mixed linear effect model with cumulative NBP as dependent variable, Year (2005–2016) as fixed effect and Site (east and west field) as random effect ($n = 24$). DayCENT NEP was validated with regression analysis with the root mean square error (RMSE) as a measure of model accuracy. The R script for calculating equivalent soil mass C and N was previously published (Dold et al., 2018). Mixed effect models were created with the R package *nlme* (Pinheiro & Bates, 2000), Moran's *I* was calculated with the R package *ape* (Paradis & Schliep, 2018), and *t* tests were performed with the R package *stats* using the program language R (R Core Team, 2019).

3. Results

3.1. Soil Chemical Parameters

There were statistically significant changes of TC, SOC, SIC, and TN concentration from 2005 to 2016, depending on soil layers (Figures 4a–4d). Mean TC (±standard error of the mean; SE) significantly

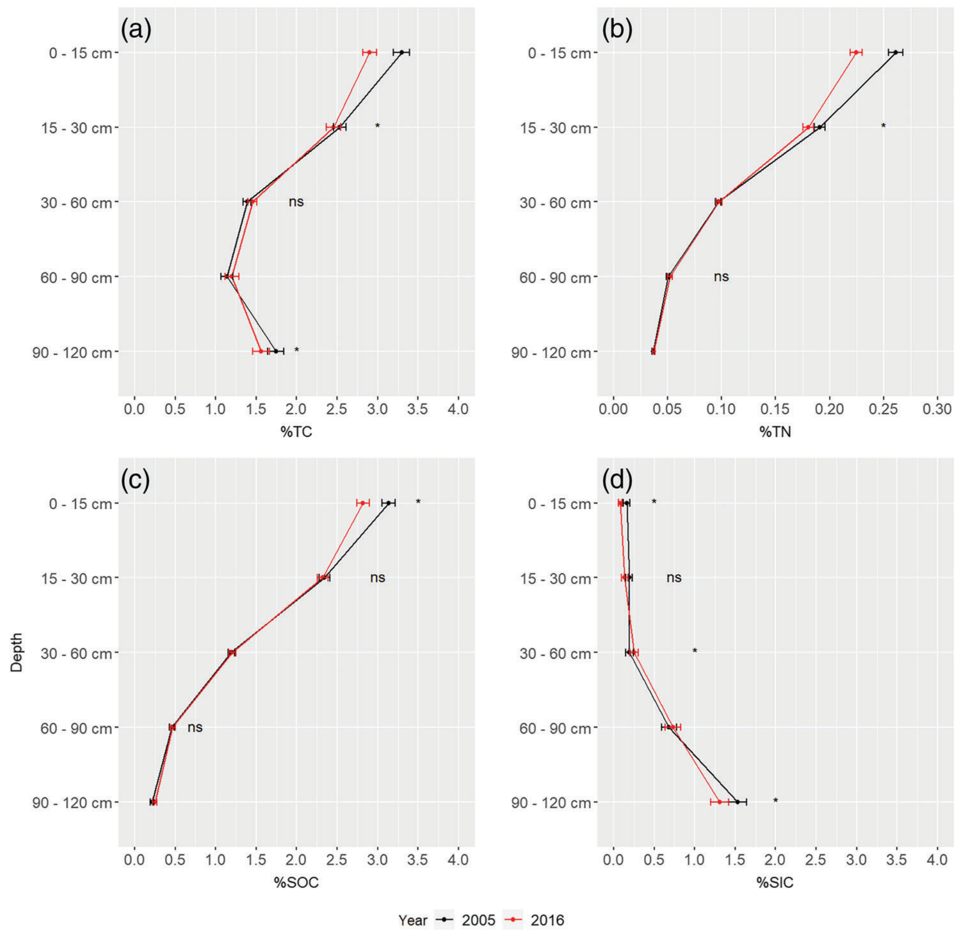

Figure 4. Mean (±SE) percent total carbon (TC), total nitrogen (TN), soil organic carbon (SOC), and soil inorganic carbon (SIC) (a–d) in 0–15, 15–30, 30–60, 60–90, and 90–120 cm in 2005 (black) and 2016 (red), respectively; ns = not significant; * = $p < 0.05$.

decreased in the 15–30 and 90–120 cm layers from 2.53% ± 0.08% and 1.74 ± 0.10% in 2005 to 2.46% ± 0.09% and 1.56% ± 0.10% in 2016, respectively (Figure 4a). Mean TN also decreased significantly in the 15–30 cm layer from 0.191% ± 0.005% in 2005 to 0.180% ± 0.005% in 2016 (Figure 3b). The reduction in TC concentration was related to a significant decrease of SOC in the top soil (Figure 4c) and a significant decrease of SIC in the subsoil (Figure 4d), respectively.

