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Long-term crop rotation and tillage effects on soil greenhouse gas emissions and crop production in Illinois, USA

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ABSTRACT

Two of the most important agricultural practices aimed at improving soil properties are crop rotations and no-tillage, yet relatively few studies have assessed their long-term impacts on crop yields and soil greenhouse gas (GHG) emissions. The objective of this study was to determine the influence of tillage and crop rotation on soil GHG emissions and yields following 15 years of treatment implementation in a long-term cropping systems experiment in Illinois, USA. The experimental design was a split-plot RCBD with crop rotation as the main plot: (continuous corn [*Zea mays* L.] (CCC), corn-soybean [*Glycine max* (L.) Merr.] (CS), continuous soybean (SSS), and corn-soybean-wheat [*Triticum aestivum* L.] (CSW); with each phase of each crop rotation present every year) and tillage as the subplot: chisel tillage (T) and no-tillage (NT). Tillage increased the yields of corn and soybean. Tillage and crop rotation had no effect on methane (CH_4) emissions ($p = 0.4738$ and $p = 0.8494$ respectively) and only rotation had an effect on cumulative carbon dioxide (CO_2) ($p = 0.0137$). However, their interaction affected cumulative nitrous oxide (N_2O) emissions significantly ($p = 0.0960$); N_2O emissions from tilled CCC were the greatest at 6.9 kg-N ha^{-1}-yr^{-1}; while emissions from NT CCC (4.0 kg-N ha^{-1}-yr^{-1}) were not different than both T CS or NT CS (3.6 and 3.3 kg-N ha^{-1-}yr^{-1}, respectively). Utilizing just a CS crop rotation increased corn yields by around 20% while reducing N_2O emissions by around 35%; soybean yields were 7% greater and N_2O emissions were not affected. Therefore results from this long-term study indicate that a CS rotation has the ability to increase yields and reduce GHG emissions compared to either CCC or SSS alone, yet moving to a CSW rotation did not further increase yields or reduce N_2O emissions.

1. Introduction

The agricultural sector produces food, fuel, and fiber but is also an important source of greenhouse gas (GHG) emissions. Agriculture contributes around 9% of total United States GHG emissions, with carbon dioxide (CO_2) making up the majority (81%), followed by methane (CH_4) (11%) and nitrous oxide (N_2O) (6%) (EPA, 2016). The global warming potential (GWP) of N_2O and CH_4 is 298 and 25 times greater than that of CO_2, respectively. Global warming potential is a measure of the amount of energy one kilogram of a certain GHG will absorb over a given time period, usually 100 years, relative to CO_2 (EPA, 2016).

Agricultural soil management which includes synthetic fertilizer application and use, tillage practices, and crop rotation systems accounts for around 80% of total N_2O emissions in the U.S. annually (EPA, 2016) (Venterea et al., 2011). Nitrous oxide emissions are directly affected by N application rate as well as fertilizer source and crop type (Eichner, 1990; FAO, 2001). Likewise, fertilizer application technique and timing, use of other chemicals, irrigation, and residual N and C from previous crops and fertilizer all affect N_2O emissions (Eichner, 1990). Application of N fertilizer stimulates N_2O production by providing a substrate for microbial N conversion through nitrification and denitrification (Venterea et al., 2005; Norton, 2008). Nitrification occurs when ammonium is either added to the soil in the form of fertilizers, as N fixation by legumes, or as mineralized soil organic matter (SOM) (Paustian et al., 2016). During this microbial process, ammonium is converted to nitrite and eventually to nitrate, yet small quantities can be lost as N_2O (Snyder et al., 2009). Likewise, in conditions of

Abbreviations: BD, bulk density; C/N, carbon to nitrogen ratio; CO_2, carbon dioxide; CH_4, methane; CCC, continuous corn rotation; CS, corn phase of the corn soybean rotation; CSW, corn phase of the corn-soybean-wheat rotation; GHG, greenhouse gas; GWP, global warming potential; N_2O, nitrous oxide; NH_4-N, ammonium-nitrogen; NO_3-N, nitrate-nitrogen; NT, no-till; SC, soybean phase of the soybean-corn rotation; SOM, soil organic matter; SSS, continuous soybean rotation; T, conventional tillage; UAN, urea ammonium nitrate; WCS, wheat phase of the wheat-corn-soybean rotation

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low soil oxygen, denitrifiers use nitrate as a terminal electron acceptor and N_2O is an intermediate step in complete denitrification to N_2 gas (Aulakh et al., 1992; Robertson et al., 2007; Paustian et al., 2016). Since spring fertilizer application in the United States Corn Belt (Illinois, Iowa, Indiana, Ohio southern and western Minnesota, and eastern Nebraska) occurs when saturating rains are common, the soil may easily become water-logged, promoting large denitrification events wherein a large proportion of annual N_2O flux can occur over short time scales (Venterea et al., 2012).

Tillage studies often have mixed results with no-till (NT) or reduced till having less, more, or no effect on N_2O emissions compared to conventional tillage systems (T) (Venterea et al., 2005; Rochette et al., 2008; Snyder et al., 2009). Snyder et al. (2009) compared various cropping rotation studies and found that continuous corn (*Zea mays* L.)-(CCC) had higher yields compared to a corn-soybean [*Glycine max* (L.) Merr.]-wheat (*Triticum aestivum* L.) (CSW) rotation. While CCC resulted in a two to three times higher N_2O emissions, it produced four to five times the food yield in caloric value compared to the CSW rotation. Parkin and Kaspar (2006) observed that a corn-soybean (CS) rotation did not differ in N_2O emissions between T and NT, but corn in the rotation emitted more N_2O than did soybeans. In a meta-analysis by Pittelkow et al. (2015) studying the long-term effects of no-till on yield in several agroecosystems, the authors found that after 5+ years of no-till, soybean and wheat yields matched that of conventional tillage; however, corn yields did not improve over time compared to conventional tillage. Relatively few studies have compared side-by-side crop rotation effects as influenced by tillage, and since both of these practices tend to influence soil properties more over time, long-term assessments are needed which allow for soils to stabilize.

