EVALUATING GREENHOUSE GAS EMISSIONS FROM ILLINOIS AGRICULTURE SYSTEMS

BY

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DISSERTATION

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ABSTRACT

Many Illinois cropping systems rely on nitrogen (N), which is an essential element and usually a limiting factor in corn (*Zea mays*, L.) production; yet N build-up in the soil might lead to nitrate ($N\text{-}NO_3$) leaching, and release of nitrous oxide (N_2O) by denitrification, thus contributing to both water and air pollution. Agricultural soil management accounts for much of the total N_2O production in the US. Two of the most important agricultural practices aimed at improving soil properties and reducing inputs 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. Likewise, the inclusion of cover crops (CCs) has been proposed to scavenge surplus soil N, which might lead to a decrease in the substrate needed for N_2O production from the field and aqueous N losses.

In chapter 2 of this dissertation, the objective 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.

In Chapter 3, the objective was to explore the relationships between the physical and chemical properties and GHG emissions of soil, and cash crop yields over a four-year time-period and following 15 years of treatment implementation in Illinois, USA. The experimental layout was a split-plot arrangement involving rotation and tillage treatments in a randomized complete block design with four replications. The studied crop rotations were CCC, CS, SSS, and CSW, with each phase being present for every year. Again, the tillage options were T and NT. We used an array of multivariate approaches to analyze both of

our datasets that included 31 soil properties, GHG emissions (N_2O, CO_2, and CH_4) and cash crop yields. The results from our analyses indicate that N_2O emissions are associated with a low soil pH, an increased Al concentration, the presence of soil nitrate throughout the growing season, an increase in plant available water (PAW) and an increased soil C concentration. Likewise, soil CO_2 respiration was correlated with low pH, elevated Al concentrations, low Ca, increased PAW, higher levels of microbial biomass carbon (MBC), and lower water aggregate stability (WAS). Emissions of CH_4 were associated with increased levels of MBC. Lastly, the yield index (YdI) was correlated with lower levels of soil Ca and available P and lower values of WAS. The association between high YdI and lower WAS can be attributed to tillage, as tillage lowers WAS, but increases yields in highly productive cropping systems in the Midwest.

In Chapter 4, the objective was to determine the effect that corn-soybean rotations with different CCs, and tillage methods have on GHG emissions and crop yields in Illinois, USA. The experimental design was a split-block arrangement of tillage (whole plot treatment, chisel vs. no-till) and CC rotations (subplot treatment) in a RCBD with 4 replications with the corn and soybean phases present each year. GHG emissions - N_2O, CO_2, and CH_4 – soil available N and yields were sampled from the corn phase of each rotation over a period of 4 years (2013-2017). CC rotations included five corn-soybean rotations that included different CCs and one that had fallows as control. Our results suggest that CC efficacy in IL is associated with winter temperature and precipitation. In two of the years, spring CC growth was poor due to unseasonably cold temperatures; however, in two of the other years, weather was favorable and spring CC biomass ranged from 2-3 Mg ha^{-1} from three of the species tested. In years where spring CC biomass was recorded, a fivefold reduction in N_2O emissions occurred due to significant reductions in soil N-NO_3. Corn yields were not improved with the utilization of CCs and a yield decrease of 12% occurred in the annual ryegrass (*Lolium multiflorum* Lam.) rotation.

In Chapter 5, conclusions among the three studies are reviewed and discussed. Combining the knowledge gained from these three studies, utilization of a crop rotation system with a cover crop has the ability to substantially reduce GHG emissions. Yield benefits were observed at the crop rotation level only; however, CC's (excluding annual ryegrass) did not reduce yields. Tillage also provided a yield increase in both studies with no increases in GHG emissions. The knowledge gained through these studies provides an insight as to how Illinois cropping systems produce GHG emissions, and more importantly, which cropping systems are able to reduce GHG emissions.

ACKNOWLEDGEMENTS

I would like to thank my advisor Dr. María Villamil who has been an excellent mentor and has helped instill a great work ethic that has made me a better scientist and scholar. I also thank her for giving me the opportunity to be her lab manager since 2012 and also as a teaching assistant for both of her courses, Forage Crops & Pasture Ecology and Crop Growth & Management. I would also like to extend my thanks to my committee Dr. Emerson D. Nafziger, Dr. DoKyoung Lee, and Dr. Cameron M. Pittelkow.

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I would also like to thank the Villamil lab members who have helped me many times with my research – Samuel Kato, Stacy Zuber, Ivan Dozier, and many, many others. They have helped me in numerous way throughout my projects by helping out with field work and lab analysis and also as co-authors in some cases. I would also like to thank the numerous undergrad workers and interns who helped me sample throughout the many years of research. I would also like to thank the University of Illinois farm crews in both Monmouth and Urbana for maintaining both studies over the several years of investigations.

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CHAPTER 1: PREFACE

Greenhouse gas emissions (GHG) are an important area of recent research and of a particular interest of mine. Specifically, agriculturally related GHG emissions are interesting due to their major contribution to global emissions and are a link to climate change. The GHG's included in this dissertation are N_2O, CO_2, and CH_4. These gases are emitted from the soil and accumulate in the atmosphere, intensifying the greenhouse effect, or the trapping of heat in the lower atmosphere. These GHG's are influential in the warming of the Earth.

The abundance of these GHG's are a result of agricultural soil management. In many countries around the world, N fertilization is essential for production of enough food to feed its citizens and also to use as a global export; this is especially true of corn production in the United States. However, N fertilization also comes with consequences; leaching into waterways and N_2O emissions occur, which threaten global air and water quality. The research included in this dissertation aims to help explain how agricultural production in Illinois affects GHG emissions. Agricultural management practices that reduce these GHG emissions are especially important to determine. Therefore, I organized three different projects (or chapters in the case of this dissertation) that employed several different management practices to elucidate their effect on GHG emissions. I also investigated the effect of these management practices on yield and other soil parameters as to assess their efficacy in a realistic scope. The cropping systems investigated in the following chapters of research include different continuous cropping systems and crop rotations with and without cover crops; in addition, the use of conventional tillage compared to no-tillage systems were studied.

My interest in GHG emissions begin quite a few years ago as part of my Master's research in environmental science studying GHG emissions from *Miscanthus x giganteus*, a bioenergy crop. This research taught me how to investigate the effect of agricultural management on one particular crop and system: how N rate affects GHG emissions from *Miscanthus x giganteus*. Using that knowledge I was hired in Dr. María Villamil's lab as a lab technician, specifically due to my expertise in GHG emissions. My first project was studying the effects of crop rotation and tillage on GHG emissions; this will be discussed in chapters 2 and 3 of this dissertation. Using some of the GHG chambers and my knowledge gained from this project I employed a similar GHG setup to a different project and site already in place studying the effects of crop rotation, tillage, and cover crop species rotation on GHG emissions.

The projects included in this dissertation have allowed me to investigate several different cropping systems commonly employed in the state of Illinois. Coupling these projects with coursework in crop sciences, especially statistical modeling and design have given me the tools needed to publish two of the three chapters in peer-reviewed journals already and chapter 4 will be submitted for publication by the time this dissertation is published. This dissertation is a culmination of much of my work spanning seven years of research; although much of that time I was employed full-time as a senior research specialist in sustainable cropping systems for the University of Illinois in the Crop Sciences Department in Dr. María Villamil's lab.

Each chapter of this dissertation was written to stand alone as published material; however, a conclusion is included in Chapter 5 to give an overview of my findings as to how agricultural management affects GHG emissions in Illinois and some management recommendations.

CHAPTER 2: LONG-TERM CROP ROTATION AND TILLAGE EFFECTS ON SOIL GREENHOUSE GAS EMISSIONS AND CROP PRODUCTION IN ILLINOIS, USA[1]

2.1. 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 (Norton, 2008; Venterea et al., 2005). 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 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; Paustian et al., 2016; Robertson et al., 2007). 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).

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[1] Chapter 2 was published in:

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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) (Rochette et al., 2008; Snyder et al., 2009; Venterea et al., 2005). 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 time's 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; USDA-ERS, 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.

2.2. Materials and Methods

2.2.1. *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 x 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 (Appendix A, Table A.1).

2.2.2. *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 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 minutes. 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 minute collection period.

2.2.3. *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 2.1 as a general description of the soils in this study.

2.2.4. *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 (Appendix A, Table A.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.

2.3. Results and Discussion

2.3.1. *Temperature, Precipitation and Soil Characteristics*

The mean annual temperature was 10.1˚C and the mean annual precipitation was 858 mm between 1989 – 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. 2.1). 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 (5.2cm) 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 2.1) 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 (Divito et al., 2011; Hickman, 2002; Karlen et al., 1994).

2.3.2. *Crop Yields*

Corn yield during 2012-2015 was affected by crop rotation and tillage, but no interaction was detected (Table 2.2). 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

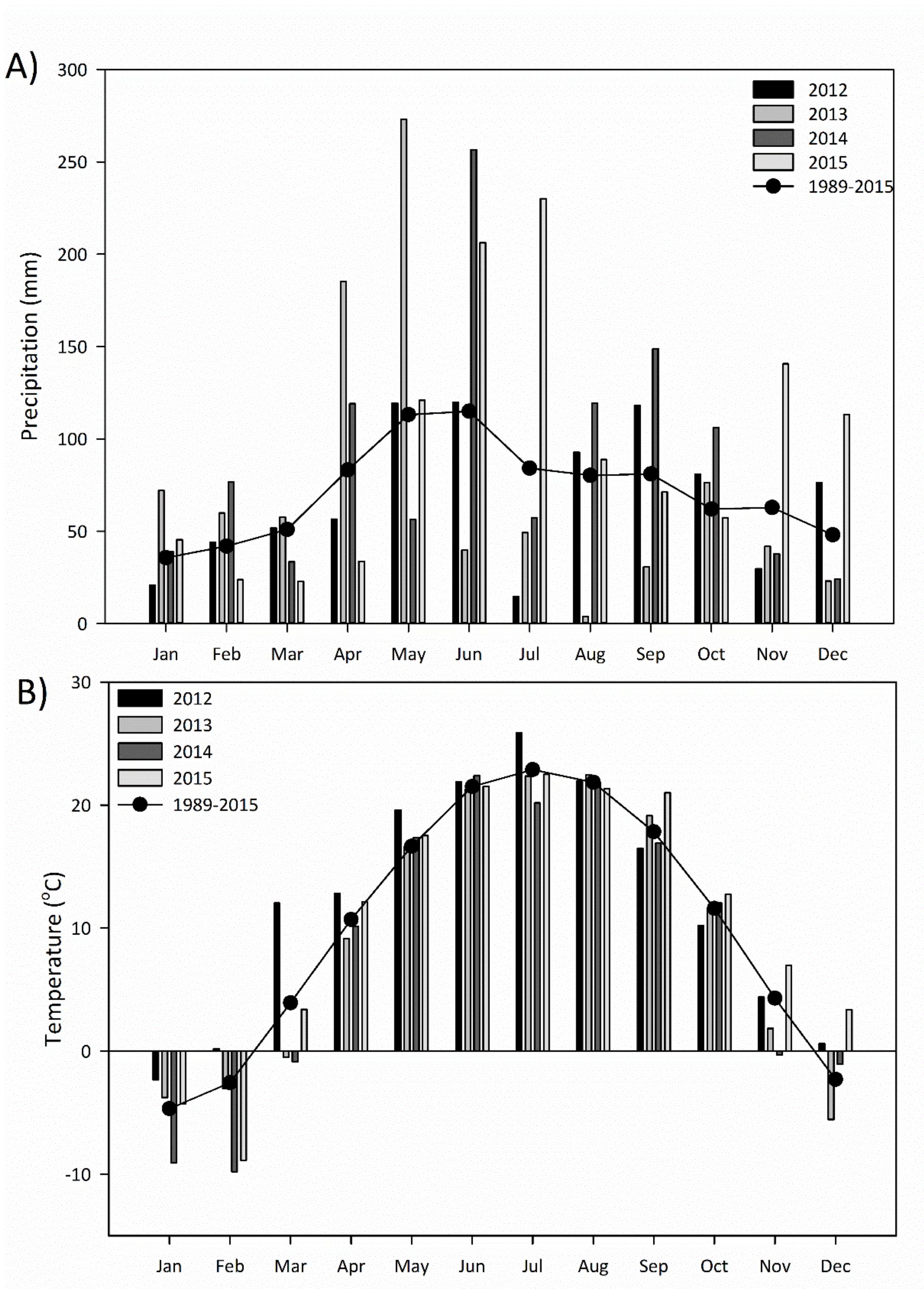

Figure 2.1. (A) Precipitation (mm) and **(B)** temperature (˚C) from 2012-2015 and the normal for the 1989-2015 period. Source: ISWS, 2016.

Table 2.1. 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 †	Tillage ‡	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

† CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SSS continuous soybean.
‡ T, chisel till; NT, no-till.

Table 2.2. 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 $p \leq 0.10$.

Rotation †	Tillage ‡	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		
		($p \leq 0.0001$)		
SC			4.4 (1.1) a	
SSS			4.1 (1.1) b	
			($p \leq 0.0001$)	
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
		($p = 0.0192$)	($p = 0.0192$)	($p = 0.1027$)

† CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SC, soybean-corn; SSS continuous soybean; WCS, wheat-corn-soybean.
‡ T, chisel till; NT, no-till.

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 (Al-Kaisi et al., 2015; Daigh et al., 2017; Gentry et al., 2013).

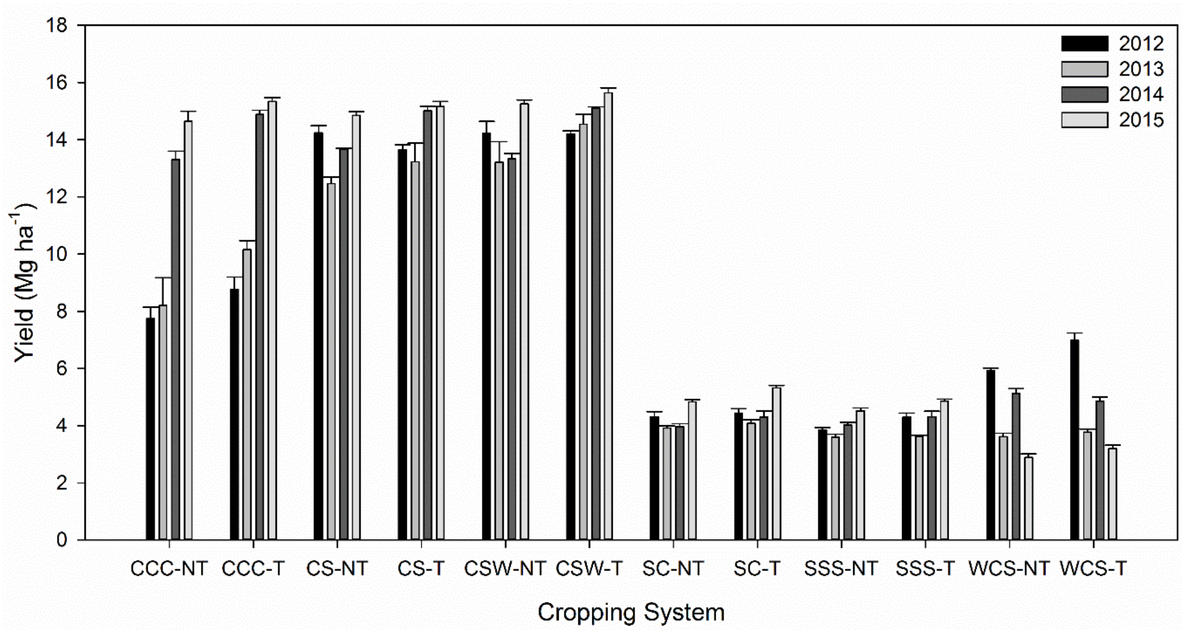

Figure 2.2. Yield results (Mg ha^{-1}) from cropping systems (CCC-NT, no-till continuous corn rotation ; CCC-T, tilled continuous corn rotation; CS-NT, no-till corn of the corn-soybean rotation; CS-T, tilled corn of the corn-soybean rotation; CSW-T tilled corn of the corn-soybean-wheat rotation; SC-NT, 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.

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. (2017) 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 (Cid et al., 2014; Halvorson et al., 2006; Rusinamhodzi et al., 2011). 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 2.2). 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 (Adee et al., 1994; Kelley et al., 2003; Pedersen and Lauer, 2003; Peterson and Varvel, 1989; Seifert et al., 2017; Sindelar et al., 2015; Wilhelm and Wortmann, 2004). Possible explanations for the yield gap between rotated soybeans and SSS have been attributed to diseases (Li et al., 2010; Pedersen and Lauer, 2003) 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 (Kumar et al., 2012; Martens, 2000; 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. (2017) 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 2.2). 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.

2.3.3. *Greenhouse Gas emissions*

A significant interaction between crop rotation and season ($p \leq 0.0001$) on daily N_2O emissions was detected (Table 2.3). 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 (Drury et al., 2014a; Ginting and Eghball, 2005; Halvorson et al., 2008; Hoben et al., 2011; Lehman et al., 2017; Leick and Engels, 2002; Parkin and Kaspar, 2006; Venterea et al., 2005) reported peaks of N_2O emissions closer to fertilizer application with larger peaks corresponding to greater N rates (MacKenzie et al., 1998; Malhi et al., 2006; McSwiney and Robertson, 2005; Omonode et al., 2011; Smith et al., 2011). Other studies in the Midwest found that crop rotations lowered N_2O emissions compared to CCC (Adviento-Borbe et al., 2006; Adviento-Borbe et al., 2007; Jacinthe and Dick, 1997; 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 2.3). 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 2.3). 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 2.3). 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 significantly greater daily CO_2 emissions compared to NT (Table 2.3). 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 (Behnke et al., 2012; Drury et al., 2006; Parkin and Kaspar, 2003; Raich and Potter, 1995). 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 2.2).

Table 2.3. 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 †	Tillage ‡	Season §	N_2O (g-N ha^{-1}-day^{-1})			CO_2 (kg-C ha^{-1}-day^{-1})			CH_4 (g-C ha^{-1}-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															
		Spring	47.9	(2.2)	a	11.9	(1.6)		2.2	(1.1)	61.1	(1.8)	14.4	(1.4)	a
CCC		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
		Spring	37.2	(2.1)	a	10.2	(1.6)		0.0	(1.1)	45.8	(1.8)	9.6	(1.4)	a
CS		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
		Spring	40.3	(2.0)	a	12.1	(1.6)		4.3	(1.2)	N/A		N/A		
CSW		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		
		Spring	7.3	(3.5)	ab	5.8	(2.2)		-2.6	(1.5)	17.7	(2.5)	4.0	(1.4)	b
SC		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
		Spring	5.1	(5.3)	ab	3.5	(2.4)		-1.8	(1.5)	23.7	(2.6)	3.1	(1.4)	b
SSS		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
			($p \leq 0.0001$)			($p = 0.9184$)			-		($p = 0.0309$)		($p \leq 0.0001$)		

† CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SC, soybean-corn; SSS continuous soybean.

‡ T, chisel till; NT, no-till.

§ Spring, March-May; Summer, June-August; Fall, September-November.

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 2.3 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 2.4). 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 (Adviento-Borbe et al., 2007; Halvorson et al., 2008; Parkin and Kaspar, 2006). 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 2.4). 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 (Adviento-Borbe et al., 2007; Eichner, 1990; Halvorson et al., 2008; Hoben et al., 2011; McSwiney and Robertson, 2005; Smith et al., 2011). While examining the interaction effect of rotation and tillage in Table 2.4, 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 2.4 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 (Johnson et al., 2010; Lebender et al., 2014; Snyder et al., 2009; Wagner-Riddle et al., 2007), yet a limitation of this study is that sampling was not conducted frequently enough to capture these emissions.

Table 2.4. 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 ≤ 0.10.

Rotation †	Tillage ‡	N_2O (kg-N ha^{-1}-yr^{-1})			CO_2 (Mg-C ha^{-1}-yr^{-1})			CH_4 (kg-C ha^{-1}-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 ≤ 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)	

† CCC, continuous corn; CS, corn-soybean; SC, soybean-corn; SSS continuous soybean; WCS, wheat-corn-soybean.
‡ T, chisel till; NT, no-till.

Similar to N_2O, cumulative CO_2 emissions were significantly influenced by crop rotation (Table 2.4). Cumulative CO_2 emissions were 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 2.4). 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.

2.3.4. *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 2.5). 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 2.5) 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 (Adviento-Borbe et al., 2007; Amos et al., 2005). 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-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 2.3). The interaction was only significant for NH_4-N between CCC and CS during 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.

Table 2.5. 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 ≤ 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.

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 (Al-Kaisi et al., 2015; Daigh et al., 2017; Gentry et al., 2013) 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 (Adviento-Borbe et al., 2007; Eichner, 1990; Halvorson et al., 2008; Hoben et al., 2011; McSwiney and Robertson, 2005; Smith et al., 2011).

2.4. *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.

CHAPTER 3: EXPLORING THE RELATIONSHIPS BETWEEN GREENHOUSE GAS EMISSIONS, YIELDS, AND SOIL PROPERTIES IN CROPPING SYSTEMS[2]

3.1. Introduction

The Midwestern United States (US) is regarded as having some of the most productive lands in the world; deep and dark Mollisols cover over half of the state of Illinois (Dunn et al., 2016). Accordingly, Illinois places in the top two states for corn (*Zea mays* L.) and soybean [*Glycine max* (L). Merr.] production, with nearly 5 million ha of corn planted and 4 million ha of soybean planted each year (USDA-NASS, 2018). Due to a large amount of production expected to feed a growing global population, significant inputs of N and P are added each year in order to achieve maximum productivity. Specifically, in 2016, 954,400 tons of N and 446,350 tons of P were applied to 98% and 86% of the planted corn area, respectively (USDA-NASS, 2018). This demand for high yield does not come without consequences; agriculture contributes around 9% of total US greenhouse gas (GHG) emissions. Of this 9%, carbon dioxide (CO_2) makes up the majority (81%), followed by methane (CH_4) (11%) and then nitrous oxide (N_2O) (6%) (EPA, 2016). In addition to gaseous losses, agricultural land is deteriorated each year due to erosion, flooding, mining, urban development, and other sensitive agricultural practices; these destructive consequences lead to soil contamination and have an overall undesirable effect on the soil quality (FAO, 2015). Therefore, the protection of fertile soil is critical to human welfare (Pimentel and Burgess, 2013).