The change (±SE) in mass-based C and N in each layer was calculated for the 11-yr period (Figure 5). The ΔTC_m significantly declined at 0–15 and 90–120 cm, while in other soil layers there was no significant change detected. The ΔTC_m in the tilled 0–30 cm layer was −9.48 ± 1.27 Mg ha^{-1}, corresponding to a rate of −0.86 ± 0.12 Mg ha^{-1} yr^{-1}. The ΔTC_m summed to −14.19 ± 6.25 Mg ha^{-1} for the 0–120 cm layer (Figure 5a), which corresponds to a rate of −1.29 ± 0.57 Mg ha^{-1} yr^{-1}. The reduction of TC_m was connected to significant decreases of both, SOC_m and SIC_m. The SOC_m content decreased in the top 0–15 cm layer with −6.25 ± 0.73 Mg ha^{-1}, while other soil layers experienced no significant change during this 11-yr period (Figure 5c). Top soil pH in the 0–15 cm layer decreased by −0.44 ± 0.11, from 6.50 ± 0.07 in 2005 to 6.06 ± 0.08 in 2016.

The ΔTN_m significantly declined in the 0–15 cm layer by −0.75 ± 0.06 Mg ha^{-1} and significantly increased in the 60–90 cm layer by 0.22 ± 0.08 Mg ha^{-1}. The cumulative ΔTN_m for the 0–120 cm depth was −0.71 ± 0.08 Mg ha^{-1}, or −0.064 ± 0.026 Mg ha^{-1} yr^{-1} (Figure 5b). This decline in N was not compensated for by N fertilizer application, which summed to a total of 0.92 ± 0.08 Mg N ha^{-1} in the 11-yr period (see section 2).