Millar et al. (2010) reported that fertilized crops take up less than 50% of the N applied, leaving the excess available for loss. Given the established connection between substrate availability and GHG emissions, the US Corn Belt tends to be a major source of agricultural GHG emissions (EPA, 2016). The large amount of land reserved to growing highly fertilized corn and N-fixing soybeans supplies the N substrate needed to emit significant quantities of N_2O; on average, 1% of the fertilizer N applied directly is emitted as N_2O (Bouwman et al., 2002). As commodity prices vary, the land area allocated to soybean has increased slowly. However, the rate of no-till adoption around the Corn Belt has decreased (USDA-ERS, 2016a, 2016b). With mixed results from cropping rotation and tillage studies and the time needed to allow for proper system stabilization, more work is needed to understand their effects on GHG emissions.

We hypothesized that crop rotations using less N fertilizer inputs would lower GHG emissions, specifically N_2O, whereas chisel tillage would increase N_2O and CO_2 emissions due to enhanced mineralization of decomposing residues. Growing corn in a rotation will increase yields due to synergistic effects of soybeans and vice-versa. Hence the objectives of this study were to evaluate the effects of long-term crop rotations, and tillage practices on GHG emissions and their relation to soil available N and crop yields.

2. Materials and methods

2.1. Site characterization and experimental layout

This study was conducted at the Northwestern Illinois Agricultural Research and Demonstration Center (40°55′50″N, 90°43′38″W), approximately 8 km northwest of Monmouth, IL. The experimental plots were initially established beginning in 1996. The mean annual precipitation is approximately 978 mm and the mean annual temperature is 16 °C (ISWS, 2016). Soils at the experimental site primarily consisted of Sable silty clay loam (fine-silty, mixed, mesic Typic Endoaquoll) and Muscatune silt loam (fine-silty, mixed, mesic Aquic Argiudoll); a small area of Osco silt loam (fine-silty, mixed, mesic Typic Argiudoll) (Soil-Survey-Staff, 2016). The plot layout consisted of a split-plot arrangement of four rotation levels and two tillage levels in a randomized complete block design with four replications. Crop rotations of continuous corn (CCC), corn-soybean (CS), corn-soybean-wheat (CSW), soybean-corn (SC), continuous soybean (SSS), and wheat-corn-soybean (WCS) were assigned to the main plots, with each phase of each rotation (a total of seven main plots) present each year. The two subplot treatments were tillage (T) and no-till (NT). The main plots were 22 m long by 12 m wide, with subplots 22 m long by 6 m wide. It is important to note that we did not sample the NT pair for the CSW rotation nor the soybean phase of the CSW rotation (SWC). Cropping systems used in the analysis included: CCC-NT, no-till continuous corn; CCC-T, tilled continuous corn; CS-NT, no-till corn of the corn-soybean rotation; CS-T, tilled corn of the corn-soybean rotation; CSW-T tilled corn of the corn-soybean-wheat rotation; SC-NT, no-till soybean of the soybean-corn rotation; SC-T, tilled soybean of the soybean-corn rotation; SSS-NT, no-till continuous soybean; SSS-T, tilled continuous soybean; WCS-NT, no-till wheat of the wheat-corn-soybean rotation; WCS-T, tilled wheat of the wheat-corn-soybean rotation.

Following fall harvest, the tilled corn and soybean plots were cultivated using a disk ripper operated at a depth of about 35 cm; in the spring a soil finisher was used to prepare the seedbed in tilled plots. Wheat plots were tilled using a rototiller in the fall before planting. No-till plots received zero tillage. Fertilizer and pest management decisions were made using best management practices according to the Illinois Agronomy Handbook (Nafziger, 2009). Application of N fertilizer to both tilled and no-till corn was done in the spring, at or before planting, as injected incorporated urea ammonium nitrate (UAN) at rates of 246 kg N ha^{-1} for CCC and 202 kg N ha^{-1} for CS and CSW. The increased fertilization rate for CCC compared to rotated corn was implemented following the Illinois Agronomy Handbook recommendations for the area (Nafziger, 2009). The wheat phase of the cropping rotation received 34 and 56 kg-N ha^{-1} at planting and as a spring topdress as UAN, respectively. No N fertilizer was applied to soybean treatments. Additional P and K fertilizer was applied in the fall every two years, based on soil test results. Corn plots were planted in April or May in 76-cm rows at a seeding rate of 86 500 ha^{-1}. Soybean plots were planted in May in 38-cm rows at a seeding rate of approximately 358 000 ha^{-1}. Wheat plots were planted in late September or early October, with seed drilled in 19-cm rows at a rate of about 3.7×10^6 seeds ha^{-1}. Due to winter wheat damage during the winter of 2013-14, wheat was replaced by oats [*Avena sativa* L.] planted on 14 April, 2014. Oat yields were similar to wheat yields found in other years, and for purposes of this report we will treat the 2014 oat crop as wheat. Yields were harvested using a plot combine (Almaco, Nevada, IA) and adjusted to 15.5%, 13%, and 13.5% moisture for corn, soybean, and wheat, respectively. Detailed information including dates are summarized in the supplemental information section (Supplemental information Table 1).

2.2. Gas sampling procedures

Soil GHG emissions were taken weekly during a period of 4 growing seasons (2012–2015) following the GRACEnet chamber-based trace gas flux measurement protocol (Parkin and Venterea, 2010). Beginning in March 2012, 0.031 m^2 polyvinyl chloride (PVC) white chamber bases were installed in the experimental plots immediately after planting and initial fertilizer application. Two chamber bases were used in corn plots: one in-row and one between-row. One chamber was used in each soybean and wheat plots. Due to severe weather, we were not able to collect wheat data during 2014 and 2015. The chamber tops were also made of white PVC, contained a vent tube, sampling septa, and insulation foam to create an air tight seal to the chamber bases. The chamber bases were left in the field for the growing season and were removed before harvest.

Soil GHG measurements were conducted near noon, when air temperatures were around the average for the day. Gas samples were

Table 1
Soil bulk density (BD, Mg m^{-3}), pH, C/N ratio (carbon to nitrogen ratio, %), and soil texture (percent of sand, silt, and clay) of the surface 0–10 cm under each rotation tillage system. Determinations were made in the spring of 2014, 17 years after the project was initiated at Monmouth, IL.