Soil management is critical both for productivity and to limit environmental degradation. Agricultural soil management includes fertilizer use, agrochemicals, tillage practices, and crop rotation systems. These management decisions influence agricultural N_2O emissions which constitute approximately 80% of the total annual N_2O emissions in the US (EPA, 2016). The global warming potentials (GWP) of N_2O and CH_4 are 298 and 25 times greater than that of CO_2, respectively. Global warming potential is a measure of the amount of energy that one kilogram of a certain GHG will absorb over a given time period, usually 100 years, relative to CO_2 (EPA, 2016). Nitrous oxide emissions are affected by the N application rate, fertilizer source, application technique and timing, use of other

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chemicals, irrigation, crop type, and residual N and C from previous crops and fertilizers (Eichner, 1990; FAO, 2001; Venterea et al., 2011). Nitrogen added to the system through fertilizers, other agrochemicals, or residue decomposition stimulates N_2O production by providing a substrate for microbial N conversion through nitrification and

denitrification (Norton, 2008; Venterea et al., 2005). Nitrification occurs when ammonium is added to the soil through either fertilizers, N fixation by legumes, or mineralized soil organic matter (SOM) (Paustian et al., 2016). Microbial transformations cause the ammonium to be converted to nitrite and eventually to nitrate, though small quantities can be lost as N_2O (Snyder et al., 2009). Similarly, low soil oxygen conditions lead to microbial denitrification as 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; Paustian et al., 2016; Robertson et al., 2007). Throughout the US Corn Belt (Illinois, Iowa, Indiana, Ohio, Southern and Western Minnesota, and Eastern Nebraska), spring fertilization application is common. However, events involving saturating rain to flooding routinely occur during this time as well, so water-logging of the soil ensues, which promotes large denitrification events due to low soil oxygen concentrations, wherein a large proportion of annual N_2O flux can occur over a short time scale, ranging from hours to weeks (Venterea et al., 2012).

The fertilization of crops is inherently leaky; many take up less than 50% of the N applied, leaving the N that is not stored in the soil subject to loss (Millar et al., 2010). Due to the excess N in the system and the connection between this N and GHG emissions, the US Corn Belt tends to be a major source of agricultural GHG emissions (EPA, 2016). Greater N_2O emissions have been reported in continuous corn operations compared to corn in rotation, due to increased fertilizer input which is common in continuous corn operations. In addition, continuous corn operations return greater amounts of residue to the soil compared to rotated corn and this increased amount of C substrate allows for greater microbial decomposition and increased denitrification (Behnke et al., 2018b; McSwiney and Robertson, 2005; Omonode et al., 2011; Snyder et al., 2009). However tillage studies have been less conclusive; no-till (NT) or reduced till can have less, more, or no effect on N_2O emissions compared to conventional tillage systems (T) (Rochette et al., 2008; Snyder et al., 2009; Venterea et al., 2005). Two common agricultural practices aimed at improving soil properties are crop rotations and no-tillage systems. These management practices directly influence the soil organic carbon (SOC) content by affecting the quantity, quality, and rate of crop residue decomposition returned to the system; SOC is an indicator of soil health and quality (Varvel, 1994; West and Post, 2002). The benefits of SOC are an increase in nutrient availability, an increased cation exchange capacity (CEC), an improved water holding capacity, and a lowered bulk density (Varvel, 1994; West and Post, 2002).

Despite the benefits to SOC under no-till systems, corn yields in the Midwest tend to be greater when a tillage regime is used compared to a no-till regime (Behnke et al., 2018b; Halvorson et al., 2006; Jagadamma et al., 2008; Parkin and Venterea, 2010). In a recent study conducted by Daigh et al. (2018) at several sites in the Midwest, yield increases due to tillage were correlated with the crop phase of the rotation, especially during non-drought conditions. Greater decreases in yield with long-term (5+ years) NT in corn systems were observed in a global meta-analysis conducted by Pittelkow et al. (2015); the reduced yield with NT systems has been attributed to waterlogging, poor establishment, compaction, and nutrient deficiencies (Cid et al., 2014; Halvorson et al., 2006; Rusinamhodzi et al., 2011).

Just as tillage has been shown to increase yields in the Midwest, crop rotation has been well documented to increase yields in both corn and soybean years (Adee et al., 1994; Al-Kaisi et al., 2015; Behnke et al., 2018b; Daigh et al., 2018; Gentry et al., 2013; Kelley et al., 2003; Pedersen and Lauer, 2003; Peterson and Varvel, 1989; Seifert et al., 2017). However, some soil properties, such as SOC, have been shown to increase with more years of growing corn due to the larger residue return from corn back to the soil system (Havlin et al., 1990; Jagadamma et al., 2007; Jagadamma et al., 2008; Studdert, 2000; Varvel, 1994; Varvel and Wilhelm, 2010). The increases in SOC can also be related to increased levels of N and P (Franzluebbers et al., 1994; Power et al., 1998). The intricate interactions of crop rotations influence the soil environment through the quantity and quality of residue decomposition. Crop rotation decreases weed and insect pest pressure and also increases the residue quality by improving the retention of N in microbial biomass (McDaniel et al., 2014). The inclusion of crops with high C/N ratios in their residue, like corn and wheat (*Triticum aestivum* L.), combined with NT has been found to increase SOC, TN, and aggregate stability (Benjamin et al., 2010; Zuber et al., 2015).

In Behnke et al. (2018b), a study published previously using some of the data that is presented subsequently in the current study, it was found that tillage increased the yields of corn and soybean. Likewise, utilizing a corn-soybean rotation (CS) increased corn yields by 20% while reducing N_2O emissions by nearly 35%; soybean yields were 7% greater with no reduction in N_2O emissions. The authors found that a CS rotation can increase yields and reduce GHG emissions compared to continuous corn or continuous soybean systems alone. Furthermore, moving to a corn-soybean-wheat rotation did not further increase yields or reduce N_2O emissions. This study highlights how management decisions can affect soil GHG emissions and crop production. As a result, the interactions between several soil properties, GHG emissions and yields need to be further evaluated. Several studies have included soil properties related to tillage and crop rotation practices, but few have taken into account GHG emissions; even fewer have been conducted on a long-term scale (15+ years). In order to understand the dynamic relationships between these variables, a multivariate statistical analysis on a large dataset is urgently needed. Thus, our goal for this project was to elucidate the relationships between GHG emissions, soil properties, and crop yields in typical cropping systems in Illinois.

3.2. Materials and Methods

3.2.1. Site Characterization and Experimental Layout

This study was established in 1996 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 mean annual precipitation in this area is approximately 978 mm and the mean annual temperature is 16 °C (ISWS, 2018). Soils at the experimental site were predominantly comprised of Sable silty clay loam (fine-silty, mixed, mesic Typic Endoaquoll) and Muscatune silt loam (fine-silty, mixed, mesic Aquic Argiudoll). In addition, the plots contained a small area of Osco silt loam (fine-silty, mixed, mesic Typic Argiudoll) (Soil-Survey-Staff, 2018). 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), soybean-wheat-corn (SWC), 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) being present during 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 being 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) for greenhouse gas (GHG) emissions; however, soil samples and yields were taken in those plots. The first letter of the cropping system abbreviation indicates the crop for which a property is being reported. The cropping systems used in the analysis included no-till continuous corn (CCC-NT); tilled continuous corn (CCC-T); no-till corn of the corn-soybean rotation (CS-NT); tilled corn of the corn-soybean rotation (CS-T); no-till corn of the corn-soybean-wheat rotation (CSW-NT); tilled corn of the corn-soybean-wheat rotation (CSW-T); no-till soybean of the soybean-corn rotation (SC-NT); tilled soybean of the soybean-corn rotation (SC-T); tilled soybean-wheat-corn (SWC-T); no-till soybean-wheat-corn (SWC-NT); no-till continuous soybean (SSS-NT); tilled continuous soybean (SSS-T); no-till wheat of the wheat-corn-soybean rotation (WCS-NT); and tilled wheat of the wheat-corn-soybean rotation (WCS-T).

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 the time of 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 kg-N ha^{-1} at planting and 56 kg-N ha^{-1} as a spring topdress of UAN. No N fertilizer was applied to soybean treatments. Additional P and K fertilizer were 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 seeds 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 the purpose of this report, we will treat the 2014 oat crop as wheat. Yields were harvested using a plot combine (Almaco, Nevada, IA, USA) and adjusted to 15.5%, 13%, and 13.5% moisture levels for corn, soybean, and wheat, respectively. Detailed information, including dates, is summarized in the Appendix B (Table B.1).

3.2.2. Gas Sampling Procedures

Soil GHG emissions were taken weekly over 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 for each of the soybean and wheat plots. Soil CO_2 emissions were used to represent soil respiration. Due to severe weather, we were not able to collect wheat data in 2014. The chamber tops were also made of white PVC, and contained a vent tube, sampling septa, and insulation foam to create an airtight 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 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 minute collection period. The number of sampling events by year is included in the supplemental information Appendix B (Table B.2).

3.2.3. Soil Sampling and Analyses

Two soil cores (0–10 cm depth) were collected from each plot and each sampling event during gas sampling for the 2013–2015 growing seasons (complete list found in Appendix B Table B.2), composited, and then analyzed for available N concentrations in 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, USA). The concentrations of NH_4–N and NO_3–N were used to calculate the soil nitrogen intensity throughout the growing season, following the protocol in (Venterea et al., 2011); this will be discussed later. In addition, to evaluate long-term treatment effects on soil properties, three soil cores, 4.3 cm in diameter, were taken in May of 2014 for each subplot to a depth of 20 cm with a tractor-mounted hydraulic probe (Amity Technology, Fargo, ND, USA). Soil cores were cut to 0–10 and 10–20 cm depths and stored refrigerated at 4 °C in plastic bags until analysis. Soil samples from depths of 0–10 and 10–20 cm were combined in this study. Soil samples were air-dried, ground, and sieved through a 2-mm sieve, and the three subsamples from each plot were composited to provide one sample per plot for the remainder of the soil analyses. The soil physical properties measured included soil texture (% sand, % silt, and % clay) by the hydrometer method (ASTM-D422, 2007); soil moisture (Ho, %) at each NO_3 and NH_4 soil sampling event (determined gravimetrically) (Carter, 1993); permanent wilting points (PWP, cm^3 cm^{-3}) (determined from separate soil cores, 4.8 cm in diameter), and plant available water (PAW, cm^3 cm^{-3}) (measured using a Decagon WP4C device (Decagon Devices, Inc., Pullman, WA, USA) following Basche et al. (2016b)). Likewise, soil bulk density (Bd, g cm^{-3}) was determined for each subsample using the core method (Blake and Hartge, 1986). Lastly, three subsamples from the 1–2-mm soil fraction were used to determine the water aggregate stability (WAS) with an Eijkelkamp wet sieving apparatus (Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands), following Kemper and Rosenau (1986). The microbial biomasses of C (MBC, μg g^{-1}) and N (MBN, μg g^{-1}) were analyzed on a Shimadzu TOC-L and TNM-L analyzer (Shimadzu Corporation, Kyoto, Japan), following the modified chloroform fumigation extraction protocol for air-dried soils described in Zuber et al. (2017). Furthermore, soil macronutrients included soil ammonia intensity (NH_4, mg-N

$kg^{-1}day^{-1}$ during the growing season), soil nitrate intensity (NO_3, mg-N $kg^{-1}day^{-1}$ during the growing season), and total soil nitrogen intensity (TIN, mg-N $kg^{-1}day^{-1}$ during the growing season), which was determined by trapezoidal integration of soil concentration over time (Venterea et al., 2011) —NH_4 and NO_3 separately and the sum of the two for TIN.

Air-dried soil samples were sent to a commercial laboratory for the determination of pH, CEC, SOM, C, N, C/N, Pa, K, S, Ca, Mg, Na, B, Fe, Mn, Cu, Zn, and Al (Brookside Laboratories, Inc., New Bremen, OH, USA). Soil pH was analyzed using potentiometry (1:1 water and soil ratio) (McLean, 1982); cation exchange capacity (CEC, cmol kg^{-1}) was determined by the summation method of exchangeable cations (Ca, Mg, K, Na, H) (Sumner and Miller, 1996). The quantities of soil organic matter (SOM, %), carbon (C, %), nitrogen (N, %), and the carbon/nitrogen ratio (C/N) were analyzed using dry combustion (McGeehan and Naylor, 1988; Nelson and Sommers, 1996). Available phosphorus (Pa, mg kg^{-1}) was measured through Bray I extraction (Bray and Kurtz, 1945) while potassium (K, mg kg^{-1}), sulfur (S, mg kg^{-1}), calcium (Ca, mg kg^{-1}), magnesium (Mg, mg kg^{-1}), sodium (Na, mg kg^{-1}), boron (B, mg kg^{-1}), iron (Fe, mg kg^{-1}), manganese (Mn, mg kg^{-1}), copper (Cu, mg kg^{-1}), zinc (Zn, mg kg^{-1}), and aluminum (Al, mg kg^{-1}) concentrations were determined following Mehlich III extraction (Mehlich, 1984) and further analysis was conducted by inductively coupled plasma (ICP).

3.2.4 Data Analysis

The experiment aimed to test the relationships between GHG emissions, soil properties, and crop yields following the effects of cropping rotation and tillage that have occurred since 1996. Cumulative GHG emissions (N_2O, CO_2, and CH_4) were linearly extrapolated to predict fluxes for the growing season. The exact number of sampling events is included in Appendix B (Table B.2). A detailed description of the cumulative GHG calculations and other information is included in a previous publication (Behnke et al., 2018b). Yields were standardized by crop to account for differences in yield levels, and values were normalized to a mean of 0 and standard deviation of 1. Therefore, the variable yield index (YdI) is unitless. The number of observations included in the original dataset before averaging by plot is included in Appendix B (Table B.3). The inclusion of both tables (Appendix B Tables B.1 and B.2) shows which variables were present throughout the growing season and which variables we sampled in the spring of 2014.

Two subsets of the data, analyzing GHG and YdI, were created to extract maximum information knowing that our software of preference to conduct multivariate analyses automatically removes observations with missing data (SAS 9.4, SAS Institute Inc., Cary, NC, USA, 2012). Thus, the first data set for GHG emissions included all 32 variables (including YdI), rendering a total of 32 observations with no missing data. A second data set for GHG emissions was comprised of 56 observations on 23 measured variables, excluding sand, silt, clay, Ho, PWP, PAW, NH_4, NO_3, and TIN. Similarly, the first data set for YdI included all 34 variables (including GHG emissions) rendering a total of 32 observations with no missing data. A second data set for YdI was comprised of 52 observations on 25 measured variables, excluding sand, silt, clay, Ho, PWP, PAW, NH_4, NO_3, and TIN.

The GHG, YdI, and soil variables measured had contrasting variances and units of measurement. The means and standard errors of the mean values for each variable were determined using the means procedure in SAS software (SAS 9.4, SAS Institute Inc., Cary, NC, USA). The mean and standard error values for each crop rotation, tillage, and crop rotation by tillage combination are included in Appendix B (Tables B4–B8). To avoid having the variable with the highest variance dominate the results, all multivariate analyses were conducted on standardized data (mean = 0, standard deviation = 1) obtained with the STANDARD procedure in SAS. Pearson's correlation coefficients were calculated using the CORR procedure in SAS to explore correlations between GHG, YdI, and soil variables (Appendix B Table B.9). Correlations between variable pairs were found to be $\geq|0.25|$ (moderate to high range) which, in most cases, indicated the need to deploy a data reduction technique such as principal component analysis (PCA) to avoid problems of multicollinearity by compiling the information into a new smaller set of uncorrelated variables. We performed a PCA using the PRINCOMP procedure in SAS. PCA creates new uncorrelated, orthogonal variables called principal components (PCs) that are linear combinations of the original raw variables that maximize the variability explained by the set of variables (Johnson and Wichern, 2002). The PCA of the available variables in the data set determines coefficients in a new linear design (Yeater and Villamil, 2017). The PCA technique uses the relationships between the original variables to develop a smaller set of components that empirically summarizes the correlations between the variables (Tabachnick and Fidell, 2013). The new reduced set of variables or PCs contains almost as much information as the original variables but reveals relationships that would not typically result. Eigenvalues represent a special set of scalars associated with a linear system of equations; eigenvalues are comprised of all the variables tested and each explains a percentage of the variability (Johnson and Wichern, 2002). The reorganized and uncorrelated PCs contain loading factors or eigenvectors based on the contribution of variability and correlation to the PC axis (Yeater and Villamil, 2017). We extracted PC scores with eigenvalues ≥1 that explained an important proportion of the total variability of each data set; these new variables are hereby called PC1 to PC8. Eight PCs were extracted from the first GHG dataset and seven PCs from the second GHG data set, as previously described. Eight PCs were extracted from both of the YdI data sets, as previously described. The PCA thus reduced the dimensionality of the first GHG dataset from 32 (correlated) variables to eight (uncorrelated) PCs (PC1 to PC8), and from 23 variables to seven uncorrelated linear combinations (PC1 to PC7) with limited loss of information in both data sets. Likewise, the PCA reduced the dimensionality of the first YdI dataset from 34 (correlated) variables to eight (uncorrelated) PCs (PC1 to PC8); and from 25 variables to eight uncorrelated linear combinations (PC1 to PC8), again with limited loss of information in both data sets. Soil, GHG, and YdI variable loadings ≥|0.25| were considered in the interpretation of each set of PCs. Next, we fitted multiple linear regression models to the PCs extracted in each case using PROC REG in SAS to evaluate the relationships between soil, GHG, and YdI. Regression analyses were conducted using stepwise selection with sle = 0.1 and sls = 0.15.

3.3. Results

3.3.1. Greenhouse Gas 32 Variable Dataset

The PCA of the 32 variable dataset for GHG emissions rendered a set of eight uncorrelated variables or PCs (PC1 to PC8, Table 3.1) with eigenvalues larger than 1, which, when added together explained about 83% of the total variability contained in the GHG database. These eight PCs incorporated the 32 original variables but contained high loading factors based on their contributions to variability and correlations with the PC. PC1 had the largest eigenvalue (8.17) and explained around 26% of the variability with its eigenvector that included high positive loadings (>0.25) for CEC, N, and Fe. In addition, PC1 included high negative loadings (<−0.25) for pH, C/N, and B. PC2 had an eigenvalue of 6.66 and explained around 20% of the variability in the 32 variable set for GHG emissions. The eigenvector for PC2 had positive loadings for PWP, C, Ca, and Cu. The eigenvalue for PC3 was 3.28 and explained an additional 11% of the total variability. The eigenvector for PC3 included positive loadings for silt and SOM. Likewise, the eigenvector for PC3 contained negative loadings for clay, NH_4, NO_3, and TIN. The eigenvalue for PC4 was 2.41 and accounted for 8% of the variability. PC4 contained positive loadings for PAW, Pa, Mn, and Zn. In addition, PC4 contained negative loadings for sand and WAS. PC5 had an eigenvalue of 2.37 and explained 7% of the variability. PC5 included positive loadings for clay, MBN, and Na. Conversely, PC5 contained negative loadings for silt, Bd, and Mn. PC6 had an eigenvalue of 1.42 and explained 4% of the variability. The eigenvector for PC6 showed positive loadings for YdI, sand and MBC, and negative loadings for WAS and Na. The eigenvalue for PC7 was 1.31 and explained an additional 4% of the variability. The eigenvector for PC7 contained positive loadings for Bd, MBN, Na, and Zn. PC7 also contained a negative loading for CEC. The final PC8 had an eigenvalue of 1.07 and explained 3% of the variability, while its eigenvector showed positive loadings for PAW, Bd, and C, and a negative loading for Pa. These eight significant PCs were used as independent variables in our multiple regression analysis.

Table 3.1. Principal component analysis based on 32 observations modeling greenhouse gas (GHG) emissions (N_2O, CO_2, and CH_4) with 32 variables, with eigenvalues and the cumulative proportion of the dataset variability explained by eight principal components (PC) extracted from eigenvalues >1. Component correlation scores (eigenvalues) with loadings greater than |0.25| are in bold.

	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8
Eigenvalue	8.17	6.66	3.28	2.41	2.37	1.42	1.31	1.07
Cum. Proportion	0.26	0.46	0.57	0.64	0.72	0.76	0.80	0.83
Soil Variable	Component Correlation Scores							
Yield Index (YdI)	-0.13	-0.16	0.13	0.11	0.19	**0.38**	-0.05	0.11
Sand	0.21	0.00	-0.01	**-0.26**	0.13	**0.33**	0.10	0.08
Silt	-0.09	-0.18	**0.30**	0.07	**-0.32**	-0.08	0.04	0.01
Clay	0.06	0.19	**-0.31**	-0.02	**0.30**	0.02	-0.06	-0.03
Ho	0.04	0.22	0.20	-0.18	-0.15	-0.10	-0.17	0.08
Permanent Wilting Points (PWP)	-0.08	**0.30**	0.10	-0.20	-0.04	-0.23	-0.09	-0.10
Plant Available Water (PAW)	0.10	-0.09	-0.06	**0.43**	0.02	0.06	-0.20	**0.44**
Soil Bulk Density (BD)	0.07	-0.03	0.06	-0.15	**-0.26**	-0.12	**0.60**	**0.25**
Water Aggregate Stability (WAS)	0.04	0.19	0.04	**-0.30**	0.03	**-0.38**	-0.05	0.08
pH	**-0.32**	-0.02	-0.13	-0.06	-0.09	-0.03	0.08	0.06
Cation Exchange Capacity (CEC)	**0.29**	0.11	0.13	0.06	0.04	-0.03	**-0.26**	-0.05
Soil Organic Matter (SOM)	0.23	0.18	**0.26**	0.01	0.07	0.11	0.05	0.20
C	0.13	**0.27**	**0.25**	0.05	0.03	0.12	0.03	**0.30**
N	**0.26**	0.18	0.18	-0.02	-0.05	0.09	0.07	0.16
C/N	**-0.26**	0.17	0.09	0.07	0.15	0.07	-0.09	0.18
Microbial Biomass Carbon (MBC)	-0.13	0.12	0.17	-0.02	-0.12	**0.45**	0.12	-0.12
Microbial Biomass Nitrogen (MBN)	-0.17	0.04	-0.03	-0.01	**0.40**	0.08	**0.37**	-0.22
NH_4	0.18	0.14	**-0.31**	-0.04	-0.15	0.11	0.08	-0.08
NO_3	0.19	0.11	**-0.37**	0.08	-0.07	0.09	0.02	0.08
Total Soil Nitrogen Intensity (TIN)	0.20	0.13	**-0.37**	0.03	-0.11	0.11	0.05	0.02
Pa	0.00	0.19	0.11	**0.39**	-0.07	0.00	-0.01	**-0.38**
K	0.23	0.05	-0.15	-0.03	-0.18	0.05	0.17	-0.12
S	**0.25**	-0.23	0.01	0.10	0.05	-0.10	0.03	0.08
Ca	0.01	**0.32**	-0.02	0.07	0.03	-0.03	0.13	0.05
Mg	-0.21	**0.25**	-0.16	0.04	-0.04	-0.05	-0.08	0.13
Na	0.05	-0.15	0.00	0.21	0.31	**-0.38**	**0.32**	0.23
B	**-0.27**	0.10	-0.13	0.13	0.05	-0.03	0.14	0.22
Fe	**0.25**	0.08	0.11	0.19	0.24	-0.12	0.04	-0.21
Mn	0.00	-0.09	-0.11	**0.32**	**-0.42**	-0.09	-0.05	-0.01
Cu	-0.11	**0.30**	-0.04	0.24	0.04	-0.17	-0.05	-0.02
Zn	0.00	0.19	0.18	0.31	-0.08	0.03	**0.34**	-0.23
Al	0.23	-0.23	0.08	-0.01	0.15	-0.14	-0.01	-0.20

3.3.2. Greenhouse Gas 23 Variable Dataset

The PCA of the 23 variable dataset for GHG emissions rendered a set of seven uncorrelated variables or PCs (PC1 to PC7, Table 3.2) with eigenvalues larger than 1, which, when added together explained about 80% of the total variability contained in the GHG database. These seven PCs incorporated the 23 original variables but contained high loading factors based on their contributions to variability and correlations with the PC. PC1 had the largest eigenvalue (6.04) and explained around 26% of the variability with its eigenvector that included high positive loadings (>0.25) for pH C/N, Mg, and B. In addition, PC1 included high negative loadings (<−0.25) for S and Al, C/N, and B. PC2 had an eigenvalue of 5.01 and explained around 22% of the variability in the 23 variable set for GHG emissions. The eigenvector for PC2 had positive loadings for CEC, SOM, C, N, Ca, and Zn. The eigenvalue for PC3 was 2.17 and explained an additional 10% of the total variability. The eigenvector for PC3 included positive loadings for YdI and MBN. Likewise, the eigenvector for PC3 contained negative loadings for Pa and Mn. The eigenvalue for PC4 was 1.56 and accounted for 8% of the variability. PC4 contained positive loadings for MBN, Na, Fe, and Cu. In addition, PC4 contained negative loadings for Bd and K. PC5 had an eigenvalue of 1.39 and explained 6% of the variability. PC5 included positive loadings for YdI, S, Na, Mn, and Zn. Conversely, PC5 contained negative loading for WAS. PC6 had an eigenvalue of 1.13 and explained 5% of the variability. The eigenvector for PC6 showed positive loadings for Pa and Zn. PC6 also contained negative loadings for YdI, CEC, and Ca. The final PC7 had an eigenvalue of 1.12 and explained 5% of the variability, while its eigenvector showed positive loadings for Bd, WAS, and Na. These seven significant PCs were used as independent variables in our multiple regression analysis.