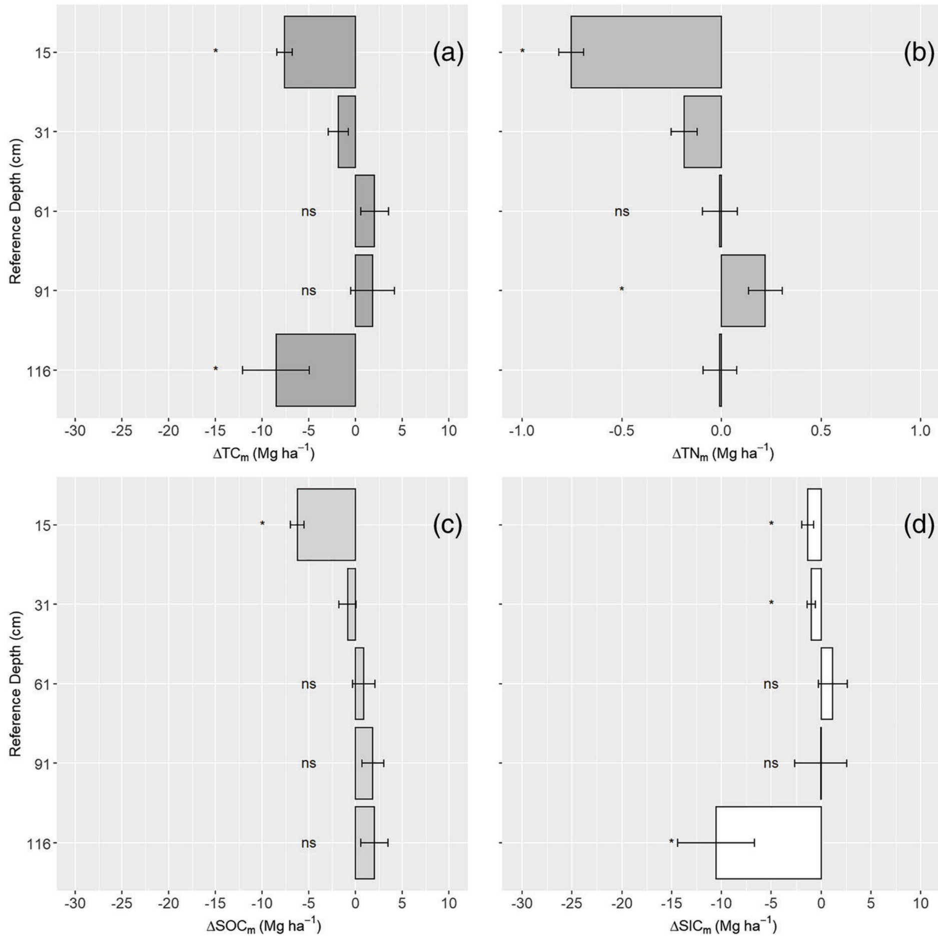

Figure 5. Changes in soil chemical parameters (ΔTC, ΔSOC, ΔSIC, and ΔTN, all in mg ha^{-1}) (a–d) between 2005 and 2016 from 0–120 cm; ns = not significant; * = $p < 0.05$.

3.2. NEP and NBP

A total NEP (±SD) of 19.39 ± 1.86 Mg ha^{-1} was taken up by the corn-soybean rotation agroecosystem from October 2005 to October 2016. The NEP was higher in corn-years (−0.54–4.9 Mg ha^{-1}) than soybean-years (−2.01–0.81 Mg ha^{-1}). Total yield C was 32.57 ± 1.81 Mg ha^{-1} and represents the amount of C removed from the field at harvest. The total NBP was estimated to −13.19 ± 0.05 Mg ha^{-1}, and corn and soybean NBP ranged from −1.69 to 0.53 and from −3.68 to −0.78 Mg ha^{-1}, respectively. A relationship between cumulative NBP and time was statistically significant ($p < 0.05$) with a slope (rate) of −1.20 ± 0.06 Mg ha^{-1} yr^{-1} (Figure 6). There was a total amount of 27.36 ± 1.92 Mg ha^{-1} of residue C input, which was left in field. Note that this input is not considered for NBP calculations, as respiration losses from residues (or its lack of it) would be monitored by the EC station (Figure 6).

3.3. DayCENT Simulation of C Stocks

The simulated and actual yield C were similar in trend and magnitude with a RMSE of 0.25 Mg C ha^{-1} and R^2 = 0.94 (Figure 7a). Simulated annual NEP followed measured EC-derived NEP with a RMSE of 77.96 g C m^{-2} and R^2 = 0.93 (Figure 7b). The simulated SOC in the 0–15 cm soil layer decreased from 64.7 ± 0.6 in 2005 to 59.0 ± 1.1 Mg ha^{-1} in 2016, which is similar to measured SOC$_m$ values (see section 3.1; Figures 7c and 8). The active pool layer decreased by 20%, from 2.25 to 1.81 Mg C ha^{-1}. The slow and passive C pool decreased from 15.8 to 12.4 and from 46.7 to 44.8 Mg C ha^{-1}, which corresponds to a reduction by 22% and 4%, respectively (Figure 8).