Rotation[a]	Tillage[b]	BD (Mg m^{-3})	pH	C/N	Sand (%)	Silt (%)	Clay (%)
CCC	T	1.32	4.9	12.2	3	72	26
	NT	1.40	5.1	12.4	3	72	26
CS	T	1.30	6.0	12.5	3	71	26
	NT	1.33	5.8	12.9	3	72	25
CSW	T	1.34	5.9	13.4	3	73	24
	NT	1.31	5.7	12.8	3	73	25
SSS	T	1.34	7.3	14.2	2	72	26
	NT	1.32	6.9	13.3	2	73	25

[a] CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SSS continuous soybean.
[b] T, chisel till; NT, no-till.

taken by placing the chamber top on the base and extracting 15 mL using a Precision-Glide ® needle syringe at 0, 10, 20, and 30 min. Gas samples were then transferred into 10 mL aluminum crimp top vials with 20 mm Pharma-Fix Butyl ® septa. Gas samples were analyzed on a gas chromatograph with an electron capture detector and flame ionization detector (Shimadzu ® GC 2014 with AOC-5000). Soil GHG fluxes were calculated as the rate of change in gas concentration inside the chamber headspace over the 30 min collection period.

2.3. Soil sampling and analyses

Two soil cores (0–10 cm depth) were collected from each plot during gas sampling for the 2013–2015 growing seasons, composited, and then analyzed for available N concentrations: ammonium and nitrate (NH_4-N and NO_3-N). Concentrations of NH_4-N and NO_3-N from soil extracts (1 M KCl) were measured colorimetrically by flow injection analysis with a Lachat Quick-Chem 8000 (Lachat Quickchem Analyzer, Lachat Instruments Loveland, CO). In addition, to evaluate long-term treatment effects on soil properties, three soil cores 4.3 cm in diameter were taken in the spring of 2014 for each subplot to 10 cm depth with a tractor mounted hydraulic probe (Amity Technology, Fargo, ND). Soil properties were determined as follows: bulk density (BD, g cm^{-3}) by the core method (Blake and Hartge, 1986), pH by potentiometry (1:1 water and soil ratio) (McLean, 1982), carbon/nitrogen ratio (C/N) by dry combustion (Nelson and Sommers, 1996), and texture (% sand, % silt, and% clay) by the hydrometer method (ASTM-D422, 2007). These soil properties are included in Table 1 as a general description of the soils in this study.

2.4. Data analysis

Greenhouse gas flux measurements were extrapolated to daily GHG emissions and in conjunction with soil available nitrogen concentrations were grouped into three periods based on sampling date; spring (March through May), summer (June through August), and fall (September through November). Grouping the dates into three "seasons" allowed us to analyze the significance of seasonality on GHG emissions. In addition, grouping the dates allowed us to analyze the soil available nitrogen dynamics throughout the growing season. Cumulative GHG emissions were linearly extrapolated to predict fluxes for the growing season. Exact number of sampling events is included in the supplemental information (Supplemental information Table 2). Yields were analyzed by cash crop to account for differences in yield levels. Since wheat did not have a second rotation, comparisons were not possible at the rotation level.

Linear mixed models were performed using the GLIMMIX procedure of SAS software version 9.4 (SAS Institute, Cary, NC). Rotation, tillage, and season were considered fixed variables, while year and block were considered random. The factor season was analyzed using a repeated measures approach selecting the variance-covariance matrix of the residuals based on the Akaike's Information Criterion (Littell et al., 2006). The repeated measures approach for analyzing methane over seasons did not converge with any of the variance covariance matrices available or distributions tested. Thus, methane data for each season was analyzed independently. Model residuals were not normally distributed, thus GHG emissions, soil variables, and yields were analyzed using a lognormal distribution link function (dist = logn) within the model statement in GLIMMIX, with a Kenward-Rogers adjustment to the degrees of freedom (ddfm = kr) to account for model complexity and missing data (Gbur et al., 2012). Least square means were separated using the lines option of LSMEANS using a Bonferroni adjustment. Statistical model and SAS codes are available upon request from the authors.

Table 2
Back-transformed mean values and standard errors (within parentheses) of corn, soybean and wheat yields (Mg ha^{-1}) under each rotation and tillage practices taken during the growing seasons of 2012–2015 from Monmouth, IL. Within a column, different lowercase letters are significant at $p \le 0.10$.

Rotation[1]	Tillage[2]	Corn (Mg ha^{-1})			Soybean (Mg ha^{-1})			Wheat (Mg ha^{-1})		
CCC		11.1	(1.1)	b						
CS		14.0	(1.1)	a						
CSW		14.4	(1.1)	a						
		($p \le 0.0001$)								
SC					4.4	(1.1)	a			
SSS					4.1	(1.1)	b			
					($p \le 0.0001$)					
WCS								4.3	(1.2)	
									N/A	
	T	13.6	(1.7)	a	4.4	(1.1)	a	4.2	(1.2)	a
	NT	12.6	(1.7)	b	4.1	(1.1)	b	4.5	(1.2)	a
		($p = 0.0192$)			($p = 0.0192$)			($p = 0.1027$)		

[1] CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SC, soybean-corn; SSS continuous soybean; WCS, wheat-corn-soybean.
[2] T, chisel till; NT, no-till.

3. Results and discussion

3.1. Temperature, precipitation and soil characteristics

The mean annual temperature was 10.1 °C and the mean annual precipitation was 858 mm between 1989 and 2015 (ISWS, 2016), and the mean maximum and minimum temperatures from March to November were 20.4 and 8.9 °C, respectively. The precipitation totals for 2012–2015 were 825, 913, 1075, and 1155 cm, respectively (Fig. 1). The 2012 growing season experienced well below the historical average precipitation during July, which impacted crop progress. If it were not for a heavy precipitation event (5.2 cm) on August 26th, 2012, the month of August would have had less than 40 mm of precipitation. Likewise, the 2013 growing season experienced well below the historical average precipitation during June-September, which impacted crop progress. The 2014 and 2015 growing seasons were above average for precipitation.

Surface soil bulk density (BD) (Table 1) values were fairly consistent throughout the site and across treatments with small differences occurring between tillage and no-till when looking at each cropping rotation. Soil pH appeared lower for rotations with more corn. Zuber et al. (2015) conducted an in depth analysis of these same soils and attributed the lower pH to the frequency of corn in the rotation. The more corn years present in the rotation, the more N fertilizer events occur and ammonia-based N fertilizer is known to acidify the soil (Karlen et al., 1994; Hickman, 2002; Divito et al., 2011).