3.3.3. Yield Index 34 Variable Dataset

The PCA of the 34 variable dataset for the yield index rendered a set of eight uncorrelated variables or PCs (PC1 to PC8, Table 3.3) with eigenvalues larger than 1, which, when added together explained about 83% of the total variability contained in the YdI database. These eight PCs incorporated the 34 original variables but contained high loading factors based on their contributions to variability and correlations with the PC. PC1 had the largest eigenvalue (8.75) and explained around 26% of the variability with its eigenvector that included high positive loadings (>0.25) for CEC and S. In addition PC1 included high negative loadings (<−0.25) for pH and B. PC2 had an eigenvalue of 6.58 and explained around 19% of the variability in the 34 variable set for yield index. The eigenvector for PC2 had positive loadings for PWP, C, Ca, and Cu. The eigenvalue for PC3 was 3.54 and explained an additional 11% of the total variability. The eigenvector for PC3 included positive loadings for CH_4, clay, NH_4, NO_3, and TIN. The eigenvalue for PC4 was 2.62 and accounted for 7% of the variability. PC4 contained positive loadings for

Table 3.2. Principal component analysis based on 52 observations modeling GHG emissions (N_2O, CO_2, and CH_4) with 23 variables, with eigenvalues and the cumulative proportion of the dataset variability explained by the seven principal components (PC) extracted with eigenvalues >1. Component correlation scores (eigenvalues) with loadings greater than |0.25| are in bold.

	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Eigenvalue	6.04	5.01	2.17	1.56	1.39	1.13	1.12
Cum. Proportion	0.26	0.48	0.58	0.64	0.70	0.75	0.80
Soil Variable	Component Correlation Scores						
YdI	0.07	−0.05	**0.37**	0.11	**0.44**	**−0.35**	−0.21
BD	−0.09	0.00	−0.03	**−0.45**	0.07	0.24	**0.60**
WAS	−0.04	0.19	0.07	0.14	−0.52	−0.06	**0.27**
pH	**0.32**	−0.21	0.00	−0.18	0.00	0.15	0.05
CEC	−0.22	**0.28**	−0.17	0.20	−0.01	**−0.30**	−0.05
SOM	−0.12	**0.39**	0.16	−0.16	0.08	−0.07	−0.01
C	0.03	**0.39**	0.18	−0.22	0.09	−0.01	0.01
N	−0.17	**0.36**	0.05	−0.21	0.07	−0.09	0.06
C/N	**0.32**	0.11	0.20	−0.03	0.00	0.13	−0.08
MBC	0.18	0.14	0.20	−0.12	0.00	0.16	−0.14
MBN	0.14	−0.02	**0.44**	**0.32**	−0.04	0.18	0.19
Pa	0.04	0.19	**−0.25**	0.18	0.22	**0.52**	−0.23
K	−0.19	0.14	−0.14	**−0.28**	−0.06	0.04	−0.10
S	**−0.26**	−0.10	0.07	−0.12	0.37	−0.11	0.09
Ca	0.19	**0.30**	−0.09	0.08	0.06	**−0.30**	0.09
Mg	**0.33**	0.12	−0.20	0.03	−0.02	−0.24	0.12
Na	−0.15	−0.10	0.12	**0.29**	**0.32**	−0.01	**0.52**
B	**0.34**	−0.01	−0.05	−0.03	0.14	−0.11	0.19
Fe	**−0.25**	0.22	0.01	**0.34**	−0.03	0.22	0.04
Mn	−0.03	−0.11	**−0.52**	0.04	**0.29**	−0.04	0.03
Cu	0.23	0.23	**−0.25**	**0.33**	0.04	0.04	0.22
Zn	0.09	**0.28**	0.04	0.01	**0.31**	**0.32**	−0.04
Al	**−0.35**	−0.11	0.12	0.14	−0.03	0.10	−0.06

PAW, Pa, Mn, and Zn. In addition, PC4 contained a negative loading for WAS. PC5 had an eigenvalue of 2.35 and explained 7% of the variability. PC5 included positive loadings for clay, MBN, Na, and Fe. Conversely, PC5 contained negative loadings for silt, Bd, and Mn. PC6 had an eigenvalue of 1.66 and explained 5% of the variability. The eigenvector for PC6 showed positive loadings for CH_4, sand, MBC, and MBN. The eigenvalue for PC7 was 1.38 and explained an additional 4% of the variability. The eigenvector for PC7 contained positive loadings for Bd, MBN, Na, and Zn. PC7 also contained a negative loading for N_2O. The final PC8 had an eigenvalue of 1.20 and explained 4% of the variability, while its eigenvector showed positive loadings for Bd, Na, and B and a negative loading for Pa. These eight significant PCs were used as independent variables in our multiple regression analysis.

3.3.4. Yield Index 25 Variable Dataset

The PCA of the 25 variable dataset for the yield index rendered a set of eight uncorrelated variables or PCs (PC1 to PC8, Table 3.4) with eigenvalues larger than 1, which, when added together explained about 82% of the total variability contained in the YdI database. These eight PCs incorporated the 25 original variables but contained high loading factors based on their contributions to variability and correlations with the PC. PC1 had the largest eigenvalue (6.73) and explained around 27% of the variability with its eigenvector that included high positive loadings (>0.25) for S and Al. In addition PC1 included high negative loadings (<−0.25) for pH, C/N, Mg, and B. PC2 had an eigenvalue of 5.23 and explained around 21% of the variability in the 25 variable set for yield index. The eigenvector for PC2 had positive loadings for CEC, SOM, C, N, Ca, and Zn. The eigenvalue for PC3 was 2.16 and explained an additional 8% of the total variability. The eigenvector for PC3 included positive loadings for N_2O, CO_2, and Mn. PC3 also contained negative loadings for WAS and MBN. The eigenvalue for PC4 was 1.58 and accounted for 7% of the variability. PC4 contained positive loadings for CH4, MBN, Na, and Fe. In addition, PC4 contained a negative loading for Bd. PC5 had an eigenvalue of 1.48 and explained 6% of the variability. PC5 included positive loadings for N_2O, CH_4, Bd, MBC, and K. Conversely, PC5 contained negative loadings for WAS, CEC, and Cu. PC6 had an eigenvalue of 1.25 and explained 5% of the variability. The eigenvector for PC6 showed positive loadings for N_2O, CO_2, Na, and B. PC6 also contained a negative loading for Pa. The eigenvalue for PC7 was 1.13 and explained an additional 4% of the variability. The eigenvector for PC7 contained positive loadings for Bd, Na, and Zn. PC7 also contained a negative loading for N_2O. The final PC8 had an eigenvalue of 1.01 and explained 4% of the variability, while its eigenvector showed positive loadings for N_2O, CH_4, WAS, and K. PC8 also had a negative loading for MBC. These eight significant PCs were used as independent variables in our multiple regression analysis.

3.3.5. Multiple Regression Analysis

Following extraction of the uncorrelated PCs from each of the datasets, multiple regression analyses were conducted to model each GHG emission type (N_2O, CO_2, and CH_4), and also to model the yield index. Multiple regression analyses were conducted to determine which variables impact GHG emissions and YdI. Modeling of N_2O emissions using the larger (32) variable dataset resulted in three PCs being retained (Table 3.5). These three PCs explained around 39% of the N_2O variability in the dataset. The PCs retained were PC1, PC3, and PC4. The variables included within each PC are listed in full in Section 3.3.1 above. Modeling of CO_2 emissions using the 32 variable dataset resulted in five PCs being retained (Table 3.5). These five PCs explained around 49% of the CO_2 variability in the dataset.

Table 3.3. Principal component analysis based on 32 observations modeling the yield index with 34 variables, with eigenvalues and cumulative proportion of the dataset variability explained by the eight principal components (PC) extracted with eigenvalues >1. Component correlation scores (eigenvalues) with loadings greater than |0.25| are in bold.

	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8
Eigenvalue	8.75	6.58	3.54	2.62	2.35	1.66	1.38	1.20
Cum. Proportion	0.26	0.45	0.56	0.63	0.70	0.75	0.79	0.83
Soil Variable	Component Correlation Scores							
N_2O	0.20	0.08	0.23	0.18	−0.01	0.07	**−0.26**	0.15
CO_2	0.22	−0.07	0.00	0.21	0.15	0.18	−0.20	0.22
CH_4	0.03	0.05	**0.25**	0.16	−0.07	**0.46**	0.13	−0.12
Sand	0.20	0.01	−0.02	−0.24	0.07	**0.35**	−0.05	0.05
Silt	−0.08	−0.19	−0.24	0.21	**−0.29**	0.03	0.04	0.05
Clay	0.05	0.20	**0.26**	−0.18	**0.29**	−0.10	−0.03	−0.06
Ho	0.02	0.22	−0.22	−0.09	−0.17	−0.04	−0.17	0.04
PWP	−0.11	**0.29**	−0.14	−0.14	−0.05	−0.06	−0.05	−0.02
PAW	0.13	−0.07	0.14	**0.37**	0.08	−0.12	−0.24	0.16
BD	0.05	−0.03	−0.07	−0.07	**−0.26**	0.13	**0.35**	**0.54**
WAS	0.00	0.18	−0.13	**−0.31**	0.00	−0.22	0.10	0.09
pH	**−0.31**	−0.05	0.12	−0.05	−0.08	0.00	0.04	0.10
CEC	**0.28**	0.14	−0.13	0.04	0.03	−0.10	−0.18	−0.15
SOM	0.21	0.21	−0.25	0.06	0.04	0.10	−0.02	0.12
C	0.11	**0.28**	−0.22	0.10	0.02	0.10	−0.08	0.19
N	0.23	0.20	−0.19	0.00	−0.08	0.04	0.03	0.11
C/N	**−0.25**	0.15	−0.04	0.12	0.18	0.12	−0.19	0.07
MBC	−0.13	0.11	−0.10	0.13	−0.15	**0.50**	−0.05	−0.15
MBN	−0.16	0.03	0.05	−0.02	**0.38**	**0.31**	0.31	−0.06
NH_4	0.16	0.16	**0.28**	−0.13	−0.19	0.06	0.14	−0.06
NO_3	0.18	0.13	**0.35**	−0.04	−0.07	0.01	0.00	0.03
TIN	0.19	0.15	**0.34**	−0.08	−0.12	0.03	0.06	−0.01
Pa	−0.01	0.19	−0.05	**0.35**	−0.03	−0.14	0.22	**−0.38**
K	0.21	0.07	0.10	−0.11	−0.21	−0.10	0.24	−0.02
S	**0.26**	−0.20	0.00	0.08	0.06	−0.02	0.03	0.08
Ca	−0.01	**0.33**	0.02	0.04	0.03	−0.07	0.11	0.16
Mg	−0.22	0.23	0.16	0.02	−0.01	−0.10	−0.10	0.12
Na	0.06	−0.14	0.01	0.14	**0.36**	−0.16	0.32	0.34
B	**−0.25**	0.08	0.16	0.11	0.09	−0.04	0.03	**0.28**
Fe	0.24	0.11	−0.09	0.14	**0.25**	−0.05	0.13	−0.16
Mn	0.01	−0.09	0.17	**0.30**	**−0.37**	−0.20	0.01	0.00
Cu	−0.12	**0.29**	0.07	0.21	0.10	−0.14	−0.02	0.01
Zn	−0.01	0.20	−0.11	**0.31**	−0.06	−0.01	**0.42**	−0.06
Al	0.23	−0.21	−0.10	−0.05	0.13	−0.06	0.14	−0.18

The PCs retained were PC1, PC2, PC4, PC6, and PC8. The variables included within each PC are listed in full in Section 3.3.1 above. Modeling of CH_4 emissions using the 32 variable dataset resulted in only one PC being retained (Table 3.5). This single PCs explained only around 11% of the CH_4 variability in the dataset. The PC retained was PC6. The variables included within the PC are listed in full in Section 3.3.1 above. Modeling of YdI emissions using the 34 variable dataset resulted in only one PC being retained (Table 3.5). This single PCs explained around 12% of the YdI variability in the dataset. The PC retained was PC2. The variable included within the PC is listed in full in Section 3.3.3 above. The variables chosen to represent the PC component in the N_2O, CO_2, CH_4, and YdI regression equations (listed below) were based on the largest loading values from the retained PCs:

$$\mathrm{N_2O} = 0.16 + 0.23(-\mathrm{pH}) - 0.20(-\mathrm{NO_3}) + 0.22(\mathrm{PAW}),$$

$$\mathrm{CO_2} = 0.30 + 0.20(-\mathrm{pH}) - 0.09(\mathrm{Ca}) + 0.17(\mathrm{PAW}) + 0.20(\mathrm{MBC}) + 0.27(\mathrm{PAW}),$$

$$\mathrm{CH_4} = 0.02 + 0.30(\mathrm{MBC}),$$

$$\mathrm{YdI} = -0.55 - 0.14(\mathrm{Ca}).$$

Table 3.4. Principal component analysis based on 52 observations modeling the yield index with 25 variables, with eigenvalues and the cumulative proportion of the dataset variability explained by the eight principal components (PC) extracted with eigenvalues >1. Component correlation scores (eigenvalues) with loadings greater than |0.25| are in bold.

	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8
Eigenvalue	6.73	5.23	2.16	1.58	1.48	1.25	1.13	1.01
Cum. Proportion	0.27	0.48	0.56	0.63	0.69	0.74	0.78	0.82
Soil Variable	Component Correlation Scores							
N_2O	0.13	0.15	**0.30**	0.24	**0.26**	**0.29**	**−0.25**	**0.26**
CO_2	0.21	0.10	0.26	0.17	0.01	**0.37**	−0.15	−0.06
CH_4	0.00	−0.04	0.09	**0.41**	**0.48**	−0.19	−0.08	**0.33**
BD	0.08	0.01	−0.04	**−0.26**	**0.31**	0.16	**0.58**	0.11
WAS	0.01	0.15	**−0.27**	−0.11	**−0.28**	−0.19	0.01	**0.59**
pH	**−0.32**	−0.20	0.04	−0.07	0.14	0.01	0.12	0.02
CEC	0.23	**0.28**	0.08	−0.04	**−0.26**	0.01	−0.18	−0.08
SOM	0.12	**0.37**	−0.16	−0.08	0.13	0.12	0.04	−0.09
C	−0.03	**0.38**	−0.18	−0.08	0.17	0.16	0.04	−0.15
N	0.16	**0.35**	−0.11	−0.19	0.10	0.05	0.08	−0.03
C/N	**−0.30**	0.10	−0.12	0.13	0.09	0.12	−0.06	−0.19
MBC	−0.17	0.14	−0.19	0.09	**0.26**	0.04	−0.10	**−0.28**
MBN	−0.13	−0.04	**−0.35**	**0.48**	−0.06	0.09	0.10	0.10
Pa	−0.04	0.19	0.24	0.19	0.04	**−0.51**	0.20	−0.17
K	0.19	0.12	0.11	−0.20	**0.28**	−0.16	0.04	**0.36**
S	**0.32**	−0.11	0.06	0.10	0.04	0.19	0.11	−0.05
Ca	−0.16	**0.32**	0.08	−0.04	−0.17	0.09	0.00	0.13
Mg	**−0.31**	0.15	0.19	−0.08	−0.13	0.13	−0.03	0.18
Na	0.15	−0.10	−0.01	**0.27**	−0.24	**0.32**	**0.52**	0.08
B	−0.31	0.01	0.13	0.01	−0.03	**0.26**	0.14	0.09
Fe	0.24	0.20	−0.05	**0.29**	−0.16	−0.16	0.05	−0.08
Mn	0.05	−0.07	**0.54**	−0.13	−0.07	−0.09	0.16	−0.18
Cu	−0.20	0.24	0.23	0.19	**−0.27**	−0.01	0.10	0.09
Zn	−0.10	**0.27**	0.07	0.19	0.10	−0.23	**0.33**	−0.10
Al	**0.33**	−0.13	−0.15	0.11	−0.07	−0.11	0.04	−0.10

Likewise, using multiple regression analysis modeling of N_2O emissions using the smaller (23) variable dataset resulted in two PCs being retained (Table 3.5). These 2 PCs only explained around 10% of the N_2O variability in the dataset, a drop of nearly 30% in explanatory capability. The PCs retained were PC1 and PC2. The variables included within each PC are listed in full in Section 3.3.2 above. Modeling of CO_2 emissions using the 23 variable dataset resulted in two PCs being retained (Table 3.5). These two PCs explained around 26% of the CO_2 variability in the dataset, a drop of 23% in explanatory capability. The PCs retained were PC1 and PC5. The variables included within each PC are listed in full in Section 3.3.2 above. Modeling of CH_4 emissions using the 23 variable dataset resulted in only one PC being retained (Table 3.5). This single PC explained only around 6% of the CH_4 variability in the dataset. The PC retained was PC6. The variables included within the PC are listed in full in Section 3.3.2 above. Modeling of YdI emissions using the 25 variable dataset resulted in two PCs being retained (Table 3.5). These PCs explained around 9% of the YdI variability in the dataset. The PCs retained were PC6 and PC8. The variables included within the PCs are listed in full in Section 3.3.4 above. The variables chosen to represent the PC component in the N_2O, CO_2, CH_4, and YdI regression equations (listed below) were based on the largest loading values from the retained PCs:

$$\mathrm{N_2O} = 0.02 - 0.10(-\mathrm{Al}) + 0.12(\mathrm{C}),$$
$$\mathrm{CO_2} = 0.02 - 0.18(-\mathrm{Al}) + 0.25(-\mathrm{WAS}),$$
$$\mathrm{CH_4} = -0.00092 + 0.27(\mathrm{Pa}),$$
$$\mathrm{YdI} = -0.08 + 0.23(-\mathrm{Pa}) - 0.22(\mathrm{WAS}).$$

3.4. Discussion

3.4.1. Nitrous Oxide

The results from the multiple regression analysis on the 32 variable dataset reveal that pH, NO_3, and PAW are the variables with the heaviest loadings in the model (Table 3.5). This means that low pH, increased levels of NO_3, and greater levels of PAW are needed to explain N_2O emissions. Wang et al. (2018) concluded that pH was the chief factor in global a meta-analysis using 1104 field measurements. Their results used a similar multivariate approach to discover that N_2O emissions increase significantly with a decrease in soil pH. We observed a similar result; the CCC-T cropping system emitted greater N_2O emissions compared to other systems (7.67 kg-N ha^{-1} $year^{-1}$, Appendix B Table B.4). Furthermore, the CCC-T rotation had the lowest mean pH (5.08, Appendix B Table B.6). Increased levels of NO_3 (similarly NH_4 and TIN contained important loadings in PC3) in the soil provided the necessary substrate for incomplete denitrification, as seen in other N_2O studies (McSwiney and Robertson, 2005; Snyder et al., 2009; Weier et al., 1993). Likewise, large loadings in PC1 (Table 3.1) included N and low C/N, which

Table 3.5. Dependent variables are based on multiple regression analyses of principal components (PC) extracted with eigenvalues >1 and retained in the model (significance level = 0.1500). Dependent variables (nitrous oxide, N_2O; carbon dioxide, CO_2; methane, CH_4; yield index YdI) were modeled using both datasets (PCs are separated by either the 32 or the 52 observation datasets). Variables contained within each PC have component correlation scores (eigenvalues) with loadings greater than |0.25|. Overall adjusted R^2 values represent the amount of variation explained by the regression analysis.