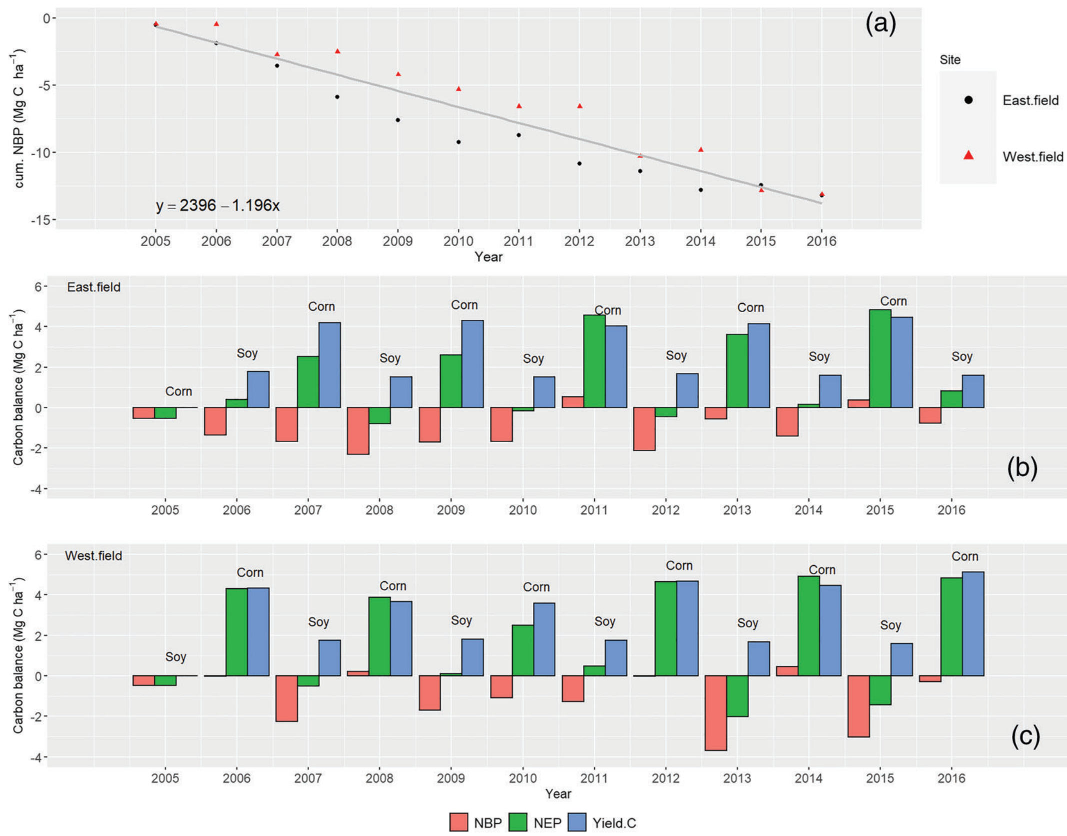

Figure 6. (a) Cumulative NBP (mg ha^{-1}) versus time on the east (black circle) and west field (red triangle); total eddy covariance derived net ecosystem production (NEP), yield C, and net biome production (NBP) (all in mg ha^{-1}) from October 2005 to October 2016 for (b) the east field and (c) the west field.

4. Discussion

Corn-soybean rotations are economically important cropping systems in the Midwestern United States and can impact the regional C and N cycles as vast land areas are cultivated with both crops. The sustainable cultivation of corn and soybeans includes maintaining soil C and N stocks, which benefits crop growth and yield and may partially ameliorate negative effects of climate change. Small changes in crop and soil management may have substantial impact on the regional scale C and N dynamics. However, long-term, deep-layer soil C and N data in combination with C fluxes are still scarce to fully evaluate the impact of corn-soybean cropping on soil C and N; such data sets would also allow validating model simulations. In this study, the change in soil parameters was investigated in two farmer-managed corn-soybean rotation systems in Central Iowa, from 2005–2016. Two methods were applied: (1) deep-core soil sampling for the analysis of SOC, SIC, TC, TN, and pH and (2) the EC method to estimate NEP and NBP as a measure of the apparent change in soil C. The two data sets were then used to (3) calibrate DayCENT in order to investigate how management practices affect SOC.

4.1. Reduction of Soil C and N as Observed With Soil Sampling

Deep-core soil sampling during the 11-yr period showed that soil C and N and soil pH significantly decreased in the observed CS fields. While observed TN_m overall decreased, a substantial share of soil TN was not lost from the agroecosystem but redistributed to deeper soil layers. This is in accordance to Schmer et al. (2014), where soil N in the 0–60 cm layer decreased, while it increased in the 60–150 cm layer in conventionally managed corn production. Nitrogen in the form of NO_3^- is very mobile in the soil solution and susceptible to leaching, especially during the off-season without plant cover. We postulate that TN_m may first have accumulated in deeper soil layers as NO_3^- and subsequently discharged through drainage lines. Recurring tillage may be the reason for the observed reduction of SOC and TN in the upper 30 cm soil layer, since long-term