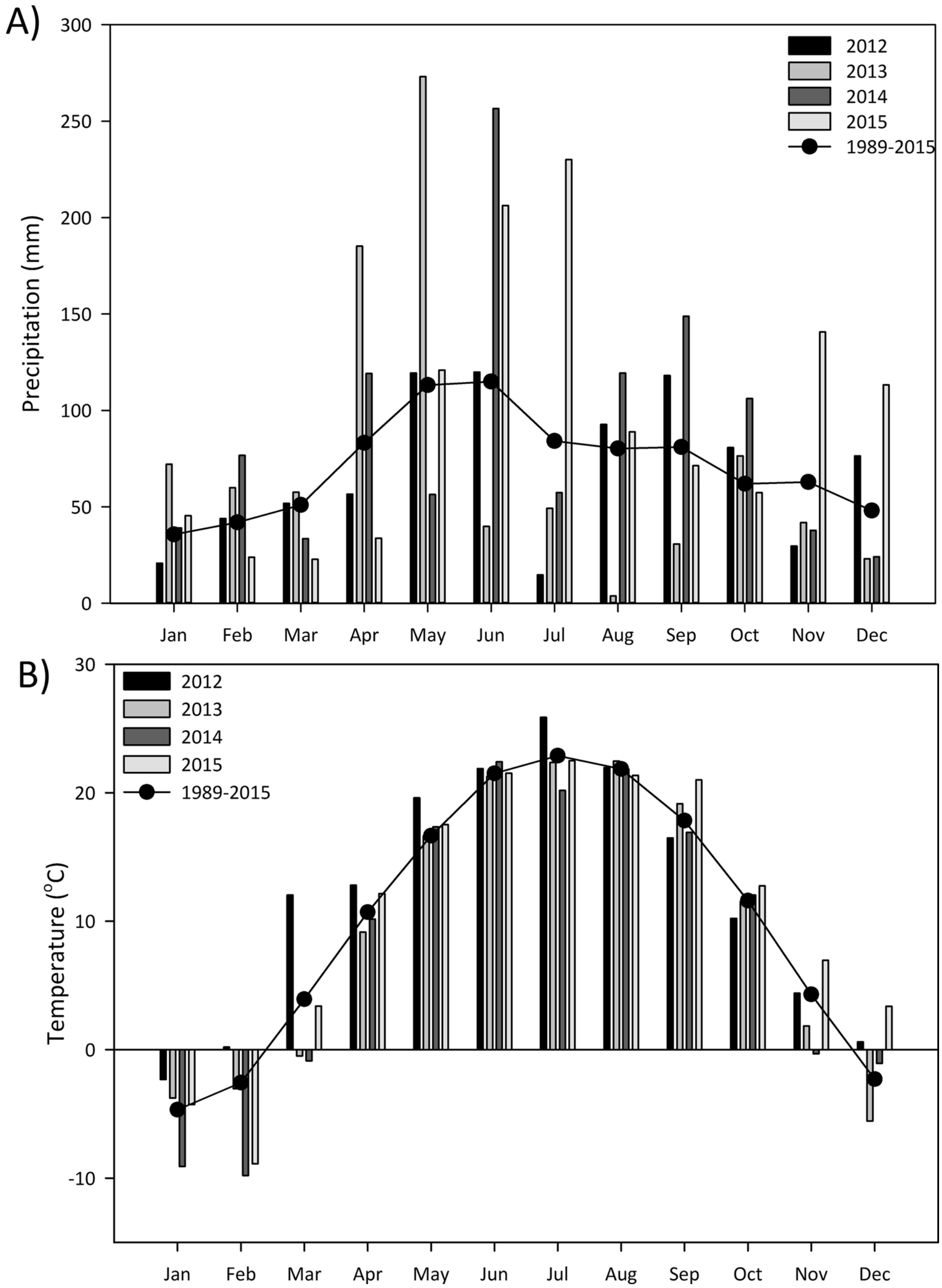

Fig. 1. **(A)** Precipitation (mm) and **(B)** temperature (°C) from 2012 to 2015 and the normal for the 1989–2015 period.
Source: ISWS, 2016.

3.2. Crop yields

Corn yield during 2012–2015 was affected by crop rotation and tillage, but no interaction was detected (Table 2). Mean corn yield increased by almost 3 Mg ha^{-1} for the CS (14.0 Mg ha^{-1}) and CSW (14.4 Mg ha^{-1}) rotations compared to the CCC (11.1 Mg ha^{-1}). In a similar study at the same research station in Monmouth, IL, Jagadamma et al. (2008) also observed a significant yield advantage for rotated corn compared to continuous corn. On highly productive IL soils, Gentry et al. (2013) synthesized that the yield gap between rotated corn and continuous corn is related to N availability, corn residue accumulation, weather, and their interactions. In this study, since the CCC plots were fertilized at higher N rates and the soil C/N ratios were similar, the weather was most likely the reason for the yield gap between rotated corn and CCC (Fig. 2). While rotated corn yields were fairly consistent throughout the study (12 Mg ha^{-1}–16 Mg ha^{-1}), CCC yields exhibited greater variability (8 Mg ha^{-1}–16 Mg ha^{-1}), with the CCC rotation experiencing the largest yield decreases in 2012 and 2013. The 2012 growing season was abnormally hot and dry, whereas 2013 was very wet during April and May and then very little precipitation occurred during June, July and August (Fig. 1). The temperature and water stresses of these two years likely contributed to lower yields for CCC. On productive Midwest soils, it has been reported that rotated corn has a lower risk for yield loss compared to CCC (Al-Kaisi et al., 2015) especially in years with scarce or excessive moisture and above-average temperatures (Gentry et al., 2013) due to water and temperature stress (Wilhelm and Wortmann, 2004). Results from this study agree with several studies in the Midwest that show that significant yield gains are possible for corn when a crop rotation plan is implemented on highly productive soils(Gentry et al., 2013; Al-Kaisi et al., 2015; Daigh et al.,