Principal Components Summary Using 32 (for GHG) and 34 (for YdI) Variables							
Dependent Variable	Retained	Estimate	*p*-Value	Variables Contained [1]	Stepwise R^2	Stepwise *p*-Value	Overall Adjusted R^2
N_2O	PC1	0.20	0.00	pH, CEC, N, C/N, S, B, Fe	0.26	0.00	0.39
	PC3	0.20	0.03	Silt, Clay, SOM, C, NH_4, NO_3, TIN	0.36	0.04	
	PC4	0.22	0.04	Sand, PAW, WAS, Pa, Mn, Zn	0.45	0.04	
CO_2	PC1	0.20	0.00	pH, CEC, N, CN, S, B, Fe	0.31	0.00	0.49
	PC2	0.20	0.08	PWP, C, Ca, Mg, Cu	0.52	0.09	
	PC4	0.17	0.05	Sand, PAW, WAS, Pa, Mn, Zn	0.46	0.06	
	PC6	0.27	0.04	YdI, Sand, WAS, MBC, Na	0.57	0.08	
	PC8	0.09	0.08	PAW, BD, C, Pa	0.39	0.06	
CH_4	PC6	0.30	0.04	YdI, Sand, WAS, MBC, Na	0.14	0.04	0.11
YdI	PC2	0.14	0.03	PWP, C, Ca, Cu	0.15	0.03	0.12
Principal Components Summary Using 23 (for GHG) and 25 (for YdI) Variables							
Dependent Variable	Retained	Estimate	*p*-Value	Variables Contained [2]	Stepwise R^2	Stepwise *p*-Value	Overall Adjusted R^2
N_2O	PC1	0.12	0.04	pH, C/N, S, Mg, B, Fe, Al	0.14	0.06	0.10
	PC2	0.10	0.06	CEC, SOM, C, N, Ca, Zn	0.08	0.05	
CO_2	PC1	0.18	0.00	pH, C/N, S, Mg, B, Fe, Al	0.21	0.00	0.26
	PC5	0.25	0.02	YdI, WAS, S, Na, Mn, Zn	0.29	0.02	
CH_4	PC6	0.27	0.04	YdI, CEC, Pa, Ca, Zn	0.08	0.04	0.06
YdI	PC6	0.23	0.05	N_2O, CO_2, Pa, Na, B	0.07	0.06	0.09
	PC8	0.22	0.10	N_2O, CH_4, WAS, MBC, K	0.12	0.10	

[1] Variables are listed in full in Tables 1 and 3; [2] Variables are listed in full in Tables 2 and 4.

mirrors our results from NO_3. PAW is defined as the difference between the water retained at field capacity and the permanent wilting point, so a higher level of PAW means that the soil can hold more water due to having larger pore spaces. Weier et al. (1993) concluded that the percentage of additional NO_3 lost via denitrification increased with increasing water-filled pore spaces and amounts of C substrate. Important loadings from the retained PC3 include SOM, which furthers the need for C substrate for N_2O emissions. Our model explained around 40% of the variation using these three variables.

Comparing the results from the 32 variable dataset, we see a large decrease in the total amount of variation explained, down from 40% in the 32 variable dataset, to 10% in the 23 variable dataset (Table 3.5). The 23 variable dataset contained only variables with equal comparisons; the loss of sand, silt, clay, Ho, PWP, PAW, NH_4, NO_3, and TIN reduced the ability to explain N_2O emissions by 30%. Exclusion of soil water dynamics and soil nitrogen intensity variables led to this loss in ability. The multiple regression analysis on the 23 variable dataset revealed that Al and C are the variables with the heaviest loadings in the model. The combination of these variables means that low levels of Al and increased levels of C are needed to explain N_2O emissions. In terms of understanding the Al dynamics occurring in this model, the means table reveals that the soybean rotation had lower values of Al compared to corn (586.38 mg kg^{-1} compared to 670.78 mg kg^{-1}, respectively; Appendix B Table B.8). This is further verified by the increased pH values (also heavy loading in PC1, Table 3.2) occurring in the soybean rotations (7.13 compared to 5.34, respectively; Appendix B Table B.6). Likewise, the CCC rotations had significantly greater emissions of N_2O compared to SSS (6.18 kg-N ha^{-1} $year^{-1}$ compared to 0.97 kg-N ha^{-1} $year^{-1}$; Appendix B Table B.4) (Behnke et al., 2018b). The effects of low pH are conveyed indirectly in this model, and can also be observed in the recent meta-analysis conducted by Wang et al. (2018). Other studies conducted on similar soils have observed that N_2O emissions occur in greater amounts when given an increased level of C substrate (Weier et al., 1993). In addition, SOM is an important loading in PC2, which has a similar effect to adding C substrate.

3.4.2. Carbon Dioxide

The results from the multiple regression analysis on the 32 variable dataset reveal that pH, Ca, PAW, and MBC are the variables with the heaviest loadings in the model (Table 3.5). Thus, low pH, low Ca, increased PAW, and higher levels of MBC are needed to explain CO_2 emissions. Linn and Doran (1984) discovered that CO_2 production increases as water-filled pore spaces are filled, regardless of the application of N fertilizer. As PAW increases, water is more prevalent in the soil, which can lead to CO_2 evolution through increased microbial activity. During wheat production, Lupwayi et al. (1999) observed that microbial biomass is more dynamic compared to SOM, and changes in management may be reflected more clearly in MBC compared to SOM. The authors also observed that the amount of MBC is directly related to CO_2 evolution; a similar observation was seen by Linn and Doran (1984), albeit with microbial activity and not MBC specifically. Low pH and low Ca levels in the soil negatively affect the levels of MBC, which limits the production of CO_2. Likewise, in environments with low pH levels, Ca is able to leach through the soil (Brady and Weil, 1996). Our model explained around 50% of the variation using these five variables.

Compared with results from the 32 variable dataset, there was a large decrease in the total amount of variation explained, down from 50% in the 32 variable dataset, to 26% in the 23 variable dataset. The 23 variable dataset was reduced by nine variables and decreased the ability to explain CO_2 emissions by 24%. The multiple regression analysis on the 23 variable dataset revealed that Al and WAS are the variables with the heaviest loadings in the model (Table 3.5). The combination of these variables means that high levels of aluminum and lower WAS are needed to explain CO_2 emissions. Al is more available at a lower pH. Similar to the N_2O model, when observing the means table, the soybean rotation had lower values of Al compared to corn (586.38 mg kg^{-1} compared to 670.78 mg kg^{-1}, respectively; Appendix B Table B.8). This was further verified by the increased pH values (also heavy loading in PC1, Table 3.2) occurring in the soybean rotations (7.13 compared to 5.34, respectively; Appendix B Table B.6). Likewise, the CCC rotations had significantly greater emissions of CO_2 compared to SSS (4.43 Mg-N ha^{-1} $year^{-1}$ compared to 2.63 kg-N ha^{-1} $year^{-1}$; Appendix B Table B.4) (Behnke et al., 2018b). Increases in WAS are related to the protection of SOM. The destruction of stable aggregates (WAS) causes decomposition of SOM and greater CO_2 emissions (Paustian et al., 2000). Our model explained around 26% of the variation using only these two variables.

3.4.3. Methane

The results from the multiple regression analysis on the 32 variable dataset reveal that MBC is the variable with the heaviest loading in the model (Table 3.5). This means that a larger MBC concentration leads to increased CH_4 production. Methane produced from agricultural practices has been found to be emitted biologically via methanogenic bacteria under anaerobic soil conditions (Chan and Parkin, 2001; Johnson et al., 2007). Methane has also been found to be consumed in agricultural soils by soil methanotropic bacteria (McLain and Martens, 2006). This phenomenon causes agricultural soils (excluding rice paddies) to be consumers, producers or neutral, depending on the time of season (Chan and Parkin, 2001). It is not surprising that the biological nature of CH_4 production is explained best by MBC. The means for CH_4 show the largest emissions from the CCC rotation compared to the other rotations (0.43 kg-C ha^{-1} $year^{-1}$, CCC; 0.25 kg-C ha^{-1} $year^{-1}$, CS; 0.22 kg-C ha^{-1} $year^{-1}$, CSW; and 0.24 kg-C ha^{-1} $year^{-1}$, SSS) (Appendix B Table B.4); however, MBC is the lowest in CCC compared to the other rotations (54.69 μg g^{-1}, CCC; 67.27 μg g^{-1}, CS; 70.72 μg g^{-1}, CSW; and 77.38 μg g^{-1}, SSS) (Appendix B Table B.6). On similar Mollisols in Ohio, Jacinthe and Lal (2005) observed that increased CH_4 uptake in soils occurs with greater MBC concentrations. Our model explained around 11% of the variation using this one variable.

Compared with the results from the 32 variable dataset, there was a decrease in the total amount of variation explained, down from 11% in the 32 variable dataset, to 6% in the 23 variable dataset. The multiple regression analysis on the 23 variable dataset revealed that Pa was the variable with the heaviest loading in the model (Table 3.5). This means that higher values of Pa are needed to explain CH_4 emissions. Our model explained around 6% of the variation using this one variable.

3.4.4. Yield Index

The results from the multiple regression analysis on the 34 variable dataset reveal that Ca is the variable with the heaviest loading in the model (Table 3.5). This single variable means that lower Ca concentrations lead to an increased YdI. Since the YdI variable is standardized by cash crop to a mean of 0 and a standard deviation of 1, direct comparisons are difficult to interpret. However, looking at the YdI means (Appendix B Table B.4) reveals that larger YdI values occur in the crop rotations (0.27, CS and 0.19, CSW) relative to the monocultures (−0.74, CCC and −0.26, SSS). Using the same yield data, Behnke et al. (2018b) found that crop rotation increased the yields of corn and soybean in the CS rotation compared to either the CCC and SSS monocultures. Since wheat was not grown continuously, a wheat comparison was not possible. As yield levels increase, Ca concentration in the removed grain increases (Heckman et al., 2003). However, Ca levels seem to be weakly correlated with crop rotation, though the crop rotations do have smaller standard errors compared to the CCC and SSS monocultures. However, the CSW rotation did have the largest values (Appendix B Table B.7). Since these soils are naturally high in Ca and were limed every two years, following the guidelines in the Illinois Agronomy Handbook (Nafziger, 2009), levels of Ca are likely not limiting. Our model explained around 12% of the variation using this one variable.

When looking at the results from the 34 variable dataset, we can see a small decrease in the total amount of variation explained—9% in the 25 variable dataset. The multiple regression analysis on the 23 variable dataset reveals that Pa and WAS are the variables with the heaviest loadings in the model (Table 3.5). Thus, low levels of Pa and lower WAS are needed to explain YdI. Similar to Ca in the 34 variable dataset, as yield levels increase, greater amounts of Pa are removed by the grain (Heckman et al., 2003). Therefore, as YdI levels increase less Pa will remain in the soil. The YdIs of the crop rotations (CS and CSW; Appendix B Table B.4) are greater compared to the monocultures (CCC and SSS; Appendix B Table B.4). This can be as attributed to the levels of Pa in the crop rotations (8.59 mg ka^{-1}, CS and 9.87 mg kg^{-1}, CSW; Appendix B Table B.7) being lower compared to those in the monocultures (13.56 mg kg^{-1}, CCC and 17.50 mg kg^{-1}, SSS; Appendix B Table B.7). Trends in WAS are less evident as the crop rotations had similar WAS means (Appendix B Table B.5). The trends in WAS may be more related to the tillage implementation as WAS levels from tilled treatments were lower than their NT counterparts (0.82 g g^{-1}, T and 0.85 g g^{-1}, NT; Appendix B Table B.5). Comparing this to the T and NT YdI levels, an inverse relationship exists (0.22, T and −0.18 NT; Appendix B Table B.4). Behnke et al. (2018b) observed a significant yield increase due to tillage used as a means of managing the high amount of corn residue produced in high organic matter soils. Other studies in the Midwest confirm an increase in yield due to tillage as well (Halvorson et al., 2006; Parkin and Kaspar, 2006). Long-term (5+ years) NT corn systems are routinely subject to reductions in yields (Pittelkow et al., 2015) due to waterlogging and poor establishment, compaction, and nutrient deficiencies (Cid et al., 2014; Halvorson et al., 2006; Rusinamhodzi et al., 2011). Villamil et al. (2015) concluded that in highly productive and highly resilient Illinois systems, tillage does not pose a threat to soil quality.

This multivariate analysis was conducted using data from Illinois on highly productive soils from different cropping systems with the objective of investigating the relationships among GHG emissions, yields, and soil properties. The two datasets including differing numbers of variables highlight the importance of utilizing data with and without missing data points. The dataset with more variables contained missing data, while the dataset containing fewer variables contained paired data with no missing data. Both datasets are important in discovering which variables are important predictors for GHG emissions and the yield index.

3.5. Conclusions

Overall, our analysis showed the complex relationships among GHG emissions, yield and soil properties. Increased N_2O emissions were correlated to low pH conditions (and an increased Al concentration), the presence of soil NO_3 throughout the growing season, an increase in plant available water and an increased C concentration. Lower soil pH was evident in the CCC rotation compared to the other rotations; CCC also had greater N_2O emissions. Greater CO_2 emissions were related to low pH (or high Al concentrations), low levels of Ca, increased PAW, higher levels of MBC, and lower WAS. Methane emissions reveal that higher levels of MBC lead to lower CH_4 emissions due to methane uptake from soil microbes. Lastly, increased levels of YdI were correlated with lower levels of soil Ca and Pa and lower values of WAS. It is important to note that lower levels of WAS were seen in the T treatments compared to the NT treatments. Likewise, the NT YdI was lower than the T YdI. Therefore increases in YdI can be attributed to tillage more than to lower levels of WAS, as is typical in highly productive Midwest cropping systems. The results from this study describe the influences that crop rotation and tillage have on the modeling of GHG emissions and yields. Our results indicate the benefits of utilizing a crop rotation compared to a monoculture. The results include a decrease in N_2O emissions and an increase in yield. This study will add valuable information to the understanding of how interconnected numerous soil properties are to GHG emissions and yield.

CHAPTER 4: COVER CROP ROTATIONS AFFECT GREENHOUSE GAS EMISSIONS AND CROP PRODUCTION IN ILLINOIS, USA

4.1. Introduction

Cover crops (CCs) have a role in lowering greenhouse gas (GHG) emissions and have a climate change alleviation potential akin to switching to no-till (NT); they also have been shown to benefit soil and water quality (Kaye and Quemada, 2017). Agriculture contributes around 9% of the total United States GHG emissions, with carbon dioxide (CO_2) making up the majority (81%), followed by methane (CH_4) (11%), nitrous oxide (N_2O) (6%), and other trace gases (2%) (EPA, 2016). However, compared to CO_2, N_2O and CH_4 are 298 and 25 times as potent, respectively (EPA, 2016). According to the US Environmental Protection Agency (EPA), around 80% of the total US annual N_2O emissions are caused by agricultural soil management, including synthetic fertilizer application and use, tillage practices, and crop rotation systems (EPA, 2016; Venterea et al., 2011). The US Midwest (Illinois, Indiana, Iowa, Michigan, Minnesota, Ohio, and Wisconsin) exemplifies one of the most intensively cultivated areas in the world (Hatfield, 2012). Millar et al. (2010), reported in their most recent literature review on the subject, that fertilized crops take up less than 50% of the N applied, potentially leaving the excess available for loss. In 2017, Illinois seeded more than 4.5 million hectares of corn (*Zea mays* L.) and nearly 4.3 million hectares of soybean [*Glycine max* (L.) Merr.] (USDA-NASS, 2018). As of 2016, 97% of corn planted received an N and 79% received a P fertilizer application with an average rate of 163 and 68 kg ha^{-1} for N and P (as P_2O_5), respectively (USDA-NASS, 2016). Considering the widespread tile drainage in the state, significant fertilizer loss to the environment is routinely observed, leading to environmental issues and human health concerns (Alexander et al., 2007; Nolan and Hitt, 2006).

Due to the excessive amount of N and P entering the Mississippi River Basin, the US EPA set a goal for states within the Midwest to reduce the amount of nutrients entering waterways. The IL Nutrient Loss Reduction Strategy recognizes the implementation of CC's as the most promising in-field strategy to help reduce the N load by 2025 (IL-NLRS, 2015). Cover crops can include legumes, grass, mustards, or mixtures of those species grown to improve soil quality; improvements in soil erosion, structure, and fertility; pest suppression; and decreased nutrient leaching from the root zone (Kaspar et al., 2012; Sainju et al., 2002; Snapp, 2005; Villamil et al., 2008; Villamil et al., 2006). In Illinois, Villamil et al. (2008; 2006) found that after three corn-soybean rotation cycles with and without CC's, a mixture of cereal rye (*Secale cereale* L.) and hairy vetch (*Vicia villosa* Roth) drilled into crop stubble each year increased soil organic carbon, nutrient retention, and water aggregate stability compared to winter fallows.

Despite the need for proactive efforts in the US Midwest region to reduce N and P entering waterways, low rates of voluntary adoption of CC's continues (Dozier et al., 2017; Plastina et al., 2018; Roth et al., 2017). Several CC species have been shown to lower N-NO_3 levels in the soil by taking up the N and sequestering it into their biomass, therefore, reducing the N that can reach waterways (Drury et al., 2014b; Kladivko et al., 2014; Malone et al., 2014) or be lost to the environment through gaseous pathways (Baggs et al., 2000; Basche et al., 2016a; Mitchell et al., 2013; Snyder et al., 2009). In a meta-analysis conducted by Tonitto et al. (2006) comparing CC's to bare fallow, N-NO_3 leaching was reduced on average by 70% and 40% utilizing grass and legume CC species, respectively. Similarly, Dozier et al. (2017) found that in Illinois following a corn-soybean, a 42% reduction in available soil N can be achieved using cereal rye following corn and hairy vetch following soybean cash crops; cereal rye can also help mitigate N_2O production by reducing the amount of N-NO_3 in a system (Dabney et al., 2001; Millar et al., 2010). Cover crops can also mitigate N_2O production taking up soil water in their living plant tissue because the decrease in soil water would not favor conditions of denitrification through which N_2O can be produced (Basche et al., 2016a; Basche et al., 2014; Davidson et al., 2000). Following CC suppression, the decomposition of CC residues in the presence of oxygen would allow for mineralization or immobilization of the residue N (Aulakh et al., 1992; Basche et al., 2014).

Another mitigation technique found to reduce N_2O emissions is utilization of crop rotation (Snyder et al., 2009; Zhao et al., 2016); in Illinois, N_2O emissions were reduced by 35% from a corn-soybean rotation compared to continuous corn, with an added yield increase of 20% (Behnke et al 2018). Other Midwestern studies have concluded that rotated corn exhibits greater yield stability compared to continuous corn due to moisture or temperature stresses (Al-Kaisi et al., 2015; Gentry et al., 2013; Wilhelm and Wortmann, 2004) and significant yield gains are routinely witnessed (Daigh et al., 2018; Gentry et al., 2013). Increased N_2O emissions from continuous corn compared to rotated corn have been linked to increased fertilizer use associated with continuous corn (Adviento-Borbe et al., 2007; Eichner, 1990; Halvorson et al., 2008; Hoben et al., 2011; McSwiney and Robertson, 2005; Smith et al., 2011). Numerous studies have documented that increasing the N fertilization rate will increase N_2O emissions (Bouwman et al., 2002; Eichner, 1990). Fertilizer N stimulates N_2O production by providing a substrate for microbial N conversion through nitrification and denitrification (Norton, 2008; Venterea et al., 2005). Nitrification occurs when ammonium ($N\text{-}NH_4$) is either added to the soil in the form of fertilizers, during biological N fixation, or as mineralized soil organic matter (Paustian et al., 2016). Nitrification is a microbial process where $N\text{-}NH_4$ is converted to nitrite and eventually to $N\text{-}NO_3$; during this process, small quantities can be lost as N_2O (Snyder et al., 2009). Additionally, in environments of low soil oxygen, denitrifying microbes use $N\text{-}NO_3$ as a terminal electron acceptor and N_2O emissions can occur as N_2O is an intermediate step in the full denitrification process to N_2 gas (Aulakh et al., 1991; Paustian et al., 2016; Robertson et al., 2007).

Historically, tillage is an important tool used to enhance crop production through the incorporation of crop residues into the soil, leading to increased aeration and temperature, expediting the breakdown of organic matter and nutrient release. In the highly fertile soils in northwestern Illinois, chisel tillage was found to increase yields compared to NT (Behnke et al., 2018b); however, Daigh et al. (2018) found that there were no differences between chisel tillage and NT throughout much of the Midwest. Likewise, the inclusion of CCs did not affect yields in corn (Miguez and Bollero, 2005) or soybeans (Ruffo et al., 2004). In NT systems, however, the accumulated residues following CC suppression may exacerbate conditions of high soil moisture common in the spring, which can lead to N_2O production.

Management practices of crop rotation, tillage, and CC implementation affect the soil environment which leads to GHG production. Relatively few CC studies have been conducted in Illinois and none contain GHG measurements. In a meta-analysis conducted by Basche et al. (2014) comparing

N_2O emissions from CCs, the type of CC was shown to have an effect on N_2O emissions; legume species were found to increase N_2O emissions, while non-legume species had little to no effect on N_2O emissions. This meta-analysis covered much of the available data at the time (2014); however, only 26 studies were included in their analysis. With mixed results from CC studies, more work is needed to understand their effects on GHG emissions, especially in Illinois.

First, we hypothesized that CC growth, regardless of species, will reduce N_2O emissions compared to a fallow control by scavenging residual soil N that could be used as a substrate in denitrification. Second, we hypothesized that chisel tillage will not increase N_2O and CH_4 emissions compared to NT due to enhanced soil aeration; conversely, chisel tillage will increase CO_2 emissions due to enhanced residue breakdown and subsequent soil respiration. Hence the objective of this study was to evaluate the effects of five different CC rotations and tillage practices on GHG emissions, soil N, and crop yields.

4.2. Materials and Methods

4.2.1. Site Characterization and Management

The study was established in the fall of 2012 at the University of Illinois, Crop Sciences Research and Education Center in Savoy, IL (40°05’73” N, –88°22’73” W). The experimental plots were located within the Drummer-Flanagan-Catlin soil catena (Soil-Survey-Staff, 2018) with 70% of the plot area containing Drummer silty clay loam (fine-silty, mixed, superactive, mesic, Typic Endoaquoll), 20% containing Flanagan silt loam (fine, smectitic, mesic, Aquic Argiudoll), and 10% containing Catlin silt loam (fine-silty, mixed, superactive, mesic, Oxyaquic Argiudoll). Two adjacent fields were initiated into a corn-soybean rotation and rotated annually; experimental plots were set up inside each crop rotation. Corn and soybean plots were planted in May or early June depending on field conditions (Table 4.1). Corn plots received pre-plant incorporated urea ammonium nitrate (UAN) at a rate of 190 kg N ha^{-1}. Following glyphosate [N-(phosphonomethyl)glycine] burndown (1.12 kg a.i. ha^{-1}) to suppress CC growth, weed biomass was negligible in all plots. Tillage (T) was conducted with a chisel plot 20 to 25 cm deep in the spring following CC suppression and before planting. No-till plots had zero tillage done. For a full description of the site see Dozier et al. (2017).