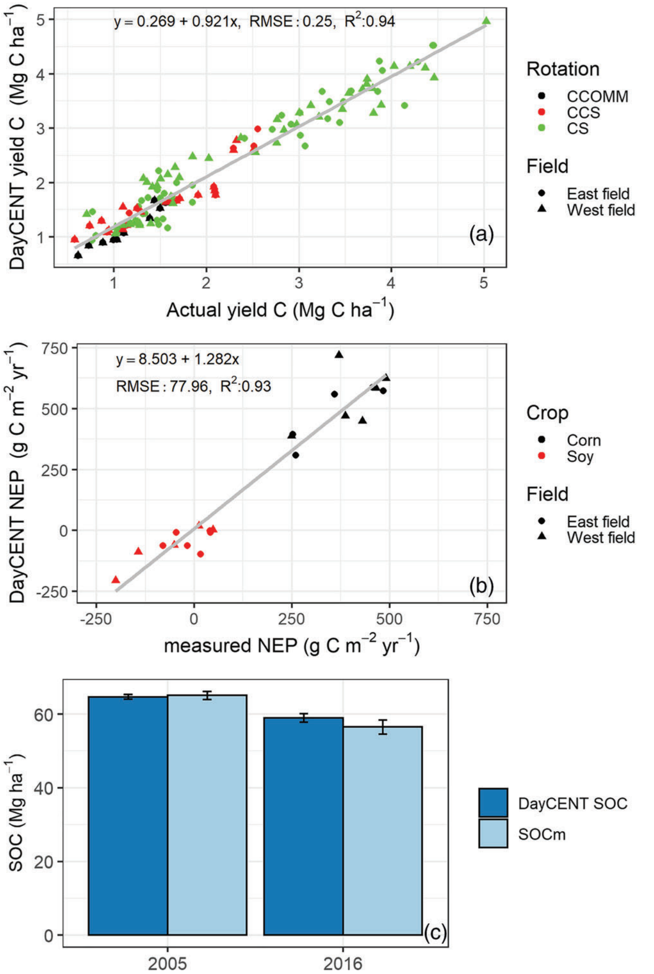

Figure 7. DayCENT model evaluation: (a) simulated yield C from the east field (circles) and west field (triangles) against county yield C data for three rotation systems: corn-corn-oats-alfalfa meadow-alfalfa meadow (CCOMM), corn-soybean-oats (CSO), and corn-soybean (CS) for the time period 1926–2016; (b) measured versus modeled annual NEP (g C m^{-2}) for corn (black) and soybeans (red) on the east field (circles) and west field (triangles), respectively; (c) mean (±SE) DayCENT SOC (dark blue) and SOC_m (light blue) in 0–15 cm in 2005 and 2016, respectively.

studies showed that the tilled soil layer loses more soil C compared to reduced tillage (Baker et al., 2007). Calculated SOC rates in topsoil (0–30 cm) range from −0.13 to −1.25 Mg ha^{-1} yr^{-1} for 23 yr of continuous corn (Moorman et al., 2004), −0.21 to 0.30 Mg ha^{-1} yr^{-1} for 12 yr of CS (Russell et al., 2005), and −0.39 Mg ha^{-1} yr^{-1} for 10 yr of continuous corn (Schmer et al., 2014). This agrees with the findings of this study that the topsoil (0–30 cm) SOC and TN are negatively affected in conventional CS rotations. This study did also show that subsoil SOC is not affected.

A possible reason for the reduction of observed SIC could be the reaction of soil carbonates (e.g., calcium carbonate, $CaCO_3$) with H^+ ions, which eventually can lead to bicarbonate (HCO^{3-}) and CO_2 formation (Emmerich, 2003). One source of H^+ ions in the top soil (i.e., acidification) could be the anhydrous N fertilizer, which is injected after soybean harvest in the rotation sequence. The NH_3 in the fertilizer oxidizes to NO_3^- releasing H^+ ions into the soil solution. Repeated anhydrous N application has reportedly increased acidification in the top soil, which led to exchangeable Ca and Mg depletion (Bouman et al., 1995). Indeed, top soil pH in the 0–15 cm layer decreased, demonstrating that the amount of H^+ ions increased. Soil pH in the 90–120 cm layer was alkaline (7.90 ± 0.03) in 2016; however, we do not know soil pH in the 90–120 cm layer in 2005, so that it is unknown if soil pH decreased in the subsoil over the study period. In addition, subsoil carbonates are common in the studied soils (DeWitt, 1984). High amounts of soil carbonates discharge this way from agricultural fields in Iowa through drainage lines into rivers (Jones & Schilling, 2013). The CO_2 in the SIC cycle can derive from organic matter (respiration) or from the atmosphere, thus linking organic and inorganic C pools. However, there is no information available on discharge amount and chemical composition of drainage water in these agricultural fields. The presented results stress the importance of deep soil layer carbon and inorganic carbon sources in carbon balance calculations, which is in accordance to previous studies on deep soil sampling (Baker et al., 2007; Harrison et al., 2011; Stahl et al., 2017; Syswerda et al., 2011) and inorganic C (Kindler et al., 2011).