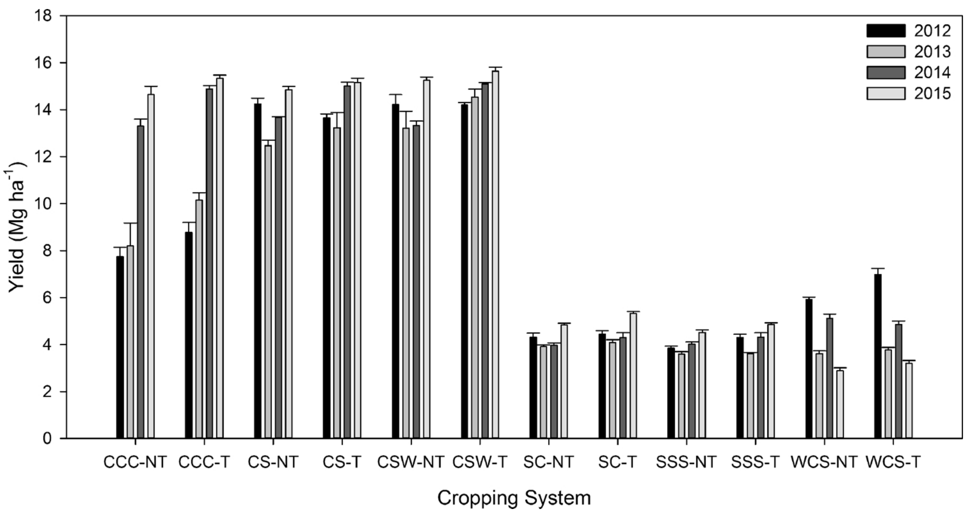

Fig. 2. Yield results (Mg ha^{-1}) from cropping systems (CCC-NT, no-till continuous corn rotation; CCC-T, tilled continuous corn rotation; CS-NT, no-till corn of the corn-soybean rotation; CS-T, tilled corn of the corn-soybean rotation; CSW-T tilled corn of the corn-soybean-wheat rotation; SC-NT, no-till soybean of the soybean-corn rotation; SC-T, tilled soybean of the soybean-corn rotation; SSS-NT, no-till continuous soybean rotation; SSS-T, tilled continuous soybean rotation; WCS-NT, no-till wheat of the wheat-corn-soybean rotation; WCS-T, tilled wheat of the wheat-corn-soybean rotation) during 2012–2015 from Monmouth, IL. The first letter of the cropping system abbreviation indicates the crop which yield is represented by the vertical bar each year. Error bars represent standard errors of treatment means for each year of the study.

2018).

Corn yields were also significantly greater under tillage (13.6 Mg ha^{-1}) compared to NT (12.6 Mg ha^{-1}). Significant yield increases due to tillage in the Midwest are fairly common (Halvorson et al., 2006; Parkin and Kaspar, 2006). In a recent study conducted by Daigh et al. (2018) at several sites in the Midwest, yield increases due to tillage were correlated to the crop phase of the rotation especially during non-drought conditions. Decreases in yield by long-term (5+ years) NT in corn systems was observed in a global meta-analysis conducted by Pittelkow et al. (2015); reduced yield in NT have been attributed to waterlogging and poor establishment, compaction, and nutrient deficiencies (Halvorson et al., 2006; Rusinamhodzi et al., 2011; Cid et al., 2014). The results from this study indicate that utilizing chisel tillage to manage corn residue in high organic matter soils will increase yields significantly assuming the added costs of tillage are not prohibitive.

In addition, main effects of crop rotation and tillage were observed on soybean yields (Table 2). Rotating soybeans with corn (SC) increased yields by around 0.3 Mg ha^{-1} compared to SSS. Studies conducted in the Midwest have also confirmed that rotated soybean experienced significant yield gains (Peterson and Varvel, 1989; Adee et al., 1994; Kelley et al., 2003; Pedersen and Lauer, 2003; Wilhelm and Wortmann, 2004; Sindelar et al., 2015; Seifert et al., 2017). Possible explanations for the yield gap between rotated soybeans and SSS have been attributed to diseases (Pedersen and Lauer, 2003; Li et al., 2010) and changes in soil physical properties, like water aggregate stability and better water infiltration in rotated soybeans compared to SSS (Fahad et al., 1982). Increased aggregate stability is related to higher soil organic carbon (Martens, 2000; Kumar et al., 2012; Zuber et al., 2015; Zuber et al., 2017) and also is related to increases in yields (Nakajima et al., 2016). At the same study site, Zuber et al. (2015) found that soil aggregate stability decreased over time under more years of soybean. Tillage also had a significant effect of 0.3 Mg ha^{-1} on soybean yield. Pittelkow et al. (2015) found that rainfed legumes from humid regions did not experience a benefit of NT; likewise, higher latitudes experienced an overall decrease in yields; the latitude of this study was around 40°N. The decrease in yields due to NT was likely the result of corn residue buildup in the soil, which could impede seedling emergence (Farooq et al., 2011). However, Daigh et al. (2018) observed no yield effect due to tillage in rotated soybean when averaged across several Midwestern sites; the authors attributed this to beneficial effects of crop rotation (corn-soybean) on yield stability and soil health. Our results indicate a yield gain to soybeans using chisel tillage; the driver of this is likely due to the rotated soybean rotation experiencing better emergence in the spring after the previous year corn stubble is broken up by tillage.

Wheat yields from the WCS rotation were not affected by tillage (continuous wheat was not evaluated as a crop rotation in this study) (Table 2). Wheat yields varied widely throughout the study; 2012 had the highest yields (Fig. 2), likely because precipitation and temperature (Fig. 1) were favorable during the wheat growing season. Unseasonably warm temperatures in March and April of 2012 allowed for favorable growth early in the spring, which is normally associated with lower temperatures. Pittelkow et al. (2015) found that in the Midwest, where it is humid and rainfed, wheat was only slightly impacted by NT.

3.3. Greenhouse gas emissions

A significant interaction between crop rotation and season ($p \leq 0.0001$) on daily N_2O emissions was detected (Table 3). Daily N_2O emissions during the spring were higher for the corn rotations compared to the soybean rotations and likewise for the CCC in the summer. The larger emissions during the spring from CCC, CS and CSW were likely due to fertilizer application during that period. Several studies in the Corn Belt (Leick and Engels, 2002; Ginting and Eghball, 2005; Venterea et al., 2005; Parkin and Kaspar, 2006; Halvorson et al., 2008; Hoben et al., 2011; Drury et al., 2014; Lehman et al., 2017) reported peaks of N_2O emissions closer to fertilizer application with larger peaks corresponding to greater N rates (MacKenzie et al., 1998; McSwiney and Robertson, 2005; Malhi et al., 2006; Omonode et al., 2011; Smith et al., 2011). Other studies in the Midwest found that crop rotations lowered N_2O emissions compared to CCC (Jacinthe and Dick, 1997; Adviento-Borbe et al., 2006; Adviento-Borbe et al., 2007; Omonode et al., 2011). The main effect of season was also found to influence N_2O emissions with more than double the daily emissions occurring during the spring compared to the summer and more than 3 times that occurring during the fall (Table 3). On productive Iowa soils Parkin and Kaspar (2006) observed an effect of season on N_2O emissions from corn-soybean rotations. Likewise, Hoben et al. (2011) saw between 61% and 95% of the cumulative flux occurred during the first 8 weeks after fertilization in Michigan. The main effect of crop rotation seemed to influence daily N_2O emissions with the corn phases emitting larger amounts of N_2O compared to the soybean phases (Table 3). In a study on similar soils in Indiana by Smith et al. (2011), the authors described significant seasonal increases in N_2O values from corn plots during the warmer months and following fertilization; soybean and grass plots were lower compared to corn plots throughout the growing season.