Cover crops were broadcast-seeded by hand into the standing cash crop in early to mid-September (Table 4.1). Seeding rates and suppression dates were selected using the online decision tool developed by the Midwest Cover Crop Council (MCCC) [online at: http://mccc.msu.edu/covercroptool/covercroptool.php]. Thus, 5.6 kg ha^{-1} for rape (*Brassica napus* L.); 9 kg ha^{-1} for radish (*Raphanus sativus* L.); 16.8 kg ha^{-1} for annual ryegrass (*Lolium multiflorum* Lam); 67.2 kg ha^{-1} for spring oat (*Avena sativa* L.); 100 kg ha^{-1} for cereal rye ; 22.4 kg/ha for each red clover (*Trifolium pratense* L.); and hairy vetch . However, some of the CC species were selected specifically to be seeded into corn or soybean; the CC species selection process included no legume preceding the soybean crop and no cereal rye preceding the corn crop. Red clover was included as soybean red clover – corn spring oat rotation, where red clover was seeded into standing the soybean crop and spring oat was seeded into the standing corn crop. Likewise, hairy vetch was seeded into the standing soybean crop and cereal rye was seeded into the standing corn crop. Thus, red clover and hairy vetch were not directly sampled in this study as all sampling was conducted following the corn phase of the corn soybean rotations. However, the interactions due to growing a cover crop rotation cannot be ignored. Therefore, the CC rotations included were as follows: (1) CrpSrp, rape following both corn and soybean; (2) CcrShv, cereal rye following corn, hairy vetch following soybean; (3) CT, fallow control; (4) CrdSrd, radish following both corn and soybean; (5) CarSar, annual ryegrass following both corn and soybean; and (6) CsoScl, spring oats following corn, clover following soybean. Fall stand counts of CCs (plants m^{-2}) were taken in early to mid-November (Table 4.1) in 2014, 2015, and 2016 using three random tosses of a 0.25 m^2 quadrat to estimate the number of CCs growing in each plot prior to winterkill. Spring CC biomass samples were collected following the same 0.25 m^2 quadrat tosses in late April to early May (Table 4.1). The CC biomass (g m^{-2}) that survived the winter was cut at ground level and oven-dried at 60˚C and weighed; CC biomass results are expressed as Mg ha^{-1}. Corn yields (Mg ha^{-1}) were taken using an Almaco (Nevada, IA) plot combine and adjusted to 15% moisture.

Table 4.1. Field event dates from Savoy, IL throughout the duration of the study. Greenhouse gas (GHG) measurements began in the previous year following corn harvest.

Field Event Type	2012	2013	2014	2015	2016	2017
Broadcast seeding date of cover crop (CC)	10/1/2012	9/16/2013	9/17/2014	9/17/2015	9/7/2016	N/A
CC stand count	N/A	N/A	11/20/2014	11/3/2015	11/11/2016	N/A
Fall soil sampling	11/16/2012	12/12/2013	12/15/2014	11/4/2015	11/16/2016	N/A
Biomass sampling	N/A	5/6/2013	4/25/2014	4/27/2015	4/25/2016	4/11/2017
Spring soil sampling	N/A	6/21/2013	5/5/2014	4/30/2015	4/29/2016	4/21/2017
CC suppression	N/A	5/7/2013	5/20/2014	4/29/2015	5/19/2016	4/12/2017
Spring tillage of T plots[1]	N/A	6/5/2013	5/20/2014	5/21/2015	5/24/2016	5/17/2017
Planting date of corn[2]	4/12/2012	6/6/2013	5/21/2014	5/22/2015	5/25/2016	5/18/2017
Harvest of corn	N/A	10/29/2013	11/3/2014	10/9/2015	10/28/2016	10/16/2017
GHG sampling dates	N/A	N/A	12/4/2013 to 5/1/2014	12/17/2014 to 5/1/2015	12/10/2014 to 5/2/2016	2/17/2014 to 4/21/2017
Number of GHG sampling events	N/A	N/A	5	7	5	4

[1] Tillage was conducted with a chisel plow 20-25 cm deep in plots designated as tilled; no-till received zero tillage.

[2] Pre-plant N fertilizer was applied at a rate of 190 kg N ha^{-1}.

N/A, not applicable.

4.2.2. Gas Sampling Procedures

Soil GHG emissions were taken periodically during the period following corn harvest and CC suppression beginning in the fall of 2013 and ending in the spring of 2017. The number of sampling events by year is included in Table 1. Greenhouse gas sampling followed the GRACEnet chamber-based trace gas flux measurement protocol (Parkin and Venterea, 2010). Beginning in December 2013, 0.031m^2 polyvinyl chloride (PVC) white chamber bases were installed in 48 plots following harvest of the corn cash crop. The chamber bases were left in the field and were removed before subsequent cash crop planting. Soil GHG measurements were taken and analyzed following the procedure explained in Behnke et al. (2018b).

4.2.3. Soil Sampling and Analysis

Two soil cores (0 to 10 cm depth) were collected from each plot and each sampling event during gas sampling, composited, and then analyzed for available N concentrations in N-NH_4 and N-NO_3 . Concentrations of N-NH_4 and N-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, USA) in years 2013-2015 and a SmartChem 200 (Westco Scientific Instruments, Inc., Danbury, CN, USA) in years 2015-2017. The trapezoidal integration protocol described in Venterea et al. (2011) was used to calculate intensity measurements for soil N-NH_4 (mg-N kg^{-1}day^{-1}); soil N-NO_3 (mg-N kg^{-1}day^{-1}); N_2O (kg-N ha^{-1} year^{-1}); CO_2 (kg-C ha^{-1} year^{-1}); and CH_4 (kg-C ha^{-1} year^{-1}). The dates used for intensity calculations ranged from the beginning of December to the beginning of May (Table 1). Soil moisture content (%), determined gravimetrically, (Carter, 1993) was taken at each GHG sampling event to correct inorganic N analyses.

4.2.4. Experimental Design and Data Analysis

The experiment aimed to test the effect of tillage and CC rotations on GHG emissions, soil available N, and crop yields following five years of management. The experimental design was a split-block arrangement of tillage (whole plots, NT and T) and CC rotation treatments (subplots) in a RCBD with four replications. Side by side fields were used each year to have each phase of the corn soybean rotations present each year. Tillage plots were split into subplot treatments of CCs, 3m by 12.5 m and each comprising a cash crop–CC rotation that was maintained across years. The field used in GHG sampling and yields alternated each year, following the corn phase of the corn-soybean rotations. The total number of observations included in the dataset from 2013 to 2017 is included in Appendix C (Table C.1).

Linear mixed models were performed using the GLIMMIX procedure of SAS software version 9.4 (SAS Institute, Cary, NC). Rotations with CCs, tillage, and years were analyzed as fixed factors, while blocks were considered random terms. Year was chosen to be analyzed as a fixed factor due to contrasting weather environments between the first two years and the last two years. Model residuals were not normally distributed, thus GHG emissions, soil available N, 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, 2012). Least square means were separated using the lines option of LSMEANS and adjusted using Bonferroni adjustment using an alpha=0.1; Fisher's least significant differences (LSD) are included for comparisons within treatments. Only descriptive statistics of means and standard errors are reported for CC biomass and stand counts due to non-estimable ls means among years, caused by missing data in years where CCs did not grow. It is important to note that not all CC species were selected to overwinter, as producers may favor those that do not increase workload in the spring, so spring biomass was not expected for rotations with either rape or radish. Simple linear regressions between variables were conducted using POC REG in SAS 9.4. An analysis of variance table is included to summarize probabilities associated to main effects and interactions for the experiment (Table 4.2).

4.3. Results

4.3.1. Weather and Cover Crop Establishment

Temperatures in November of 2013 and 2014 were below the historic average recorded minimum temperatures of -3.7˚C on 25 October 2013 and -4.4˚C on 2 November 2014 (Fig. 4.1) (ISWS, 2018). Precipitation values for November 2013 to 2016 were 36, 66, 117, and 87 mm, respectively; the historical average is 84 mm for November, so two years were below the average and two were at or above the average. Mean temperatures in November from 2013 to 2016 were 3.6, 1.7, 7.8, and 7.9 ˚C, respectively; the historic average is nearly 6 ˚C, hence again, the first two years were below the average and the last two years were above the average temperature for the month of November. Mean temperatures in January and February of 2014 were -6.9 and -6.7 ˚C, respectively and March was 1.4 ˚C. Likewise, temperatures in January and February of 2015 were on average -3.7 and -6.7 ˚C, respectively and March was 3.4 ˚C. The historical means for January, February, and March are -2.8, -0.4, and 5.2 ˚C, respectively. March precipitation for 2013-2015 was below average at 40.3 mm, compared to an average March of 77.5 mm.

Fall CC stand counts and spring CC biomass experienced no observable CC growth, so our statistical analyses are limited to presentation of treatment means and standard errors and were not included in the analysis of variance table (Table 4.2). The following statements regarding CC stand counts and spring biomass are not intended to reflect statistical significance since linear models could not be fit to these variables. Stand count for CC species was negligible for fall of 2013 and was not included in Table 4.3. Stand counts in fall 2014 averaged nearly 75 plants m^{-2} for tillage and 70 plants m^{-2} for NT. Fall CC stand counts in 2015 averaged 253 and 272 plants m^{-2} for till and NT respectively. Fall 2016 stand counts were 54 and 45 plants m^{-2} for till and NT, respectively. Averaged across years (2014 to 2016), CarSar averaged nearly 220 plants m^{-2}, followed by CcrShv at 155 plants m^{-2}, then CsoScl at 138 plants m^{-2}, then CrdSrd 65 plants m^{-2}, and finally CrpSrp at 50 plants m^{-2}. Stand counts were greatest for all CC species in the fall of 2015 compared to 2014 and 2016.

Spring CC biomass in 2014 was only observed in the CcrShv plots at 0.46 Mg ha^{-1} (Table 4.4). Spring CC biomass in 2015 was lower for CcrShv at 0.17 Mg ha^{-1}, but CarSar and CrpSrp also experienced some biomass accumulation at 0.24 and 0.10 Mg ha^{-1}, respectively. Spring CC biomass in 2016 was the greatest at 2.5, 2.48, and 1.74 Mg ha^{-1} for CcrShv, CarSar, and CrpSrp, respectively. Spring CC biomass in 2017 only saw CcrShv and CarSar biomass growth at 1.86 and 1.76 Mg ha^{-1}, respectively. Tillage increased CC biomass in years 2014, 2015, and 2017 (0.49 vs 0.43; 0.26 vs 0.18; and 1.89 vs 1.73 Mg ha^{-1}, respectively), while 2016 observed an advantage of NT compared to tillage (2.67 vs. 2.03 Mg ha^{-1}). Fall stand counts and spring CC biomass were positively correlated ($p < 0.0001$; $r^2 = 0.27$). There was no observable spring CC biomass for the CrdSrd or CsoScl CC rotations in any year.

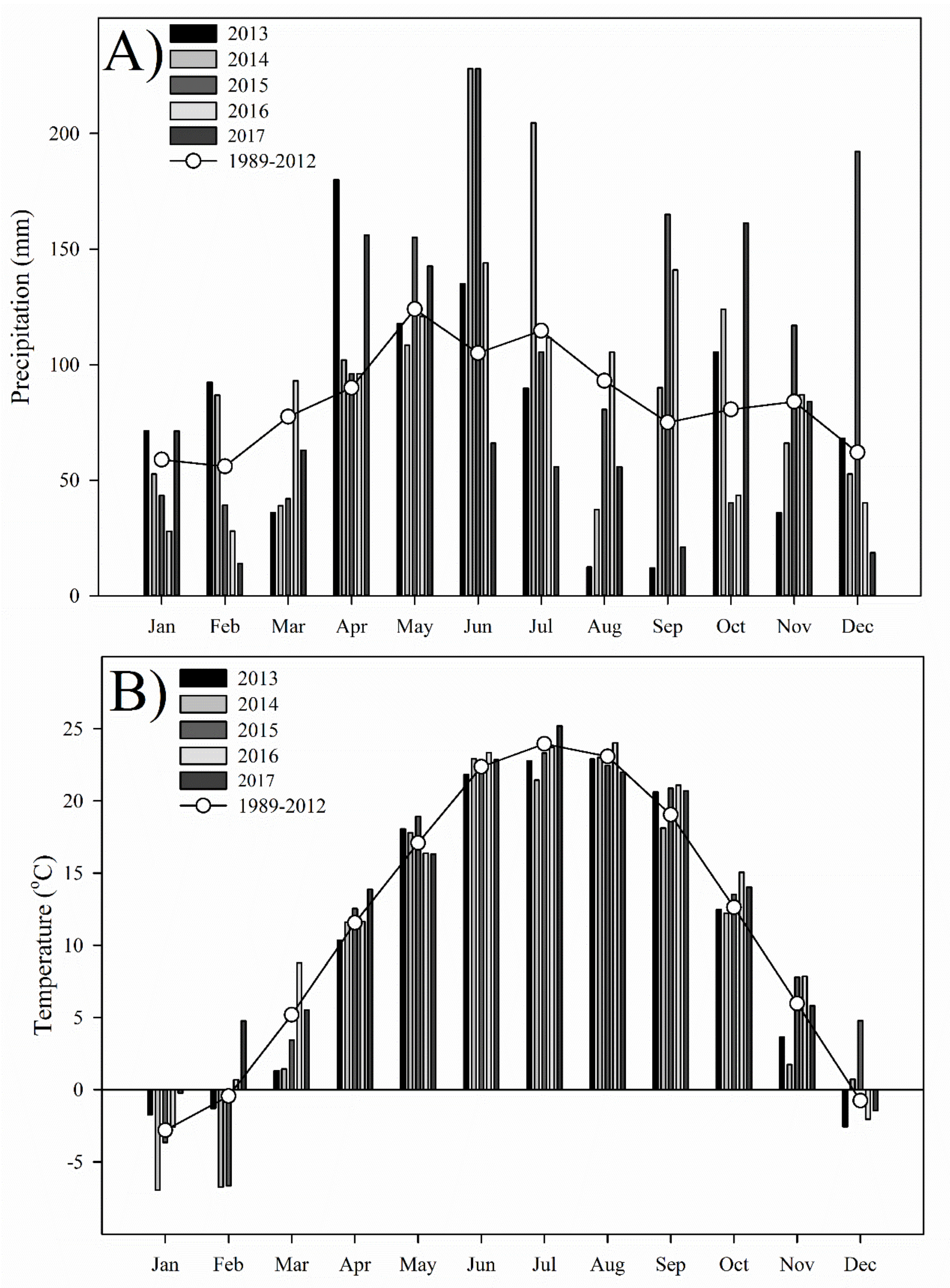

Figure 4.1. (A) Precipitation (mm) and (B) temperature (˚C) from 2013 to 2017 during the study along with the respective historical averages for the 1989 to 2012 period. Source: Illinois State Water Survey (2018).

Table 4.2. Analysis of variance results to assess the effect of year, tillage, cc rotation, and their interactions for each variable from Urbana, IL.

Factors	N_2O		CO_2		CH_4		$N\text{-}NO_3$		$N\text{-}NH_4$		Corn Yield	
	DF	P-Value	DF	P-Value	DF	P-Value	DF	P-Value	DF	P-Value	DF	P-Value
Year	3	*<.0001*	3	*<.0001*	3	*<.0001*	3	<.0001	3	*<.0001*	4	*<.0001*
Tillage	1	0.424	1	0.832	1	0.25	1	0.115	1	0.780	1	*0.028*
Year*Tillage	3	0.424	3	0.321	3	0.547	3	*0.007*	3	0.912	4	*0.082*
CC	5	0.626	5	0.413	5	0.634	5	0.422	5	0.725	5	*0.104*
Year*CC	15	0.314	15	0.561	15	0.216	15	0.464	15	0.413	20	0.753
Tillage*CC	5	0.200	5	0.527	5	0.455	5	0.853	5	0.520	5	0.868
Year*Tillage*CC	15	0.901	15	0.952	15	0.682	15	0.988	15	0.936	20	0.538

Table 4.3. Means and standard errors associated with cover crop stand counts (plants m-2) for each species and tillage option taken in the fall of 2014 to 2016. Fall 2013 counts were negligible and they are not included in this table.

Cover crop[1]	Tillage[2]	Fall 2014		Fall 2015		Fall 2016	
		Mean	SEM[3]	Mean	SEM	Mean	SEM
CrpSrp		44.83	10.28	98.50	8.89	5.71	0.48
CcrShv		39.33	4.81	371.67	33.13	54.17	7.90
CT		.[4]	.	.	.	.	.
CrdSrd		62.67	5.59	88.83	6.91	44.17	6.18
CarSar		176.17	15.04	366.67	42.97	112.33	17.59
CsoScl		7.33	1.15	388.17	53.62	17.11	9.95
	T	74.89	16.27	253.27	36.13	54.22	11.74
	NT	70.30	13.90	272.27	39.67	44.84	10.06

[1] CrpSrp, rape following both corn and soybean; CcrShv, cereal rye following corn, hairy vetch following soybean; CT, fallow control; CrdSrd, radish following both corn and soybean; CarSar, annual ryegrass following both corn and soybean; CsoScl, spring oats following corn, clover following soybean.

[2] T, chisel till; NT, no-till.

[3] SEM, standard error of the mean values.

[4] no observable biomass.

Table 4.4. Mean values of cover crop biomass dry weight (Mg ha^{-1}) determined each year, for each cover crop rotation and each tillage option (NT and T).

Cover crop[1]	Tillage[2]	Spring 2014		Spring 2015		Spring 2016		Spring 2017	
		Mean	SEM[3]	Mean	SEM	Mean	SEM	Mean	SEM
CrpSrp		.[4]	.	0.10	.[5]	1.74	0.18	.	.
CcrShv		0.46	0.06	0.17	0.08	2.5	0.27	1.86	0.16
CT		.	.	.	.	.	.	.	.
CrdSrd		.	.	.	.	.	.	.	.
CarSar		.	.	0.27	0.04	2.48	0.33	1.76	0.08
CsoScl		.	.	.	.	.	.	.	.
	T	0.49	0.06	0.26	0.06	2.03	0.12	1.89	0.14
	NT	0.43	0.04	0.18	0.05	2.67	0.31	1.73	0.11

[1] CrpSrp, rape following both corn and soybean; CcrShv, cereal rye following corn, hairy vetch following soybean; CT, fallow control; CrdSrd, radish following both corn and soybean; CarSar, annual ryegrass following both corn and soybean; CsoScl, spring oats following corn, clover following soybean.

[2] T, chisel till; NT, no-till.

[3] SEM, standard error of the mean values.

[4] no observable biomass.

[5] only 1 observation so SEM was not possible.

4.3.2. Greenhouse Gas Emissions

All GHG emissions (N_2O, CO_2, and CH_4) included in this study experienced a significant main effect due to year (Table 4.2). Back transformed mean N_2O emissions from 2014 to 2017 ranged from 0.28 to 1.68 kg-N ha^{-1} and observed a significant ($\alpha = 0.1$) main effect of year ($p \leq 0.0001$) (Table 4.5). Emissions of N_2O for the first two years (2014 and 2015) were around 5 times more that emissions measured during the last two years of the study (2016 and 2017). No effect due to tillage, CC species, or their interaction effect was detected. Spring CC biomass and N_2O emissions were negatively correlated ($p < 0.0001$; $r^2 = 0.31$).

Similar to N_2O, back transformed mean CO_2 emissions from 2014 to 2017 identified a significant main effect of year ($p < 0.0001$) (Table 4.5). Mean CO_2 emissions ranged from 127.10 to 1160.26 kg-C ha^{-1} (Table 4.5). The lowest CO_2 emission years were 2015 and 2017 and were 2.5 times and 8 times lower compared to 2016 and 2014, respectively. Like N_2O, no effect or interaction due to tillage or CC species was detected. The last GHG measured was CH_4, which also experienced a significant main effects of year ($p \leq 0.0001$) (Table 4.5). Back transformed mean CH_4 emissions ranged from 0.47 to 2.28 kg-C ha^{-1} with 2015 being significantly lower compared to the other years by 4 times. Similarly, CH_4 experienced no effect or interaction caused by tillage or CC species. Neither CO_2, nor CH_4 emissions correlated to spring CC biomass ($p = 0.4014$, $r^2 = -0.005$; and $p = 0.1766$, $r^2 = 0.02$, respectively).

4.3.3. Soil Inorganic Nitrogen

Soil N-NO_3 experienced a significant year*tillage interaction and soil N-NH_4 experienced a significant main effect of year (Table 2). Back transformed mean N-NO_3 during 2014 to 2017 ranged from 0.08 to 1.19 g-N kg^{-1} day^{-1} and observed a significant interaction between year and tillage ($p = 0.0065$) (Table 4.5). 2014 observed the greatest soil N-NO_3 for both the T and NT treatments at 1.16 and 1.19 g-N kg^{-1} day^{-1}. Each year the N-NO_3 decreased significantly, except for the 2015 T interaction as it was not different from 2014 (Table 4.5). Spring CC biomass and N-NO_3 were negatively correlated ($p < 0.0001$, $r^2 = 0.24$). Conversely, N_2O emissions were positively correlated to N-NO_3 ($p < 0.001$, $r^2 = 0.31$). Mean N-NH_4 during 2014 to 2017 ranged from 0.38 to 7.90 g-N kg^{-1} day^{-1} and observed a significant main effect of year ($p \leq 0.0001$) (Table 4.5). Each year was significantly different with 2016 comprising the largest N-NH_4.

4.3.4. Corn Yields

Corn yields experienced a marginally significant year*tillage interaction ($p<0.08$) as well as a marginally significant main effect of the CC species ($p < 0.10$) (Table 4.2). Back transformed mean corn yield during 2013 to 2017 ranged from 3.60 to 14.05 Mg ha^{-1} (Table 4.5). The greatest yield occurred in 2014 with 13.82 and 14.28 Mg ha^{-1} occurring from the T and NT treatments, respectively. Overall, tillage increased yields by 0.64 Mg ha^{-1}. The marginal effect of CC species was due to CarSar lowering yields by approximately 1.0 Mg ha^{-1} compared to the other CC species and the fallow control (Table 4.5). Spring CC biomass and corn yield were negatively correlated ($p < 0.0001$, $r^2 = 0.28$).

Table 4.5. Least square means and back-transformed mean values (within parentheses) of GHG emissions, soil available N intensity, and corn yield by year, tillage practice, and cover crop species during 2013 - 2017 from Urbana, IL. Within a column and below the effect or interaction, Fisher's least square difference (LSD) values are included; significance is set at α = 0.10.