4.2. Carbon Fluxes in Comparison to Soil C Reduction

In addition to soil C chemical analysis, eddy-flux derived NEP and yield C were used to calculate NBP as a measure of soil C change and to monitor the annual carbon balance. The high spatial variation and slow soil C changes impede using soil C analysis over short-term periods (Baker & Griffis, 2005). The EC method can monitor short-term changes of the C budget. However, the NBP is the "apparent" change in SOC (Baker & Griffis, 2005), as EC-derived data are subject to possible F_c underestimation during nighttime, include several assumptions and corrections (Burba, 2013), and depend on various interpolation techniques to compensate for missing data.

The overall positive NEP values indicate that CO_2-C assimilation from plants was higher than CO_2-C release from roots and soil for the CS rotation. The NEP was higher in corn-years than soybean-years (Dold et al., 2017; Verma et al., 2005). Soybean-years were on average C neutral with both sink (i.e., C sequestered) and source years (i.e., C released), while corn-years were always C sinks throughout the observation period (excluding the 2005 corn-year off-season; Figure 5a). Note that the presented sink-source relationships among crops do not include yield C removal. Total yield C was higher in corn-years than soybean-years (Dold et al., 2017) and represents the amount of C removed from the field at harvest. The difference between NEP and yield C is the NBP, which represents the actual amount of C lost or gained from the rotation system. This means that a site-year can be a NEP C-sink, but a NBP C source. If we define C-neutral conditions within the range of $-0.5 < NBP < 0.5$ Mg ha^{-1}, then there were four source, six neutral, and one sink corn site-year,

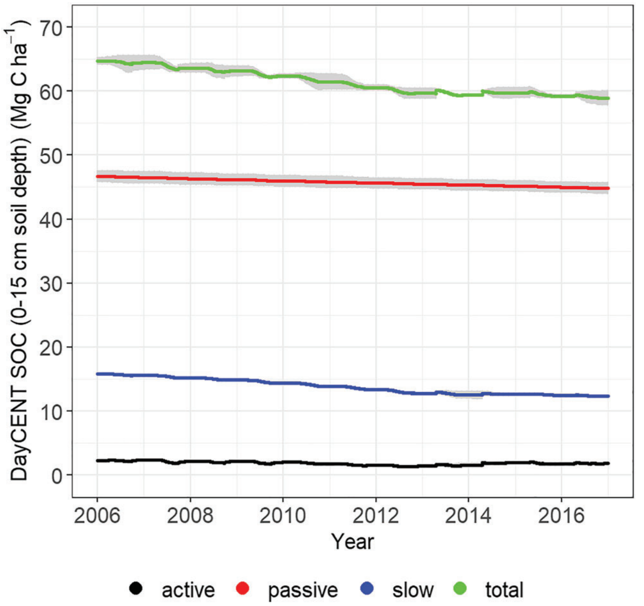

Figure 8. Daily DayCENT simulated total SOC stocks as well as in the active, slow, and passive pool (all in mg ha^{-1}) in 0–15 cm soil depth from 2005–2017 averaged for both fields.

while all soybean-years were a C source. Note that much of the corn residue is respired in the upcoming soybean-year; continuous corn or soybean fields may have different C sink-source estimates. Considering both crops, the negative slope of cumulative NBP over time indicates that C is lost from the CS rotation systems at a substantial rate. This is despite the substantial amounts of residue C input, which was left in field.

Only a few studies have been able to compare NBP with soil C analysis, and to the best of our knowledge, even less on CS rotation systems. It is noteworthy that all studies found difference in absolute values among methods. Higher soil C rates than EC-derived rates have been found in previous studies, including deeper soil layers (Curtis et al., 2002; Leifeld et al., 2011; Stahl et al., 2017). Abraha et al. (2016) found in a 6-yr study that CS was a C source with deep-core sampling and C neutral with the EC method; another CS site was a C sink with deep-core sampling and C source with the EC method. Abraha et al. (2018) presented 8-yr CS EC data set, noting that measured NEP and NBP would need further verification with additional deep-core soil sampling. Verma et al. (2005) found a nonsignificant reduction in equivalent mass soil C in the top 30 cm, probably due to the short study period of 3 yr and a similar trend with the EC method. Zenone et al. (2011) correlated NEP with soil C stocks for one growing season in a CS. The presented study complements previous findings, as we uniquely combine equivalent mass topsoil and subsoil C with EC-derived NEP in a CS. The study period was 11 yr, and significant changes in soil C are more likely to be detected after longer time periods (Necpálová et al., 2014). In this study, both methods showed a reduction in C over the 11-yr period by of -1.29 ± 0.57 in 0–120 cm (TC_m) and -1.20 ± 0.06 Mg ha^{-1} yr^{-1} (NBP), respectively. However, it is not clear to what extent the EC method can observe F_c originating from deep soil layers. The EC method provides an integrated measure, and it is not possible to monitor F_c specific to deeper soil layers without an additional setup or measurement approaches. Recent studies suggest that the bulk of soil CO_2 respiration originates from the top soil layers (Hicks Pries et al., 2017; Xiao et al., 2015). In addition, long-term studies on soil C sequestration suggest most impact on the topsoil layer (Baker et al., 2007; Schmer et al., 2014). This would indicate that F_c measured with the EC method rather originates from topsoil C. The rate of TC_m in the tilled 0–30 cm layer was -0.86 ± 0.12 Mg ha^{-1} yr^{-1}, which is higher (i.e., lower C reduction) than recorded by the EC stations. While the magnitude of soil C loss among methods differs, both soil C analysis and F_c measurements demonstrated the same trend of C reduction in the studied corn-soybean rotation.