Similar to N_2O, daily CO_2 emissions were significantly affected by a rotation effect and CCC had greater emissions compared to SSS, but not different from CS, CSW and SC (Table 3). On comparable soils in Iowa, a seasonal rotation effect was detected by Wilson and Al-Kaisi (2008) with CCC emitting more than CS. Likewise, tillage produced

Table 3
Back-transformed mean values and standard errors (within parentheses) of daily soil GHG emissions and average soil inorganic N under each rotation and tillage practice taken during the growing seasons of 2012–2015 from Monmouth, IL. Within a column, different lowercase letters are significant at $p \leq 0.10$.

Rotation[1]	Tillage[2]	Season[3]	N_2O ($g\text{-}N\ ha^{-1}\text{-}day^{-1}$)			CO_2 ($kg\text{-}C\ ha^{-1}\text{-}day^{-1}$)			CH_4 ($g\text{-}C\ ha^{-1}\text{-}day^{-1}$)		NO_3-N (ppm)		NH_4-N (ppm)		
Rotation Effect															
CCC			18.5	(1.6)		13.0	(1.4)	a	N/A		17.4	(1.5)	5.4	(1.4)	
CS			13.9	(1.6)		12.0	(1.3)	ab	N/A		16.0	(1.5)	4.7	(1.4)	
CSW			15.8	(1.8)		12.7	(1.6)	ab	N/A		–		–		
SC			5.7	(1.9)		9.1	(1.4)	ab	N/A		8.8	(1.7)	3.2	(1.4)	
SSS			4.7	(2.1)		6.1	(1.5)	b	N/A		11.6	(1.7)	3.0	(1.4)	
			($p \leq 0.0001$)			($p = 0.0005$)			N/A		($p \leq 0.0001$)		($p \leq 0.0001$)		
Tillage Effect															
	T		10.4	(1.7)		10.7	(1.3)	a	N/A		13.1	(1.5)	3.9	(1.4)	
	NT		9.9	(1.7)		9.7	(1.4)	b	N/A		12.9	(1.6)	4.0	(1.4)	
			($p = 0.8128$)			($p \leq 0.0001$)			N/A		($p = 0.8756$)		($p = 0.7477$)		
Season Effect															
		Spring	19.3	(2.7)		7.9	(1.7)	ab	N/A		32.9	(2.1)	6.4	(1.4)	
		Summer	9.3	(1.4)		20.5	(1.3)	a	N/A		9.3	(1.4)	2.9	(1.4)	
		Fall	5.8	(1.4)		6.6	(1.3)	b	N/A		7.1	(1.5)	3.4	(1.4)	
			($p = 0.0887$)			($p = 0.0069$)			N/A		($p = 0.1394$)		($p \leq 0.0001$)		
Rotation x Season Effect															
CCC		Spring	47.9	(2.2)	a	11.9	(1.6)		2.2	(1.1)	61.1	(1.8)	14.4	(1.4)	a
		Summer	23.0	(1.5)	a	23.6	(1.3)		3.1	(1.1)	12.9	(1.5)	3.1	(1.4)	b
		Fall	5.8	(1.6)	ab	7.8	(1.5)		4.1	(1.0)	6.7	(1.6)	3.6	(1.4)	b
CS		Spring	37.2	(2.1)	a	10.2	(1.6)		0.0	(1.1)	45.8	(1.8)	9.6	(1.4)	a
		Summer	15.2	(1.6)	ab	23.4	(1.3)		1.2	(1.1)	11.4	(1.5)	3.2	(1.4)	b
		Fall	4.7	(1.6)	b	7.2	(1.4)		3.3	(1.0)	7.8	(1.6)	3.4	(1.4)	b
CSW		Spring	40.3	(2.0)	a	12.1	(1.6)		4.3	(1.2)	N/A		N/A		
		Summer	9.2	(2.1)	ab	26.5	(1.7)		4.8	(1.1)	N/A		N/A		
		Fall	10.6	(2.4)	ab	6.3	(2.4)		−3.6	(1.0)	N/A		N/A		
SC		Spring	7.3	(3.5)	ab	5.8	(2.2)		−2.6	(1.5)	17.7	(2.5)	4.0	(1.4)	b
		Summer	4.6	(1.7)	ab	17.8	(1.4)		1.8	(1.1)	6.0	(1.4)	2.7	(1.4)	b
		Fall	5.5	(1.7)	ab	7.4	(1.4)		1.8	(1.0)	6.4	(1.5)	3.1	(1.4)	b
SSS		Spring	5.1	(5.3)	ab	3.5	(2.4)		−1.8	(1.5)	23.7	(2.6)	3.1	(1.4)	b
		Summer	4.8	(1.7)	ab	13.9	(1.4)		2.2	(1.1)	8.4	(1.4)	2.6	(1.4)	b
		Fall	4.2	(1.7)	b	4.7	(1.4)		3.0	(1.0)	7.8	(1.5)	3.4	(1.4)	b
			($p \leq 0.0001$)			($p = 0.9184$)			–		($p = 0.0309$)		($p \leq 0.0001$)		

[1] CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SC, soybean-corn; SSS continuous soybean.
[2] T, chisel till; NT, no-till.
[3] Spring, March-May; Summer, June-August; Fall, September-November.

significantly greater daily CO_2 emissions compared to NT (Table 3). On northern Corn Belt soils Johnson et al. (2010) found that tillage increased CO_2 fluxes seasonally, but not annually. A main effect of season was also detected for CO_2 emissions; summer CO_2 emissions were larger compared to fall, but not different from spring emissions. Other studies have observed peaks in CO_2 emissions during the summer months due to warmer soil temperatures from a variety of crop systems (Raich and Potter, 1995; Parkin and Kaspar, 2003; Drury et al., 2006; Behnke et al., 2012). While it is true that all crop systems emit greater amounts of CO_2 during the warmer summer months, SSS has the ability to decrease CO_2 emissions albeit with a significant yield penalty (Table 2).