Year[1]	Tillage[2]	Cover Crop Rotation[3]	N_2O (kg N ha^{-1})	CO_2 (kg C ha^{-1})	CH_4 (kg C ha^{-1})	NO_3 (g N kg^{-1} day^{-1})	NH_4 (g N kg^{-1} day^{-1})	Corn Yield (Mg ha^{-1})
2013			.[4]	.	.	.	.	2.24 (9.38)
2014			0.52 (1.68)	7.06 (1160.26)	0.50 (1.64)	0.16 (1.17)	-0.96 (0.38)	2.64 (14.05)
2015			0.47 (1.60)	4.85 (127.10)	-0.76 (0.47)	-0.28 (0.76)	-0.20 (0.82)	2.17 (8.75)
2016			-1.02 (0.36)	5.93 (377.43)	0.82 (2.28)	-1.04 (0.35)	2.07 (7.90)	1.32 (3.74)
2017			-1.28 (0.28)	5.13 (169.76)	0.63 (1.88)	-2.44 (0.09)	0.53 (1.69)	2.33 (10.27)
			LSD = 0.29	LSD = 0.43	LSD = 0.46	LSD = 0.18	LSD = 0.17	LSD = 0.06
‡NT			-0.37 (0.69)	5.76 (318.17)	0.39 (1.47)	-0.81 (0.44)	0.34 (1.41)	2.10 (8.93)
T			-0.29 (0.75)	5.72 (305.48)	0.21 (1.23)	-0.99 (0.37)	0.37 (1.45)	2.18 (9.57)
			LSD = 0.20	LSD = 0.36	LSD = 0.31	LSD = 0.19	LSD = 0.22	LSD = 0.05
2013	NT		.	.	.	.	.	2.18 (8.80)
2013	T		.	.	.	.	.	2.30 (10.00)
2014	NT		0.48 (1.61)	7.22 (1370.87)	0.70 (2.02)	0.18 (1.19)	-1.01 (0.36)	2.66 (14.28)
2014	T		0.56 (1.75)	6.89 (981.91)	0.29 (1.33)	0.15 (1.16)	-0.90 (0.40)	2.63 (13.82)
2015	NT		0.49 (1.62)	4.87 (129.72)	-0.71 (0.49)	-0.33 (0.72)	-0.21 (0.81)	2.11 (8.25)
2015	T		0.46 (1.58)	4.82 (124.54)	-0.81 (0.45)	-0.23 (0.79)	-0.19 (0.83)	2.23 (9.29)
2016	NT		-0.98 (0.37)	5.72 (305.61)	0.75 (2.12)	-0.78 (0.46)	2.06 (7.83)	1.28 (3.60)
2016	T		-1.07 (0.34)	6.41 (466.15)	0.90 (2.45)	-1.31 (0.27)	2.07 (7.96)	1.36 (3.88)
2017	NT		-1.46 (0.23)	5.24 (188.59)	0.80 (2.23)	-2.32 (0.10)	0.53 (1.70)	2.27 (9.73)
2017	T		-1.10 (0.33)	5.03 (152.80)	0.46 (1.59)	-2.56 (0.08)	0.52 (1.68)	2.38 (10.84)
			LSD = 0.41	LSD = 0.63	LSD = 0.66	LSD = 0.30	LSD = 0.31	LSD = 0.10
		CrpSrp	-0.19 (0.83)	5.57 (262.91)	0.25 (1.30)	-0.82 (0.44)	0.41 (1.50)	2.18 (8.84)
		CcrShv	-0.38 (0.69)	6.01 (408.50)	0.23 (1.24)	-1.04 (0.35)	0.36 (1.43)	2.15 (8.60)
		CT	-0.46 (0.63)	5.66 (287.06)	0.16 (1.23)	-0.91 (0.40)	0.29 (1.34)	2.16 (8.70)
		CrdSrd	-0.47 (0.63)	5.42 (226.65)	0.55 (1.71)	-0.93 (0.40)	0.44 (1.55)	2.18 (8.82)
		CarSar	-0.28 (0.75)	6.05 (423.60)	0.11 (1.13)	-0.91 (0.40)	0.31 (1.36)	2.03 (7.63)
		CsoScl	-0.20 (0.82)	5.74 (310.35)	0.49 (1.72)	-0.80 (0.45)	0.34 (1.41)	2.14 (8.46)
			LSD = 0.41	LSD = 0.68	LSD = 0.61	LSD = 0.24	LSD = 0.21	LSD = 0.11[5]

[1] 2013, fall 2012 - spring 2013; 2014, fall 2013 - spring 2014; 2015, fall 2014 - spring 2015; 2016, fall 2015 - spring 2016; 2017, fall 2016 - spring 2017.

[2] NT, no-till; T, chisel till.

[3] CrpSrp, rape following both corn and soybean; CcrShv, cereal rye following corn, hairy vetch following soybean; CT, fallow control; CrdSrd, radish following both corn and soybean; CarSar, annual ryegrass following both corn and soybean; CsoScl, spring oats following corn, clover following soybean.

[4] no data taken.

[5] marginally significant.

4.4. Discussion

4.4.1. Cover Crop Growth

This study is the lone experiment investigating the effects of tillage and CC rotations on GHG emissions and crop yields in the state of Illinois to date; likewise, this is one of few of its kind in the Midwest region. Establishment of CC species in the fall of 2013 was poor and stand counts were negligible for all species and were not reported; lower than average temperatures and precipitation (Fig. 4.1) likely caused the lack of CC stand in the fall of 2013. A similar weather pattern occurred in fall 2014 resulting in a low CC stand count. Due to the low establishment of CC species in the fall, subsequent spring biomass was negatively affected. Temperatures in January, February, and March of 2014 were abnormally cold and the only CC species to produce spring biomass was CcrShv (Table 4.4). In a review of other studies in the Midwest, Appelgate et al. (2017) found that rye species accounted for more than 79% of the spring biomass accumulation due to its ability to survive most winters in this region. The CrdSrd rotation was not expected to over-winter as is common for that species. Similar to 2014, cold temperatures in January, February, and March of 2015 impeded spring biomass growth and was very low; however, CarSar and CrpSrp did survive the winter as did CcrShv again. Due to a lack of cold tolerance, Appelgate et al. (2017) found that rape, oat, and radish have limited potential as CC species in the Midwest due to high rates of winterkill (Appelgate et al., 2017). In addition, at the same site, Dozier et al. (2017) concluded that the seeding method coupled with poor fall growing conditions was likely the reasoning for the poor fall CC establishment.

Contrary to the previous two years, warmer than average temperatures in the fall of 2015 and timely November precipitation events created conditions for successful fall CC stands. As a result, spring 2016 biomass was the largest recorded in this study with CcrShv, CarSar, and CrpSrp all successfully overwintering and producing 2-3 Mg ha^{-1} in biomass for each CC species. Several studies in the Midwest have observed CC biomass in excess of 2 Mg ha^{-1} (Appelgate et al., 2017; Kaspar and Bakker, 2015; Kaspar et al., 2012). Similarly, in the fall of 2016, warmer November temperatures allowed for successful CC establishment; coupled with warmer than average February and March temperatures, spring biomass near 2 Mg ha^{-1} was observed for CcrShv and CarSar. A lack of consistent fall CC growth in our study indicates that simulated aerial seeding may be a poor CC planting technique in central Illinois. This likely affected CC growth patterns and may have led to lowered fall stand counts and subsequent spring biomass production.

4.4.2. Environmental effects

The limited CC growth affected the ability of CCs to successfully intercept soil N-NO_3 and subsequently negatively affected N_2O emissions. The negative correlation between spring biomass and soil N-NO_3 ($p < 0.0001$, $r^2 = 0.24$) suggests that when CC biomass occurs, soil N-NO_3 can be reduced. Likewise, a similar negative correlation between spring CC biomass and N_2O ($p < 0.0001$, $r^2 = 0.31$) suggests that when CC biomass occurs, N_2O emissions can be reduced. Emissions of N_2O during the first two years (2014 and 2015) were significantly larger compared to the last two years (2016 and 2017) 1.64 vs 0.32 kg-N ha^{-1} (Fig. 4.3). Mitchell et al. (2013), found that the mechanism behind this is likely due to soil N-NO_3 uptake by CCs; this would decrease substrate needed for denitrification (Baggs, 2000, Snyder, et al., 2009). Also, by allowing CC residue to decompose on the soil surface with oxygen available, mineralization or immobilization of the residue N can occur and denitrification should be reduced (Aulakh et al., 1992; Basche et al., 2014). Tillage treatment was found to have no effect on N_2O emissions; this has been observed in other studies comparing the effect of conventional tillage to NT (Rochette et al., 2008; Snyder et al., 2009; Venterea et al., 2005). It is important to note that we did not sample GHG emissions following CC residue incorporation, or not in the case of NT, so those effects cannot be inferred from this study.

In this study, the increase in N_2O emissions during the first two years is likely related to the lack of CC biomass growth suppressed by adverse weather. Due to the extreme cold in the winters of 2014 and 2015, the lack of spring CC biomass resulted in less N-NO_3 taken up in actively growing CCs providing the substrate needed for N_2O emissions. In the springs of 2016 and 2017, warmer winters allowed for actively growing CC to take up N in their biomass, leaving less N in the soil for conversion to N_2O. This is corroborated by an observed positive correlation between N_2O and N-NO_3 ($p < 0.0001$, $r^2 = 0.31$). Furthermore, actively growing CCs take up soil water in living plant tissue; the decrease in soil water would not favor conditions of denitrification and therefore lower the amount of N_2O produced (Basche et al., 2014; Davidson et al., 2000). The herbicide application error in 2016 led to an accumulation of N-NH_4 in the soil (Table 4.5), which resulted in the corn and weed species and subsequent CC species preferentially taking up much of the remaining N-NO_3 that was available (Curran et al., 2018). This is supported by 2017 having the lowest N-NO_3 values (0.09 g N kg^{-1} day^{-1}). The lack of soil N-NO_3 likely led to low N_2O emissions in 2016 and 2017 due to an absence of available substrate for N_2O emissions to occur. Our results also indicate that T reduced N-NO_3 concentrations in only one of the years, 2016 compared to NT; therefore, year was likely the driver of the interaction between year and tillage.

The largest CO_2 emissions occurred in 2014 and were nearly four times as large as 2016 and nearly eight times as much as 2015 and 2017. This effect could be attributed to an increase in soil respiration due to a lack of CC growth and an increase in soil temperatures associated with bare soil compared to covered soil. Plant residues are known to have a higher albedo and thermal radiative properties compared to bare soil, causing lower temperature at the soil surface (Paustian et al., 2000); other studies have shown a positive correlation between CO_2 and soil temperature (Behnke et al., 2012; Drury et al., 2006). Emissions of CH_4 behaved similar to CO_2 and were only different in 2015. Both CO_2 and CH_4 experienced a lack of tillage effect; Behnke et al. (2018b) observed a similar result comparing chisel tillage to NT from various crop rotations in Illinois. Other studies in the Corn Belt (Illinois, Iowa, Indiana, Ohio, Minnesota, and Nebraska) detected comparable CO_2 emission results (Drury et al., 2006; Johnson et al., 2010).

4.4.3. Corn Yields

Mean corn yields were approximately 9 Mg ha^{-1} for the duration of the study. The interaction between year and tillage is likely driven by strong main effects of year and tillage because each year by tillage combination is not different; however, overall tillage increased yields by 0.64 Mg ha^{-1} (Table 4.5). Yield advantages associated with tillage has been observed in other Midwestern studies (Behnke et al., 2018b; Halvorson et al., 2006; Parkin and Kaspar, 2006). Decreases in yield were observed following five or more years of NT in a global meta-analysis conducted by Pittelkow et al. (2015) due to waterlogging and poor establishment, compaction, and nutrient deficiencies (Cid et al., 2014; Halvorson et al., 2006;

Rusinamhodzi et al., 2011). Results from this study suggest that in high organic matter soils with large amounts of corn residue, tillage increases yields.

Furthermore, no interaction was observed between tillage and CC type, so the utilization of tillage to manage CC residue cannot be inferred. Corn yields were negatively correlated to CC biomass ($p < 0.0001$, $r^2 = 0.28$), meaning that increased CC biomass led to a decrease in corn yields. This was likely due to a significant yield decrease of 1 Mg ha^{-1} associated with the CarSar rotation was observed compared to the other CC species and the control. Yield losses associated with CarSar were also observed from a farmer focus group with a location in Illinois (Plastina et al., 2018). Actively growing CCs can take up necessary water early in the growing season, which may have contributed to the negative correlation between yield and spring CC biomass. In a study observing different CC species and their effect on organic cropping rotations in IL, Welch et al. (2016) found that in years where soil water is limiting, certain CC mixtures take up soil water at the detriment of the subsequent cash crop. It is important to note that following the initial CC termination glyphosate application, an operator error in the spring of 2016 resulted in no herbicide being applied to the study leading to the very low mean corn yield of 3.74 Mg ha^{-1} (Table 4.5). The low yield during 2016 likely led to such a large year effect. We did not omit the 2016 year from our analysis because the application error occurred throughout the entire study.

Overall, levels of N_2O decreased with increasing CC biomass, confirming our hypothesis that CC growth will reduce N_2O emissions. Tillage (chisel or NT) was found to have no effect on N_2O and CH_4 emissions, confirming our hypothesis. Similarly tillage had no effect on CO_2 emissions, contradicting our hypothesis. Results from this study indicate that weather greatly affects the potential benefits that CC can offer in IL. These benefits include reductions in soil N-NO_3 and lowered N_2O emissions when spring CC biomass occurs greater than 0.5 Mg ha^{-1}. Annual ryegrass has the ability to survive most winters in IL and can reduce soil N; however, there is a slight yield reduction of around 12%. Future research should focus on CC mixtures that are more likely to overwinter successfully in Illinois, such as cereal rye, annual ryegrass, and/or hairy vetch. In addition, seeding techniques that ensure good seed-to-soil contact are vital to allow for enough fall biomass to over winter successfully.

CHAPTER 5: CONCLUSIONS

This dissertation is a compilation of two published works and the last will be submitted for publication studying the effects of cropping systems on GHG emissions. All three projects were conducted in Illinois on highly productive soils, but had different management treatments. Management treatments included in these studies were tillage versus no-till systems, various crop rotation systems versus continuous monoculture, and the inclusion of cover crops versus a fallow control. Crop rotation and the inclusion of CC's into a system are some of the proposed tactics for reducing GHG emissions, so by studying the effects of each of these various cropping systems on GHG emissions, management recommendations can be supposed.

The results presented in this dissertation and published in Behnke et al. (2018b) indicate that shifting from a continuous monoculture of corn or soybean alone to a crop rotational system will not only reduce GHG emissions, but will also increase yields for each year of the rotated crop. The reduction in GHG emissions is likely due to the decreased use of N fertilizer in non-corn years compared to high N input required by CCC. Specifically, rotated corn reduced N_2O emissions by 2 kg N ha^{-1} compared to continuous corn. Another benefit of rotated corn is improved yield stability compared to CCC during poor environmental years. Soybean yields were also improved by rotating with corn compared to SSS; however, N_2O emissions were not different between rotated soybean and SSS. Some possible reasons that rotated soybean compared to SSS are lower instances of diseases and changes in soil properties, such as an increase in WAS and better water infiltration due to increases in soil organic matter. For both corn and soybean, tillage was found to increase yields by aiding in the decomposition of residues common in high organic matter environments and providing a warmer and weed-free seedbed for emerging seedlings. Tillage also had no effect on GHG emissions compared to no-till in this study.

A further investigation into this crop rotation and tillage study was published in Behnke et al. (2018a) and revealed that increases in N_2O emissions were correlated to low soil pH conditions, elevated levels of soil NO_3 throughout the growing season, elevated levels of plant available water, and increased soil C levels. The crop rotation that closest resembles these conditions is CCC; the CCC system had the lowest soil pH and consequently had the greatest N_2O emissions. Likewise, increases in CO_2 emissions were related to low soil pH, low levels of Ca, increased plant available water, higher levels of microbial biomass C, and lower WAS. However, these results are less evident compared to the N_2O as the CCC rotation had the greatest CO_2 emissions and the lowest soil pH, but had the lowest microbial biomass C and highest WAS. It is important to note that CO_2 emissions were not different among corn rotations and only the CCC rotation was greater than SSS, but not different from rotated corn or rotated soybean. Emissions of CH_4 were related to increased levels of microbial biomass C due to uptake of CH_4 by soil microbes; CH_4 emissions were not different among rotations or tillage.

The final chapter of this dissertation examined the inclusion of CC's into a corn-soybean rotation system. Results indicate that of N_2O emissions can be reduced when CC biomass is greater than 0.5 Mg ha^{-1}; this is due to the uptake of soil N-NO_3 by the actively growing CC, which reduces the substrate needed for N_2O evolution. Similar to the crop rotation and tillage study from Monmouth, IL, the use of tillage was found to have no effect on GHG emissions when including CC's or the fallow control. This study highlights the effect that weather has on the potential benefits that CC may offer in IL. Two of the four years, the weather was advantageous for CC growth and large amounts of CC biomass was recorded in CC species that successfully overwintered; however, the other two years, severe cold winters eliminated nearly all CC spring growth, negating potential benefits that the CCs could offer. One of the CC species included in this experiment was annual ryegrass; it has the ability to survive most winters in IL, but also reduced yields of the following cash crop by 12%.

Combining the information from each of these three studies shows that utilizing a crop rotation (corn-soybean or corn-soybean-wheat) and the inclusion of a winter hardy CC species or mixture (cereal rye + hairy vetch) in IL has the potential to lower GHG emissions significantly. In addition, utilizing a crop rotation boosts yields for each subsequent cash crop and including a CC species does not negatively affect yields (excluding annual ryegrass). Therefore, my recommendation for growers in IL is to shift away from a continuous monoculture and into a crop rotation system. In highly productive soils, tillage was found to improve yields, but had no effect on GHG emissions. Including CC's into a crop rotational system may not provide a yield benefit, but does provide environmental benefits, such as reduced GHG emissions and lowered winter soil N-NO_3 concentrations, which are subject to leaching.

CHAPTER 6: REFERENCES

Adee E., Oplinger E., Grau C. (1994) Tillage, rotation sequence, and cultivar influences on brown stem rot and soybean yield. Journal of Production Agriculture 7:341-347.

Adviento-Borbe M., Doran J., Drijber R., Dobermann A. (2006) Soil electrical conductivity and water content affect nitrous oxide and carbon dioxide emissions in intensively managed soils. Journal of environmental quality 35:1999-2010.

Adviento-Borbe M., Haddix M., Binder D., Walters D., Dobermann A. (2007) Soil greenhouse gas fluxes and global warming potential in four high-yielding maize systems. Global Change Biology 13:1972-1988.

Al-Kaisi M.M., Archontoulis S.V., Kwaw-Mensah D., Miguez F. (2015) Tillage and Crop Rotation Effects on Corn Agronomic Response and Economic Return at Seven Iowa Locations. Agronomy Journal 107:1411-1424. DOI: 10.2134/agronj14.0470.

Alexander R.B., Smith R.A., Schwarz G.E., Boyer E.W., Nolan J.V., Brakebill J.W. (2007) Differences in phosphorus and nitrogen delivery to the Gulf of Mexico from the Mississippi River Basin. Environmental science & technology 42:822-830.

Amos B., Arkebauer T.J., Doran J.W. (2005) Soil surface fluxes of greenhouse gases in an irrigated maize-based agroecosystem. Soil Science Society of America Journal 69:387-395.

Appelgate S.R., Lenssen A.W., Wiedenhoeft M.H., Kaspar T.C. (2017) Cover Crop Options and Mixes for Upper Midwest Corn–Soybean Systems. Agronomy Journal 109:968-984. DOI: 10.2134/agronj2016.08.0453.

ASTM-D422. (2007) Standard Test Method for Particle-Size Analysis of Soils. ASTM D422. DOI: 10.1520/d0422-63r07e02.

Aulakh M., Doran J., Mosier A. (1992) Soil denitrification—significance, measurement, and effects of management, Advances in Soil Science, Springer. pp. 1-57.

Aulakh M., Walters D., Doran J., Francis D., Mosier A. (1991) Crop residue type and placement effects on denitrification and mineralization. Soil Science Society of America Journal 55:1020-1025.

Baggs E., Rees R., Smith K., Vinten A. (2000) Nitrous oxide emission from soils after incorporating crop residues. Soil use and management 16:82-87.

Basche A.D., Archontoulis S.V., Kaspar T.C., Jaynes D.B., Parkin T.B., Miguez F.E. (2016a) Simulating long-term impacts of cover crops and climate change on crop production and environmental outcomes in the Midwestern United States. Agriculture, Ecosystems & Environment 218:95-106. DOI: https://doi.org/10.1016/j.agee.2015.11.011.

Basche A.D., Kaspar T.C., Archontoulis S.V., Jaynes D.B., Sauer T.J., Parkin T.B., Miguez F.E. (2016b) Soil water improvements with the long-term use of a winter rye cover crop. Agricultural Water Management 172:40-50.

Basche A.D., Miguez F.E., Kaspar T.C., Castellano M.J. (2014) Do cover crops increase or decrease nitrous oxide emissions? A meta-analysis. Journal of Soil and Water Conservation 69:471-482. DOI: 10.2489/jswc.69.6.471.

Behnke G.D., David M.B., Voigt T.B. (2012) Greenhouse gas emissions, nitrate leaching, and biomass yields from production of Miscanthus× giganteus in Illinois, USA. BioEnergy Research 5:801-813.

Behnke G.D., Pittelkow C.M., Nafziger E.D., Villamil M.B. (2018a) Exploring the Relationships between Greenhouse Gas Emissions, Yields, and Soil Properties in Cropping Systems. Agriculture 8:62.

Behnke G.D., Zuber S.M., Pittelkow C.M., Nafziger E.D., Villamil M.B. (2018b) Long-term crop rotation and tillage effects on soil greenhouse gas emissions and crop production in Illinois, USA. Agriculture, Ecosystems & Environment 261:62-70.

Benjamin J.G., Halvorson A.D., Nielsen D.C., Mikha M.M. (2010) Crop Management Effects on Crop Residue Production and Changes in Soil Organic Carbon in the Central Great Plains. Agronomy Journal 102:990-997. DOI: 10.2134/agronj2009.0483.

Blake G., Hartge K. (1986) Bulk density. In 'Methods of soil analysis. Part 1. Physical and mineralogical methods' Soil Science Society of America:363-375.

Bouwman A., Boumans L., Batjes N. (2002) Emissions of N2O and NO from fertilized fields: Summary of available measurement data. Global Biogeochemical Cycles 16:1-13.

Brady N., Weil R. (1996) The Nature and Properties of Soils, 740 pp, Prentice Hall, Upper Saddle River, New Jersey, USA.

Bray R.H., Kurtz L. (1945) Determination of total, organic, and available forms of phosphorus in soils. Soil Science 59:39-46.

Carter M.R. (1993) Soil sampling and methods of analysis CRC Press.

Chan A., Parkin T. (2001) Effect of land use on methane flux from soil. Journal of Environmental Quality 30:786-797.

Christianson L., Harmel R. (2015) 4R Water quality impacts: An assessment and synthesis of forty years of drainage nitrogen losses. Journal of environmental quality 44:1852-1860.

Cid P., Carmona I., Murillo J.M., Gómez-Macpherson H. (2014) No-tillage permanent bed planting and controlled traffic in a maize-cotton irrigated system under Mediterranean conditions: Effects on soil compaction, crop performance and carbon sequestration. European Journal of Agronomy 61:24-34.