4.3. DayCENT Soil C Dynamics

The long-term data sets of F_c, SOC_m, and climate data were used to simulate the C dynamics with DayCENT. It also allowed for the combined model evaluation with soil and EC data (Figure 6), which is an improvement to previous studies (Chang et al., 2013). DayCENT-simulated yield C, NEP, and soil C in the 0–15 cm soil layer were all in accordance to observed values. This required the initialization of the model, construction of a detailed daily schedule file, and adjusting parametrization until field conditions were matched (Table 4). The detailed calibration of the crop production submodel captured the wide range of yields reported over the 1925–2005 time period. This allowed the harvest indices to be used to remove the grain component and provide accurate stocks of residue to the soil surface. The agreement of simulated with measured NEP infers that modeled turnover rates are adequately capturing the decomposition rates occurring in the various forms of C in the soil. The results in this study show that soil C is being lost from all three C pools, with highest percent reduction in the active and slow C pool. This would indicate that also recalcitrant C forms mineralized over time from the topsoil layer, most likely due to tillage activities. However, these pools of carbon are just conceptual since we have no measured data on C pools available to validate DayCENT simulations and rely on the complete evaluation of total soil C, NEP, and yield C. The validated DayCENT simulations may be useful for extrapolating C dynamics on bigger larger spatial and temporal scales and future projections of carbon dynamics.

5. Conclusions

Corn and soybean are the dominant crops in the Midwestern United States that are grown on vast land areas and therefore can influence the regional carbon and nitrogen cycle. Small changes in crop and soil management of these cropping systems may substantially alter carbon and nitrogen dynamics at the regional scale. Long-term assessment of soil carbon changes, preferably with different approaches, is needed to understand how agricultural production activities can impact soil chemical and physical properties and can provide valuable insight as to which management options are beneficial. In this study, carbon dynamics in a conventional corn-soybean rotation in the Midwestern United States were investigated using EC-derived data, soil chemical analysis, and DayCENT modeling. All methods demonstrated that SOC declined between 2005 and 2016 under conventional soil and crop management practices. In addition, top soil N decreased and partly accumulated in deeper soil layers, and additional fertilizer inputs did not compensate for this reduction. Soil analysis showed that SOC reduction was highest in the top 15 cm, probably due to tillage activities, while SIC reduction was greatest in the 90–120 cm layer. The decrease in inorganic C could be due to weathering of soil carbonates. Top soil pH also decreased, and this acidification might be a result of repeated injection of anhydrous N following soybean harvest to provide N for the subsequent corn crop. The production system was a carbon source in soybean-years and a carbon sink or carbon neutral in corn-years, yet yield C losses could not be compensated. The current crop management of the studied field reflects the conventional tillage management system of corn-soybean production in Iowa. Therefore, similar trends can be expected at a regional scale under similar crop and soil management and climate. The validated DayCENT model may be able to quantify carbon changes on large scales and future carbon change scenarios. According to these results, the investigated corn-soybean production system suggests adverse effects on soil chemical parameters and that alternative crop management systems such as reduced tillage may be needed for amelioration.

Conflict of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The eddy flux data can be accessed online (via https://mesonet.agron.iastate.edu/nstl_flux/). The soil data publication is available on the USDA Ag Data Commons repository (https://doi.org/10.15482/USDA.ADC/1518763). The R script for calculating the equivalent soil mass was published in Dold et al. (2018).

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