Combined seasonal analysis of methane was not possible due to statistical constraints in SAS, so the rotation by season effect was conducted separately by season. This made completion of Table 3 impossible.

Over the four year study, there was a significant interaction at the $p \leq 0.10$ of crop rotation and tillage on cumulative N_2O emissions ($P = 0.0960$) (Table 4). The CCC-T treatment had the largest emissions compared to all other practices, but it was not different from the CCC-NT system. Cumulative N_2O emissions from the CCC-NT, CS-T, and CS-NT were not statistically different, but were all larger compared to the soybean phases due to N fertilization (Parkin and Kaspar, 2006; Adviento-Borbe et al., 2007; Halvorson et al., 2008). While the interaction was significant, rotation was highly significant and was likely the driver of the interaction; therefore decreasing the number of corn years in a rotation will lower the N_2O emissions. The corn year of the cropping rotation (CCC and CS) showed an increased amount of total in-season N_2O emissions compared to the soybean (SC and SSS) or wheat (WCS) phases of the rotation (Table 4). The larger emissions from the CCC rotation are likely due to the increased N fertilizer amounts compared to CS and CSW rotations as other studies have observed (Eichner, 1990; McSwiney and Robertson, 2005; Adviento-Borbe et al., 2007; Halvorson et al., 2008; Hoben et al., 2011; Smith et al., 2011). While examining the interaction effect of rotation and tillage in Table 4, we observe that the interaction is driven by the trend in lower measurements of N_2O emissions for CCC under NT compared to T, yet we did not detect a tillage effect for the other rotations under study. Table 4 shows that there is a consistent and statistically significant effect of the rotation on N_2O emissions. Likewise, the SC rotation had larger total in-season N_2O emissions compared to the WCS rotation, which may be attributed to residual N from the fertilization occurring to corn the previous year (Mosier et al., 2006). In contrast, N_2O emissions for SSS and WCS were not different. In general, cool temperatures when wheat is grown are not conducive to large N_2O emissions due to low soil temperatures inhibiting the microbial mineralization of N from OM, which can limit the NO_3-N substrate needed for nitrification and denitrification processes (Aulakh et al., 1992; Johnson et al., 2005; Snyder et al., 2009). However, it should be noted that freeze-thaw fluxes during the winter can be significant sources of annual N_2O emissions (Wagner-Riddle et al., 2007; Snyder et al., 2009; Johnson et al., 2010; Lebender et al., 2014), yet a limitation of this study is that sampling was not conducted frequently enough to capture these emissions.

Similar to N_2O, cumulative CO_2 emissions were significantly influenced by crop rotation (Table 4). Cumulative CO_2 emissions were

Table 4
Back-transformed mean values and standard errors (within parentheses) of cumulative GHG emissions under each rotation and tillage practices taken during the growing seasons of 2012–2015 from Monmouth, IL. Within a column, different lowercase letters are significant at $p \leq 0.10$.

Rotation[1]	Tillage[2]	N_2O ($kg\text{-}N\ ha^{-1}\text{-}yr^{-1}$)			CO_2 ($Mg\text{-}C\ ha^{-1}\text{-}yr^{-1}$)			CH_4 ($kg\text{-}C\ ha^{-1}\text{-}yr^{-1}$)	
Rotation Effect									
CCC		5.2	(1.1)		3.8	(1.2)	a	0.2	(1.7)
CS		3.4	(1.1)		3.7	(1.2)	ab	0.2	(1.7)
SC		0.9	(1.1)		2.8	(1.2)	abc	0.2	(1.7)
SSS		0.8	(1.1)		2.4	(1.2)	bc	0.3	(1.7)
WCS		0.5	(1.2)		2.3	(1.2)	c	0.2	(1.8)
			($p \leq 0.0001$)			($p = 0.0137$)			($p = 0.8494$)
Tillage Effect									
	T	1.4	(1.07)		2.9	(1.19)		0.2	(1.64)
	NT	1.5	(1.07)		3.0	(1.19)		0.3	(1.62)
			($p = 0.4067$)			($p = 0.3830$)			($p = 0.4738$)
Rotation x Tillage Effect									
CCC	T	6.9	(1.1)	a	4.2	(1.2)		0.2	(1.7)
CCC	NT	4.0	(1.1)	ab	3.5	(1.2)		0.2	(1.7)
CS	T	3.6	(1.1)	b	3.6	(1.2)		0.3	(1.8)
CS	NT	3.3	(1.1)	b	3.9	(1.2)		0.2	(1.8)
SC	T	0.8	(1.1)	c	2.4	(1.2)		0.2	(1.8)
SC	NT	1.0	(1.1)	c	2.3	(1.2)		0.4	(1.9)
SSS	T	0.9	(1.1)	c	3.2	(1.2)		0.3	(1.8)
SSS	NT	0.8	(1.2)	c	2.7	(1.2)		0.3	(1.8)
WCS	T	0.5	(1.2)	c	2.2	(1.2)		0.2	(2.1)
WCS	NT	0.5	(1.2)	c	2.4	(1.2)		0.2	(1.9)
			($p = 0.0960$)			($p = 0.1110$)			($p = 0.9750$)

[1] CCC, continuous corn; CS, corn-soybean; SC, soybean-corn; SSS continuous soybean; WCS, wheat-corn-soybean.
[2] T, chisel till; NT, no-till.

largest for CCC, CS, and SC, but only the CCC rotation was statistically greater than SSS and WCS, while CS was statistically greater than WCS (Table 4). Cumulative CO_2 emissions were similar to the values reported from northern Corn Belt soils (Drury et al., 2006; Johnson et al., 2010); similar to this study, both groups did not observe an effect of tillage. Wilson and Al-Kaisi (2008) also described similar values and also an effect of rotation on annual CO_2 emissions; however, in their study on similar soils in Iowa, they found that CCC emitted more CO_2 compared to CS. Greater cumulative in-season CO_2 emissions from CCC in their study were attributed to greater residue amounts.