Curran W., Hoover R., Mirsky S., Roth G., Ryan M., Ackroyd V., Wallace J., Dempsey M., Pelzer C. (2018) Evaluation of Cover Crops Drill Interseeded into Corn Across the Mid-Atlantic Region. Agronomy Journal.

Dabney S., Delgado J., Reeves D. (2001) Using winter cover crops to improve soil and water quality. Communications in Soil Science and Plant Analysis 32:1221-1250.

Daigh A.L., Dick W.A., Helmers M.J., Lal R., Lauer J.G., Nafziger E., Pederson C.H., Strock J., Villamil M., Mukherjee A. (2017) Yields and yield stability of no-till and chisel-plow fields in the Midwestern US Corn Belt. Field Crops Research.

Daigh A.L.M., Dick W.A., Helmers M.J., Lal R., Lauer J.G., Nafziger E., Pederson C.H., Strock J., Villamil M., Mukherjee A., Cruse R. (2018) Yields and yield stability of no-till and chisel-plow fields in the Midwestern US Corn Belt. Field Crops Research 218:243-253. DOI: https://doi.org/10.1016/j.fcr.2017.04.002.

David M.B., Del Grosso S.J., Hu X., Marshall E.P., McIsaac G.F., Parton W.J., Tonitto C., Youssef M.A. (2009) Modeling denitrification in a tile-drained, corn and soybean agroecosystem of Illinois, USA. Biogeochemistry 93:7-30. DOI: 10.1007/s10533-008-9273-9.

Davidson E.A., Keller M., Erickson H.E., Verchot L.V., Veldkamp E. (2000) Testing a Conceptual Model of Soil Emissions of Nitrous and Nitric Oxides: Using two functions based on soil nitrogen availability and soil water content, the hole-in-the-pipe model characterizes a large fraction of the observed variation of nitric oxide and nitrous oxide emissions from soils. Bioscience 50:667-680.

Divito G.A., Rozas H.R.S., Echeverría H.E., Studdert G.A., Wyngaard N. (2011) Long term nitrogen fertilization: Soil property changes in an Argentinean Pampas soil under no tillage. Soil and Tillage Research 114:117-126.

Dozier I.A., Behnke G.D., Davis A.S., Nafziger E.D., Villamil M.B. (2017) Tillage and Cover Cropping Effects on Soil Properties and Crop Production in Illinois. Agronomy Journal:1261-1270.

Drury C., Reynolds W., Tan C., McLaughlin N., Yang X., Calder W., Oloya T., Yang J. (2014a) Impacts of 49–51 years of fertilization and crop rotation on growing season nitrous oxide emissions, nitrogen uptake and corn yields. Canadian Journal of Soil Science 94:421-433.

Drury C., Reynolds W., Tan C., Welacky T., Calder W., McLaughlin N. (2006) Emissions of nitrous oxide and carbon dioxide. Soil Science Society of America Journal 70:570-581.

Drury C.F., Tan C.S., Welacky T.W., Reynolds W.D., Zhang T.Q., Oloya T.O., McLaughlin N.B., Gaynor J.D. (2014b) Reducing Nitrate Loss in Tile Drainage Water with Cover Crops and Water-Table Management Systems. Journal of Environmental Quality 43:587-598. DOI: 10.2134/jeq2012.0495.

Dunn M., Ulrich-Schad J., Prokopy L., Myers R., Watts C., Scanlon K. (2016) Perceptions and use of cover crops among early adopters: Findings from a national survey. Journal of Soil and Water Conservation 71:29-40.

Eichner M.J. (1990) Nitrous oxide emissions from fertilized soils: summary of available data. Journal of Environmental Quality 19:272-280.

EPA A. (2016) Inventory of US greenhouse gas emissions and sinks: 1990-2014, EPA 430-R-16-002.

Fahad A., Mielke L., Flowerday A., Swartzendruber D. (1982) Soil physical properties as affected by soybean and other cropping sequences. Soil Science Society of America Journal 46:377-381.

FAO I. (2001) Global estimates of gaseous emissions of NH3, NO, and N2O from agricultural land. Food and Agriculture Organization of the United Nations (FAO) and International Fertilizer Industry Association (IFA), Rome, p 106.

FAO I. (2015) Status of the World's Soil Resources (SWSR)–Main Report. Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils, Rome, Italy 650.

Farooq M., Flower K.C., Jabran K., Wahid A., Siddique K.H.M. (2011) Crop yield and weed management in rainfed conservation agriculture. Soil and Tillage Research 117:172-183. DOI: http://dx.doi.org/10.1016/j.still.2011.10.001.

Franzluebbers A., Hons F., Zuberer D. (1994) Long-term changes in soil carbon and nitrogen pools in wheat management systems. Soil Science Society of America Journal 58:1639-1645.

Gbur E. (2012) Analysis of generalized linear mixed models in the agricultural and natural resources sciences Crop Science Society of America.

Gbur E.E., Stroup W.W., McCarter K.S., Durham S., Young L.J., Christman M., West M., Kramer M. (2012) Analysis of Generalized Linear Mixed Models in the Agricultural and Natural Resources Sciences American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, WI.

Gentry L.E., David M.B., McIsaac G.F. (2014) Variation in riverine nitrate flux and fall nitrogen fertilizer application in East-central illinois. J Environ Qual 43:1467-74. DOI: 10.2134/jeq2013.12.0499.

Gentry L.F., Ruffo M.L., Below F.E. (2013) Identifying factors controlling the continuous corn yield penalty. Agronomy Journal 105:295-303.

Ginting D., Eghball B. (2005) Nitrous Oxide Emission from No-Till Irrigated Corn Joint contribution of Univ. Nebraska. Agric. Res. Div. and USDA-ARS, Lincoln, NE, as paper No. 14723. Soil Science Society of America Journal 69:915-924. DOI: 10.2136/sssaj2004.0292.

Halvorson A.D., Del Grosso S.J., Reule C.A. (2008) Nitrogen, tillage, and crop rotation effects on nitrous oxide emissions from irrigated cropping systems. Journal of Environmental Quality 37:1337-1344.

Halvorson A.D., Mosier A.R., Reule C.A., Bausch W.C. (2006) Nitrogen and Tillage Effects on Irrigated Continuous Corn Yields Contribution from USDA-ARS. Agronomy Journal 98:63-71. DOI: 10.2134/agronj2005.0174.

Hatfield J. (2012) Agriculture in the Midwest. Great Lakes Integrated Sciences and Assessment Tech. Rep.

Havlin J., Kissel D., Maddux L., Claassen M., Long J. (1990) Crop rotation and tillage effects on soil organic carbon and nitrogen. Soil Science Society of America Journal 54:448-452.

Heckman J.R., Sims J.T., Beegle D.B., Coale F.J., Herbert S.J., Bruulsema T.W., Bamka W.J. (2003) Nutrient Removal by Corn Grain Harvest. Agronomy Journal 95:587-591. DOI: 10.2134/agronj2003.5870.

Hickman M.V. (2002) Long-term tillage and crop rotation effects on soil chemical and mineral properties. Journal of plant nutrition 25:1457-1470.

Hoben J., Gehl R., Millar N., Grace P., Robertson G. (2011) Nonlinear nitrous oxide (N2O) response to nitrogen fertilizer in on-farm corn crops of the US Midwest. Global Change Biology 17:1140-1152.

IL-NLRS. (2015) Illinois Nutrient Loss Reduction Strategy.

ISWS. (2016) Water and Atmospheric Resources Monitoring Program. Illinois Climate Network.

ISWS. (2018) Water and Atmospheric Resources Monitoring Program. Illinois Climate Network.

Jacinthe P.-A., Dick W.A. (1997) Soil management and nitrous oxide emissions from cultivated fields in southern Ohio. Soil and Tillage Research 41:221-235.

Jacinthe P.-A., Lal R. (2005) Labile carbon and methane uptake as affected by tillage intensity in a Mollisol. Soil and Tillage Research 80:35-45.

Jagadamma S., Lal R., Hoeft R.G., Nafziger E.D., Adee E.A. (2007) Nitrogen fertilization and cropping systems effects on soil organic carbon and total nitrogen pools under chisel-plow tillage in Illinois. Soil and Tillage Research 95:348-356. DOI: 10.1016/j.still.2007.02.006.

Jagadamma S., Lal R., Hoeft R.G., Nafziger E.D., Adee E.A. (2008) Nitrogen fertilization and cropping system impacts on soil properties and their relationship to crop yield in the central Corn Belt, USA. Soil and Tillage Research 98:120-129.

Johnson J.M., Archer D., Barbour N. (2010) Greenhouse gas emission from contrasting management scenarios in the northern Corn Belt. Soil Science Society of America Journal 74:396-406.

Johnson J.M.F., Franzluebbers A.J., Weyers S.L., Reicosky D.C. (2007) Agricultural opportunities to mitigate greenhouse gas emissions. Environmental Pollution 150:107-124. DOI: https://doi.org/10.1016/j.envpol.2007.06.030.

Johnson J.M.F., Reicosky D.C., Allmaras R.R., Sauer T.J., Venterea R.T., Dell C.J. (2005) Greenhouse gas contributions and mitigation potential of agriculture in the central USA. Soil and Tillage Research 83:73-94. DOI: http://dx.doi.org/10.1016/j.still.2005.02.010.

Johnson R.A., Wichern D.W. (2002) Applied multivariate statistical analysis Prentice hall Upper Saddle River, NJ.

Karlen D., Wollenhaupt N., Erbach D., Berry E., Swan J., Eash N., Jordahl J. (1994) Long-term tillage effects on soil quality. Soil and Tillage Research 32:313-327.

Kaspar T., Bakker M. (2015) Biomass production of 12 winter cereal cover crop cultivars and their effect on subsequent no-till corn yield. Journal of Soil and Water Conservation 70:353-364.

Kaspar T.C., Jaynes D.B., Parkin T.B., Moorman T.B., Singer J.W. (2012) Effectiveness of oat and rye cover crops in reducing nitrate losses in drainage water. Agricultural Water Management 110:25-33. DOI: 10.1016/j.agwat.2012.03.010.

Kaye J.P., Quemada M. (2017) Using cover crops to mitigate and adapt to climate change. A review. Agronomy for Sustainable Development 37:4. DOI: 10.1007/s13593-016-0410-x.

Kelley K.W., Long J.H., Todd T.C. (2003) Long-term crop rotations affect soybean yield, seed weight, and soil chemical properties. Field Crops Research 83:41-50. DOI: http://dx.doi.org/10.1016/S0378-4290(03)00055-8.

Kemper W., Rosenau R. (1986) Aggregate stability and size distribution. In ‘Methods of soil analysis. Part 1. Physical and mineralogical methods’. Soil Science Society of America:426-442.

Kladivko E.J., Kaspar T.C., Jaynes D.B., Malone R.W., Singer J., Morin X.K., Searchinger T. (2014) Cover crops in the upper midwestern United States: Potential adoption and reduction of nitrate leaching in the Mississippi River Basin. Journal of Soil and Water Conservation 69:279-291. DOI: 10.2489/jswc.69.4.279.

Kumar S., Kadono A., Lal R., Dick W. (2012) Long-term tillage and crop rotations for 47–49 years influences hydrological properties of two soils in Ohio. Soil Science Society of America Journal 76:2195-2207.

Lebender U., Senbayram M., Lammel J., Kuhlmann H. (2014) Effect of mineral nitrogen fertilizer forms on N2O emissions from arable soils in winter wheat production. Journal of Plant Nutrition and Soil Science 177:722-732.

Lehman R.M., Osborne S.L., Duke S.E. (2017) Diversified No-Till Crop Rotation Reduces Nitrous Oxide Emissions, Increases Soybean Yields, and Promotes Soil Carbon Accrual. Soil Science Society of America Journal 81:76-83.

Leick B., Engels C. (2002) Effects of various nitrogen fertilisers on nitrous oxide emissions from arable soils. Plant Nutrition:882-883.

Li C., Li X., Kong W., Wu Y., Wang J. (2010) Effect of monoculture soybean on soil microbial community in the Northeast China. Plant and Soil 330:423-433. DOI: 10.1007/s11104-009-0216-6.

Linn D.M., Doran J.W. (1984) Effect of Water-Filled Pore Space on Carbon Dioxide and Nitrous Oxide Production in Tilled and Nontilled Soils1. Soil Science Society of America Journal 48:1267-1272. DOI: 10.2136/sssaj1984.03615995004800060013x.

Lupwayi N., Rice W., Clayton G. (1999) Soil microbial biomass and carbon dioxide flux under wheat as influenced by tillage and crop rotation. Canadian Journal of Soil Science 79:273-280.

MacKenzie A.F., Fan M.X., Cadrin F. (1998) Nitrous Oxide Emission in Three Years as Affected by Tillage, Corn-Soybean-Alfalfa Rotations, and Nitrogen Fertilization. Journal of Environmental Quality 27:698-703. DOI: 10.2134/jeq1998.00472425002700030029x.

Malhi S.S., Lemke R., Wang Z., Chhabra B.S. (2006) Tillage, nitrogen and crop residue effects on crop yield, nutrient uptake, soil quality, and greenhouse gas emissions. Soil and Tillage Research 90:171-183.

Malone R.W., Jaynes D.B., Kaspar T.C., Thorp K.R., Kladivko E., Ma L., James D.E., Singer J., Morin X.K., Searchinger T. (2014) Cover crops in the upper midwestern United States: Simulated effect on nitrate leaching with artificial drainage. Journal of Soil and Water Conservation 69:292-305. DOI: 10.2489/jswc.69.4.292.

Martens D.A. (2000) Management and crop residue influence soil aggregate stability. Journal of Environmental Quality 29:723-727.

McDaniel M.D., Grandy A.S., Tiemann L.K., Weintraub M.N. (2014) Crop rotation complexity regulates the decomposition of high and low quality residues. Soil Biology and Biochemistry 78:243-254. DOI: https://doi.org/10.1016/j.soilbio.2014.07.027.

McGeehan S., Naylor D. (1988) Automated instrumental analysis of carbon and nitrogen in plant and soil samples. Communications in Soil Science and Plant Analysis 19:493-505.

McLain J.E., Martens D.A. (2006) Moisture controls on trace gas fluxes in semiarid riparian soils. Soil Science Society of America Journal 70:367-377.

McLean E. (1982) Soil pH and lime requirement. In "Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties" Soil Science Society of America:199-224.

McSwiney C.P., Robertson G.P. (2005) Nonlinear response of N2O flux to incremental fertilizer addition in a continuous maize (Zea mays L.) cropping system. Global Change Biology 11:1712-1719.

Mehlich A. (1984) Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. Communications in Soil Science and Plant Analysis 15:1409-1416.

Miguez F.E., Bollero G.A. (2005) Review of Corn Yield Response under Winter Cover Cropping Systems Using Meta-Analytic Methods. Crop Science 45:2318. DOI: 10.2135/cropsci2005.0014.

Millar N., Robertson G.P., Grace P.R., Gehl R.J., Hoben J.P. (2010) Nitrogen fertilizer management for nitrous oxide (N2O) mitigation in intensive corn (Maize) production: an emissions reduction protocol for US Midwest agriculture. Mitigation and Adaptation Strategies for Global Change 15:185-204. DOI: 10.1007/s11027-010-9212-7.

Mitchell D.C., Castellano M.J., Sawyer J.E., Pantoja J. (2013) Cover Crop Effects on Nitrous Oxide Emissions: Role of Mineralizable Carbon. Soil Science Society of America Journal 77:1765. DOI: 10.2136/sssaj2013.02.0074.

Mosier A.R., Halvorson A.D., Reule C.A., Liu X.J. (2006) Net global warming potential and greenhouse gas intensity in irrigated cropping systems in northeastern Colorado. Journal of environmental quality 35:1584-1598.

Nafziger E. (2009) Illinois Agronomy Handbook. Urbana, IL: University of Illinois Extension:224.

Nakajima T., Shrestha R.K., Lal R. (2016) On-Farm Assessments of Soil Quality in Ohio and Michigan. Soil Science Society of America Journal 80:1020-1026. DOI: 10.2136/sssaj2016.01.0003.

Nelson D.W., Sommers L.E. (1996) Total carbon, organic carbon, and organic matter. In "Methods of Soil Analysis Part 3. Chemical Methods". Soil Science Society of America:961-1010.

Nolan B.T., Hitt K.J. (2006) Vulnerability of shallow groundwater and drinking-water wells to nitrate in the United States. Environmental science & technology 40:7834-7840.

Norton J.M. (2008) Nitrification in agricultural soils. Agronomy Journal 49:173.

Omonode R.A., Smith D.R., Gál A., Vyn T.J. (2011) Soil nitrous oxide emissions in corn following three decades of tillage and rotation treatments. Soil Science Society of America Journal 75:152-163.

Parkin T.B., Kaspar T.C. (2003) Temperature controls on diurnal carbon dioxide flux. Soil Science Society of America Journal 67:1763-1772.

Parkin T.B., Kaspar T.C. (2006) Nitrous oxide emissions from corn–soybean systems in the Midwest. Journal of Environmental Quality 35:1496-1506.

Parkin T.B., Venterea R.T. (2010) USDA-ARS GRACEnet project protocols, chapter 3. Chamber-based trace gas flux measurements. Sampling protocols. Beltsville, MD p:1-39.

Paustian K., Lehmann J., Ogle S., Reay D., Robertson G.P., Smith P. (2016) Climate-smart soils. Nature 532:49-57.

Paustian K., Six J., Elliott E.T., Hunt H.W. (2000) Management options for reducing CO2 emissions from agricultural soils. Biogeochemistry 48:147-163. DOI: 10.1023/a:1006271331703.

Pedersen P., Lauer J.G. (2003) Corn and soybean response to rotation sequence, row spacing, and tillage system. Agronomy Journal 95:965-971.

Peterson T.A., Varvel G. (1989) Crop yield as affected by rotation and nitrogen rate. I. Soybean. Agronomy Journal 81:727-731.

Pimentel D., Burgess M. (2013) Soil erosion threatens food production. Agriculture 3:443-463.

Pittelkow C.M., Linquist B.A., Lundy M.E., Liang X., van Groenigen K.J., Lee J., van Gestel N., Six J., Venterea R.T., van Kessel C. (2015) When does no-till yield more? A global meta-analysis. Field Crops Research 183:156-168. DOI: http://dx.doi.org/10.1016/j.fcr.2015.07.020.

Plastina A., Liu F., Miguez F., Carlson S. (2018) Cover crops use in Midwestern US agriculture: perceived benefits and net returns. Renewable Agriculture and Food Systems:1-11.

Power J.F., Koerner P., Doran J.W., Wilhelm W. (1998) Residual effects of crop residues on grain production and selected soil properties. Soil Science Society of America Journal 62:1393-1397.

Raich J.W., Potter C.S. (1995) Global patterns of carbon dioxide emissions from soils. Global Biogeochemical Cycles 9:23-36.

Robertson G., Groffman P., Paul E. (2007) Soil microbiology, biochemistry, and ecology. Soil Microbiology, Biochemistry and Ecology:421-446.

Rochette P., Worth D.E., Lemke R.L., McConkey B.G., Pennock D.J., Wagner-Riddle C., Desjardins R. (2008) Estimation of N2O emissions from agricultural soils in Canada. I. Development of a country-specific methodology. Canadian Journal of Soil Science 88:641-654.

Roth R.T., Ruffatti M.D., O'Rourke P.D., Armstronga S.D. (2017) A cost analysis approach to valuing cover crop environmental and n cycling benefits: A central Illinois on farm case study. Agricultural systems.

Ruffo M.L., Bullock D.G., Bollero G.A. (2004) Soybean Yield as Affected by Biomass and Nitrogen Uptake of Cereal Rye in Winter Cover Crop Rotations. Agronomy Journal 96:800-805. DOI: 10.2134/agronj2004.0800.

Rusinamhodzi L., Corbeels M., van Wijk M.T., Rufino M.C., Nyamangara J., Giller K.E. (2011) A meta-analysis of long-term effects of conservation agriculture on maize grain yield under rain-fed conditions. Agronomy for Sustainable Development 31:657. DOI: 10.1007/s13593-011-0040-2.

Sainju U., Singh B., Whitehead W. (2002) Long-term effects of tillage, cover crops, and nitrogen fertilization on organic carbon and nitrogen concentrations in sandy loam soils in Georgia, USA. Soil and Tillage Research 63:167-179.

Seifert C., Roberts M., Lobell D. (2017) Continuous Corn and Soybean Yield Penalties across Hundreds of Thousands of Fields. Agronomy Journal 109:541-548.

Sindelar A.J., Schmer M.R., Jin V.L., Wienhold B.J., Varvel G.E. (2015) Long-Term Corn and Soybean Response to Crop Rotation and Tillage. Agronomy Journal 107:2241-2252. DOI: 10.2134/agronj15.0085.

Smith D.R., Hernandez-Ramirez G., Armstrong S.D., Bucholtz D.L., Stott D.E. (2011) Fertilizer and Tillage Management Impacts on Non-Carbon-Dioxide Greenhouse Gas Emissions. Soil Science Society of America Journal 75:1070. DOI: 10.2136/sssaj2009.0354.

Snapp S.S., S. M. Swinton, R. Labarta, D. Mutch, J. R. Black, R. Leep, J. Nyiraneza, and K. O'Neil. (2005) Evaluating Cover Crops for Benefits, Costs and Performance within Cropping System Niches. Agronomy Journal 97:322–332.

Snyder C., Bruulsema T., Jensen T., Fixen P. (2009) Review of greenhouse gas emissions from crop production systems and fertilizer management effects. Agriculture, Ecosystems & Environment 133:247-266.

Soil-Survey-Staff. (2016) Official Soil Series Descriptions. Natural Resources Conservation Service, United States Department of Agriculture.

Soil-Survey-Staff. (2018) Official Soil Series Descriptions. Natural Resources Conservation Service, United States Department of Agriculture.

Studdert G.A. (2000) Crop rotations and nitrogen fertilization to manage soil organic carbon dynamics. Soil Science Society of America Journal 64:1496-1503.

Sumner M., Miller W. (1996) Cation exchange capacity and exchange coefficients. Methods of Soil Analysis Part 3—Chemical Methods:1201-1229.

Tabachnick B.G., Fidell L.S. (2013) Using multivariate statistics. 6th ed. Pearson Education, Inc.

Tonitto C., David M., Drinkwater L. (2006) Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: A meta-analysis of crop yield and N dynamics. Agriculture, Ecosystems & Environment 112:58-72.

Tortosa G., Hidalgo A., Salas A., Bedmar E.J., Mesa S., Delgado M.J. (2015) Nitrate and flooding induce N2O emissions from soybean nodules. Symbiosis 67:125-133. DOI: 10.1007/s13199-015-0341-3.