3.4. Soil inorganic nitrogen

A three way interaction for soil NO_3-N concentrations over the growing season was observed between crop rotation, tillage, and season (Table 5). Higher concentrations of soil NO_3-N occurred in the corn and soybean plots in the spring compared to the fall. The greater concentrations of soil NO_3-N from the corn rotations during the spring can be explained by the spring application of N fertilizer, then decreasing throughout the growing season as a result of plant uptake, denitrification, and leaching below sampling depth (Drury et al., 2006). Peaks in NO_3-N were also detected during spring in the soybean plots (Table 5) and is most likely due to breakdown of plant residues (Baggs et al., 2000) and possibly biological N fixation (Baggs et al., 2000; Tortosa et al., 2015). Interestingly, our results align with those from other studies showing that peaks in soil NO_3-N do not necessarily correspond to large fluxes of N_2O (Amos et al., 2005; Adviento-Borbe et al., 2007). While high soil NO_3-N concentrations may not automatically trigger N_2O emissions in this system, prolonged periods of high soil NO_3-N would likely pose a problem for N leaching losses owing to downward movement of mobile NO_3-N into tile drainage lines. This usually occurs in the spring when soils are at their highest N content due to fertilization and when soils are most saturated due to the frequent rain (Gentry et al., 2014). Nitrate loss in the Midwest is estimated at between 3.8 to 21 $kg\text{-}N\ ha^{-1-}\ ya^{-1}$ (David et al., 2009). Christianson and Harmel (2015) observed that on average 20% of the N applied to corn is lost in drainage. The three way interaction was not evident for NH_4-N; however, a rotation by season effect was observed (Table 3). The interaction was only significant for NH_4-N between CCC and CS during

Table 5
Back-transformed mean values and standard errors (within parentheses) of soil inorganic N under each rotation and tillage practices taken during the growing seasons of 2012–2015 from Monmouth, IL. Values indicated are back-transformed averages. Values in parentheses () are standard errors. Within a column, different lowercase letters are significant at $P \leq 0.10$.

Rotation	Tillage	Season	NO_3-N (ppm)			NH_4-N (ppm)	
Rotation x Tillage x Season Effect							
CCC	T	Spring	64.3	(1.8)	a	14.6	(1.4)
	T	Summer	12.9	(1.5)	abc	3.5	(1.4)
	T	Fall	5.4	(1.6)	bc	4.2	(1.5)
	NT	Spring	58.0	(1.8)	abc	14.2	(1.4)
	NT	Summer	13.0	(1.5)	abc	2.7	(1.4)
	NT	Fall	8.2	(1.6)	abc	3.2	(1.5)
CS	T	Spring	61.2	(1.9)	ab	9.7	(1.4)
	T	Summer	11.7	(1.5)	abc	3.2	(1.4)
	T	Fall	7.8	(1.7)	abc	3.3	(1.5)
	NT	Spring	34.3	(1.8)	abc	9.4	(1.4)
	NT	Summer	11.2	(1.5)	abc	3.3	(1.4)
	NT	Fall	7.8	(1.5)	abc	3.5	(1.5)
SC	T	Spring	16.2	(2.6)	abc	3.7	(1.5)
	T	Summer	6.0	(1.5)	bc	2.6	(1.4)
	T	Fall	5.4	(1.5)	c	3.3	(1.5)
	NT	Spring	19.3	(2.6)	abc	4.3	(1.5)
	NT	Summer	5.9	(1.4)	bc	2.7	(1.4)
	NT	Fall	7.6	(1.5)	abc	2.8	(1.5)
SSS	T	Spring	19.9	(2.8)	abc	2.8	(1.5)
	T	Summer	7.6	(1.5)	abc	2.5	(1.4)
	T	Fall	10.4	(1.5)	abc	3.7	(1.5)
	NT	Spring	28.2	(2.5)	abc	3.4	(1.5)
	NT	Summer	9.2	(1.4)	abc	2.7	(1.4)
	NT	Fall	5.9	(1.5)	bc	3.1	(1.5)
				($p = 0.0491$)			($p = 0.9776$)

†CCC, continuous corn; CS, corn-soybean; SC, soybean-corn; SSS continuous soybean. ‡ T, chisel till; NT, no-till. § Spring, March-May; Summer, June-August; Fall, September-November.

the spring compared to all other rotation by season pairs. This can be explained by the N fertilization input in the form of injected UAN contributing to the high soil NH_4-N values during spring. In contrast, the soybean rotations had similar NH_4-N concentrations throughout the growing season.

Throughout approximately 20–30% of the US Midwest, corn is grown after corn which poses significant risks for growers. The risks include lower yields compared to rotated corn (Gentry et al., 2013; Al-Kaisi et al., 2015; Daigh et al., 2018) and significant air and water pollution due to greater fertilizer inputs necessary for growers to obtain similar yields compared to rotated corn (Zhao et al., 2016). However, the additional fertilizer can be lost as N_2O or leached as aqueous NO_3 to tile lines. Based on the results of our study and agreeing with other studies, utilizing a crop rotation can be an effective strategy to mitigate GHG emissions, especially N_2O (Eichner, 1990; McSwiney and Robertson, 2005; Adviento-Borbe et al., 2007; Halvorson et al., 2008; Hoben et al., 2011; Smith et al., 2011).

4. Conclusions

This study was conducted in Illinois on highly productive soils aiming to investigate the effects of crop rotation and tillage on crop yields, GHG emissions, and soil available N. Results from this study indicated that yields of rotated corn were significantly greater and yields seemed to be more stabilized during suboptimal conditions. Soybean yields were also significantly greater when grown in rotation compared to a monoculture. The benefit of chisel tillage to corn and soybean yields in high organic matter and high residue systems was significant and an increase in N_2O and CO_2 emissions was not observed in this study. In addition, growing corn in a rotation has the ability to significantly lower cumulative N_2O emissions by nearly 2 kg-N ha^{-1}-yr^{-1}. Cumulative N_2O emissions from rotated soybeans were also not different from SSS even though the corn phase of the CS rotation received N fertilizer. Therefore, shifting from a CCC rotation to a CS or CSW rotation will lower N_2O and CO_2 emissions, while also increasing yields during the corn and soybean phases of the rotation. The results of this study will add valuable information to the impact of long term agricultural management practices on GHG emissions in the US Corn Belt.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.agee.2018.03.007.

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