USDA-ERS. (2016a) Corn. USDA Economic Research Service.

USDA-ERS. (2016b) Soybeans & Oil Crops. USDA Economic Research Service.

USDA-NASS. (2016) Agricultural chemical use program.

USDA-NASS. (2018) USDA's National Agricultural Statistics Service.

Varvel G.E. (1994) Rotation and nitrogen fertilization effects on changes in soil carbon and nitrogen. Agronomy Journal 86:319-325.

Varvel G.E., Wilhelm W.W. (2010) Long-Term Soil Organic Carbon as Affected by Tillage and Cropping Systems All rights reserved. Soil Science Society of America Journal 74:915-921. DOI: 10.2136/sssaj2009.0362.

Venterea R.T., Bijesh M., Dolan M.S. (2011) Fertilizer source and tillage effects on yield-scaled nitrous oxide emissions in a corn cropping system. Journal of Environmental Quality 40:1521-1531.

Venterea R.T., Burger M., Spokas K.A. (2005) Nitrogen oxide and methane emissions under varying tillage and fertilizer management. Journal of Environmental Quality 34:1467-1477.

Venterea R.T., Halvorson A.D., Kitchen N., Liebig M.A., Cavigelli M.A., Grosso S.J.D., Motavalli P.P., Nelson K.A., Spokas K.A., Singh B.P. (2012) Challenges and opportunities for mitigating nitrous oxide emissions from fertilized cropping systems. Frontiers in Ecology and the Environment 10:562-570.

Villamil M., Miguez F., Bollero G. (2008) Multivariate analysis and visualization of soil quality data for no-till systems. Journal of environmental quality 37:2063-2069.

Villamil M.B., Bollero G.A., Darmody R.G., Simmons F.W., Bullock D.G. (2006) No-Till Corn/Soybean Systems Including Winter Cover Crops. Soil Science Society of America Journal 70:1936-1944. DOI: 10.2136/sssaj2005.0350.

Villamil M.B., Little J., Nafziger E.D. (2015) Corn residue, tillage, and nitrogen rate effects on soil properties. Soil and Tillage Research 151:61-66. DOI: http://dx.doi.org/10.1016/j.still.2015.03.005.

Wagner-Riddle C., Furon A., Mclaughlin N.L., Lee I., Barbeau J., Jayasundara S., Parkin G., Von Bertoldi P., Warland J. (2007) Intensive measurement of nitrous oxide emissions from a corn–soybean–wheat rotation under two contrasting management systems over 5 years. Global Change Biology 13:1722-1736.

Wang Y., Guo J., Vogt R.D., Mulder J., Wang J., Zhang X. (2018) Soil pH as the chief modifier for regional nitrous oxide emissions: New evidence and implications for global estimates and mitigation. Global Change Biology 24.

Weier K.L., Doran J.W., Power J.F., Walters D.T. (1993) Denitrification and the Dinitrogen/Nitrous Oxide Ratio as Affected by Soil Water, Available Carbon, and Nitrate. Soil Science Society of America Journal 57:66-72. DOI: 10.2136/sssaj1993.03615995005700010013x.

Welch R.Y., Behnke G.D., Davis A.S., Masiunas J., Villamil M.B. (2016) Using cover crops in headlands of organic grain farms: Effects on soil properties, weeds and crop yields. Agriculture, Ecosystems & Environment 216:322-332. DOI: https://doi.org/10.1016/j.agee.2015.10.014.

West T.O., Post W.M. (2002) Soil organic carbon sequestration rates by tillage and crop rotation. Soil Science Society of America Journal 66:1930-1946.

Wilhelm W.W., Wortmann C.S. (2004) Tillage and Rotation Interactions for Corn and Soybean Grain Yield as Affected by Precipitation and Air Temperature Agronomy Journal 96:425-432. DOI: 10.2134/agronj2004.4250.

Wilson H.M., Al-Kaisi M.M. (2008) Crop rotation and nitrogen fertilization effect on soil CO2 emissions in central Iowa. Applied Soil Ecology 39:264-270. DOI: http://dx.doi.org/10.1016/j.apsoil.2007.12.013.

Yeater K.M., Villamil M.B. (2017) Multivariate Methods for Agricultural Research. Applied Statistics in Agricultural, Biological, and Environmental Sciences:1-32.

Zhao X., Christiansen L.E., Harmel D., Pittelkow C.M. (2016) Assessment of drainage nitrogen losses on a yield-scaled basis. Field Crops Research 199:156-166. DOI: 10.1016/j.fcr.2016.07.015.

Zuber S.M., Behnke G.D., Nafziger E.D., Villamil M.B. (2015) Crop rotation and tillage effects on soil physical and chemical properties in Illinois. Agronomy Journal 107:971-978.

Zuber S.M., Behnke G.D., Nafziger E.D., Villamil M.B. (2017) Multivariate assessment of soil quality indicators for crop rotation and tillage in Illinois. Soil and Tillage Research 174:147-155.

APPENDIX A: SUPPLEMENTAL TABLES FOR CHAPTER 2

Table A.1. Field event dates from Monmouth, IL over the duration of the study. Wheat plot operations began the previous year due to fall planting.

Field event type	2012	2013	2014	2015
Tilled wheat plots	3-Oct-2011	28-Sep-2012	2-Oct-2013	7-Oct-2014
Planted wheat crop	3-Oct-2011	28-Sep-2012	3-Oct-2013	7-Oct-2014
Fall wheat fertilization	24-Oct-2011	17-Oct-2012	21-Oct-2013	1-Nov-2014
Fall tillage of corn and soybean plots[1]	8-Nov-2011	9-Nov-2012	4-Nov-2013	14-Nov-2014
Spring wheat fertilization	20-Mar-2012	5-Apr-2013	11-Apr-2014[3]	1-Apr-2015
Secondary tillage in corn and soybean plots[2]	4-Apr-2012	1-May-2013	18-Apr-2014	24-Apr-2015
Spring corn fertilization	18-Apr-2012	17-May-2013	22-Apr-2014	1-May-2015
Corn planting	18-Apr-2012	16-May-2013	22-Apr-2014	1-May-2015
Soybean planting	10-May-2012	24-May-2013	22-May-2014[4]	13-May-2015
Harvest of wheat	20-Jun-2012	10-Jul-2013	31-Jul-2014	10-Jul-2015
Harvest of corn	24-Sep-2012	2-Oct-2013	30-Sep-2014	23-Sep-2015
Harvest of soybean	27-Sep-2012	2-Oct-2013	7-Oct-2014	24-Sep-2015

[1] Chisel tillage used a disk-ripper 14" deep in plots designated as tilled; no till received zero tillage

[2] Secondary tillage used a field cultivator in plots designated as tilled; no-till received zero tillage

[3] Winter wheat crop was terminated due to poor stands stemming from harsh winter conditions; spring oats were planted 4/17/2014 and fertilized 4/11/2014

[4] Soybean plots receiving tillage had secondary tillage 5/8/2014

Table A.2. Number of sampling events from Monmouth, IL by year and season.

Season[1]	Number of Observations			
	2012	2013	2014	2015
Spring	8	2	4	5
Summer	9	9	8	13
Fall	1	3	2	3

[1] Spring, March-May; Summer, June-August; Fall, September-November.

APPENDIX B: SUPPLEMENTAL TABLES FOR CHAPTER 3

Table B.1. Field event dates from Monmouth, IL throughout the duration of the study. Wheat plot operations began in the previous year due to fall planting.

Field Event Type	2012	2013	2014	2015
Tilled wheat plots [1]	3 October 2011	28 September 2012	2 October 2013	7 October 2014
Planting date of all wheat plots	3 October 2011	28 September 2012	3 October 2013	7 October 2014
Fall wheat fertilization	24 October 2011	17 October 2012	21 October 2013	1 November 2014
Fall tillage of corn and soybean plots [1]	8 November 2011	9 November 2012	4 November 2013	14 November 2014
Spring wheat fertilization	20 Mar 2012	5 April 2013	11 April 2014[3]	1 April 2015
Secondary tillage in corn and soybean plots [2]	4 April 2012	1 May 2013	18 April 2014	24 April 2015
Spring corn fertilization	18 April 2012	17 May 2013	22 April 2014	1 May 2015
Planting date of all corn plots	18 April 2012	16 May 2013	22 April 2014	1 May 2015
Planting date of all soybean plots	10 May 2012	24 May 2013	22 May 2014[4]	13 May 2015
Harvest of all wheat plots	20 June 2012	10 July 2013	31 July 2014	10 July 2015
Harvest of all corn plots	24 September 2012	2 October 2013	30 September 2014	23 September 2015
Harvest of all soybean plots	27 September 2012	2 October 2013	7 October 2014	24 September 2015

[1] Chisel tillage used a disk-ripper 36-cm deep in plots designated as tilled; no-till received zero tillage.
[2] Secondary tillage used a field cultivator in plots designated as tilled; no-till received zero tillage.
[3] Winter wheat crop was terminated due to poor stands stemming from harsh winter conditions; spring oats were planted 17 April 2014 and fertilized 11 April 2014.
[4] Soybean plots receiving tillage had secondary tillage on 8 May 2014.

Table B.2. Number of GHG sampling events from Monmouth, IL by year and season.

Season [1]	Number of Observations			
	2012	2013	2014	2015
Spring	8	2	4	5
Summer	9	9	8	13
Fall	1	3	2	3

[1] Spring, March-May; Summer, June–August; Fall, September–November.

Table B.3. Number of observations, season of sampling, and year of sampling originally included for each variable throughout the study (2012–2015) from Monmouth, IL.

Variable	No. of Obs.	Season of Sampling [1]	Year(s) of Sampling
YdI	192	Summer & Fall	2012–2015
N_2O	2531	Spring, Summer, Fall & Winter	2012–2015
CO_2	2531	Spring, Summer, Fall & Winter	2012–2015
CH_4	2531	Spring, Summer, Fall & Winter	2012–2015
Sand	176	Spring	2012
Silt	176	Spring	2012
Clay	176	Spring	2012
Ho	1970	Spring, Summer, Fall & Winter	2013–2015
PWP	192	Spring	2012
PAW	192	Spring	2012
BD	336	Spring	2014
WAS	336	Spring	2014
pH	112	Spring	2014
CEC	112	Spring	2014
SOM	112	Spring	2014
C	112	Spring	2014
N	112	Spring	2014
C/N	112	Spring	2014
MBC	224	Spring	2014
MBN	224	Spring	2014
NH_4	1970	Spring, Summer, Fall & Winter	2013–2015
NO_3	1970	Spring, Summer, Fall & Winter	2013–2015
TIN	1970	Spring, Summer, Fall & Winter	2013–2015
Pa	112	Spring	2014
K	112	Spring	2014
S	112	Spring	2014
Ca	112	Spring	2014
Mg	112	Spring	2014
Na	112	Spring	2014
B	112	Spring	2014
Fe	112	Spring	2014
Mn	112	Spring	2014
Cu	112	Spring	2014
Zn	112	Spring	2014
Al	112	Spring	2014

[1] Spring, March–May; Summer, June–August; Fall, September–November; Winter, December–February.

Table B.4. Mean values of yield index (YdI), nitrous oxide (N_2O, kg-N ha^{-1} year^{-1}), carbon dioxide (CO_2, Mg-C ha^{-1} year^{-1}), and methane (CH_4, kg-C ha^{-1} year^{-1}), determined by crop rotation (R) and tillage (T) and for each R and T combination.

Crop Rotation (R)	Tillage (T)	YdI		N_2O		CO_2		CH_4	
		Mean	SEM [1]	Mean	SEM	Mean	SEM	Mean	SEM
CCC		−0.74	0.11	6.18	0.73	4.43	0.42	0.43	0.07
CS		0.27	0.09	2.42	0.15	3.57	0.22	0.25	0.07
CSW		0.19	0.07	2.17	0.35	2.98	0.28	0.22	0.09
SSS		−0.26	0.12	0.97	0.14	2.63	0.15	0.24	0.12
	T [2]	0.22	0.08	3.26	0.41	3.63	0.24	0.31	0.05
	NT	−0.18	0.10	2.00	0.33	2.97	0.20	0.21	0.09
Rotation x Tillage									
CCC [3]	T	−0.46	0.04	7.67	0.83	5.11	0.68	0.52	0.07
CCC	NT	−1.02	0.07	4.69	0.59	3.75	0.18	0.34	0.11
CS	T	0.64	0.12	2.06	0.12	3.47	0.47	0.13	0.09
CS	NT	0.23	0.02	2.06	0.33	3.35	0.24	0.08	0.19
CSW	T	0.09	0.05	3.17	0.53	4.85	0.25	0.07	0.06
CSW	NT	−0.35	0.02	0.97	0.06	2.96	0.29	−0.03	0.30
SC	T	0.28	0.20	2.43	0.13	3.89	0.52	0.34	0.08
SC	NT	−0.06	0.16	3.12	0.21	3.57	0.63	0.45	0.12
SWC	T	0.43	0.09	2.33	0.36	2.30	0.22	0.43	0.17
SWC	NT	−0.09	0.07	0.34	0.09	1.46	0.16	0.29	0.32
SSS	T	0.01	0.11	1.10	0.24	2.49	0.19	0.34	0.17
SSS	NT	−0.53	0.10	0.85	0.17	2.76	0.24	0.14	0.17
WCS	T	0.52	0.03	4.07	0.64	3.32	0.24	0.34	0.08
WCS	NT	0.53	0.10	_ [4]	_	_	_	_	_

[1] SEM, standard error of the mean values;

[2] T, chisel till; NT, no-till;

[3] CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SC, soybean-corn; SWC, soybean-wheat-corn; SSS continuous soybean; WCS, wheat-corn-soybean;

[4] _, no samples taken.

Table B.5. Mean values of sand (%), silt (%), clay (%), average soil moisture (Ho, %), permanent wilting point (PWP, $cm^3\ cm^{-3}$), plant available water (PAW, $cm^3\ cm^{-3}$), bulk density (Bd, $Mg\ m^{-3}$), water aggregate stability (WAS, $g\ g^{-1}$), determined by crop rotation (R) and tillage (T) and for each R and T combination.

Crop	Tillage	Sand		Silt		Clay		Ho		PWP		PAW		Bd		WAS	
Rotation (R)	(T)	Mean	SEM [1]	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM
CCC		2.50	0.16	70.44	0.39	27.06	0.37	18.51	0.23	0.11	0.00	0.35	0.01	1.37	0.03	0.84	0.02
CS		2.47	0.12	71.22	0.66	26.31	0.69	17.45	0.21	0.10	0.00	0.34	0.01	1.34	0.02	0.83	0.01
CSW		2.50	0.12	72.19	0.50	25.31	0.52	18.83	0.81	0.11	0.00	0.31	0.01	1.35	0.02	0.84	0.01
SSS		2.00	0.00	72.31	0.69	25.69	0.69	17.34	0.42	0.11	0.00	0.31	0.01	1.33	0.02	0.82	0.02
	T [2]	2.44	0.10	71.48	0.44	26.08	0.47	17.75	0.41	0.10	0.00	0.34	0.01	1.32	0.01	0.82	0.01
	NT	2.38	0.09	71.71	0.45	25.92	0.45	18.51	0.43	0.11	0.00	0.32	0.01	1.37	0.02	0.85	0.01
Rotation × Tillage																	
CCC [3]	T	2.50	0.29	70.50	0.54	27.00	0.46	18.47	0.34	0.11	0.00	0.37	0.01	1.32	0.01	0.81	0.02
CCC	NT	2.50	0.20	70.38	0.66	27.13	0.66	18.55	0.35	0.11	0.00	0.33	0.02	1.42	0.03	0.87	0.01
CS	T	2.63	0.38	71.00	1.49	26.38	1.70	17.23	0.21	_	_	_	_	1.34	0.03	0.83	0.03
CS	NT	2.75	0.14	71.00	1.54	26.25	1.65	18.09	0.29	_	_	_	_	1.34	0.03	0.86	0.03
CSW	T	2.38	0.13	72.25	1.05	25.38	1.11	17.46	0.41	0.11	0.00	0.33	0.00	1.34	0.04	0.83	0.02
CSW	NT	2.50	0.29	72.13	0.94	25.38	0.72	21.13	1.27	0.12	0.01	0.30	0.02	1.40	0.04	0.89	0.02
SC	T	2.25	0.14	71.00	1.47	26.75	1.45	17.24	0.39	0.10	0.00	0.36	0.02	1.29	0.02	0.85	0.01
SC	NT	2.25	0.14	71.88	1.34	25.88	1.33	17.23	0.64	0.11	0.01	0.32	0.02	1.41	0.06	0.80	0.02
SWC	T	_ [4]	_	_	_	_	_	14.81	0.27	_	_	_	_	1.28	0.02	0.81	0.03
SWC	NT	_	_	_	_	_	_	_	_	_	_	_	_	1.36	0.07	0.83	0.02
SSS	T	2.00	0.00	72.25	1.09	25.75	1.09	17.10	0.68	0.11	0.00	0.32	0.02	1.30	0.01	0.79	0.02
SSS	NT	2.00	0.00	72.38	1.03	25.63	1.03	17.57	0.57	0.11	0.00	0.31	0.02	1.36	0.03	0.86	0.02
WCS	T	2.88	0.24	71.88	1.11	25.25	1.23	21.93	0.51	_	_	_	_	1.38	0.03	0.81	0.03
WCS	NT	2.25	0.25	72.50	1.32	25.25	1.44	_	_	_	_	_	_	1.35	0.03	0.85	0.02

[1] SEM, standard error of the mean values;

[2] T, chisel till; NT, no-till;

[3] CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SC, soybean-corn; SWC, soybean-wheat-corn; SSS continuous soybean; WCS, wheat-corn-soybean;

[4] _, no samples taken.

Table B.6. Mean values of pH, cation exchange capacity (CEC, cmol kg^{-1}), soil organic matter (SOM, %), carbon (C, %), nitrogen (N, %), carbon to nitrogen ratio (C/N), microbial biomass carbon (MBC, μg g^{-1}), and microbial biomass nitrogen (MBN, μg g^{-1}), determined by crop rotation (R) and tillage (T) and for each R and T combination.

Crop Rotation (R)	Tillage (T)	pH		CEC		SOM		C		N		C/N		MBC		MBN	
		Mean	SEM [1]	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM
CCC		5.34	0.19	39.36	2.13	4.06	0.07	2.62	0.07	0.21	0.00	12.82	0.21	54.69	5.60	4.06	0.69
CS		6.19	0.18	29.58	2.00	3.77	0.08	2.45	0.06	0.19	0.01	13.47	0.24	67.27	8.00	7.55	1.37
CSW		6.23	0.14	28.80	1.38	4.08	0.09	2.72	0.06	0.20	0.00	13.90	0.20	70.72	6.88	7.09	0.69
SSS		7.13	0.16	22.77	1.04	3.39	0.16	2.32	0.14	0.17	0.01	14.13	0.44	77.38	18.42	7.73	0.88
	T[2]	6.29	0.17	29.62	1.60	3.79	0.09	2.52	0.06	0.19	0.00	13.69	0.23	68.45	7.69	6.96	0.84
	NT	6.16	0.13	29.72	1.43	3.98	0.08	2.63	0.06	0.20	0.00	13.62	0.16	68.34	5.12	6.81	0.65
Rotation × Tillage																	
CCC[3]	T	5.08	0.21	41.51	2.62	3.96	0.08	2.51	0.06	0.20	0.00	12.60	0.30	48.91	6.10	3.92	1.14
CCC	NT	5.60	0.29	37.22	3.34	4.17	0.09	2.74	0.11	0.22	0.00	13.05	0.28	60.46	9.32	4.19	0.94
CS	T	5.78	0.32	37.40	3.63	3.83	0.09	2.48	0.09	0.20	0.01	12.87	0.37	62.33	14.72	7.53	4.40
CS	NT	5.76	0.24	33.97	2.78	4.09	0.11	2.63	0.04	0.20	0.01	13.52	0.46	72.08	10.06	3.37	1.08
CSW	T	5.87	0.36	32.72	3.69	4.26	0.27	2.81	0.14	0.21	0.01	13.70	0.37	65.96	6.77	2.90	0.81
CSW	NT	5.75	0.49	36.23	5.14	4.24	0.21	2.76	0.10	0.22	0.01	13.06	0.35	62.87	8.65	4.57	1.03
SC	T	6.75	0.33	23.22	1.54	3.45	0.18	2.27	0.15	0.17	0.01	13.83	0.62	44.85	8.30	8.34	1.78
SC	NT	6.47	0.32	23.72	2.26	3.70	0.12	2.44	0.15	0.18	0.01	13.67	0.51	89.84	23.21	10.98	1.94
SWC	T	6.80	0.21	23.63	1.73	3.76	0.27	2.48	0.26	0.18	0.01	13.76	0.63	94.17	39.34	9.33	0.95
SWC	NT	6.37	0.21	25.57	1.42	3.77	0.23	2.55	0.19	0.19	0.01	13.88	0.48	63.02	14.78	7.90	1.11
SSS	T	7.33	0.20	22.28	1.72	3.21	0.18	2.23	0.16	0.16	0.01	14.34	0.74	88.83	32.97	7.36	1.70
SSS	NT	6.94	0.25	23.26	1.39	3.56	0.27	2.41	0.24	0.17	0.01	13.92	0.58	65.94	20.22	8.11	0.78
WCS	T	6.40	0.34	26.59	1.56	4.08	0.06	2.84	0.08	0.20	0.00	14.74	0.67	74.14	4.98	9.34	1.81
WCS	NT	6.21	0.30	28.08	1.69	4.37	0.15	2.87	0.06	0.21	0.01	14.27	0.21	64.18	3.76	8.53	1.50

[1] SEM, standard error of the mean values;

[2] T, chisel till; NT, no-till;

[3] CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SC, soybean-corn; SWC, soybean-wheat-corn; SSS continuous soybean; WCS, wheat-corn-soybean;

[4] _, no samples taken.

Table B.7. Mean values of soil ammonia intensity (NH_4, mg-N $kg^{-1}day^{-1}$ during the growing season), soil nitrate intensity (NO_3, mg-N $kg^{-1}day^{-1}$ during the growing season), total soil nitrogen intensity(TIN, mg-N $kg^{-1}day^{-1}$ during the growing season), available phosphorus (Pa, mg kg^{-1}), potassium (K, mg kg^{-1}), sulfur (S, mg kg^{-1}), calcium (Ca, mg kg^{-1}), magnesium (Mg, mg kg^{-1}), and sodium (Na, mg kg^{-1}), determined by crop rotation (R) and tillage (T) and for each R and T combination.

Crop Rotation (R)	Tillage (T)	NH_4		NO_3		TIN		Pa		K		S		Ca		Mg		Na	
		Mean	SEM [1]	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM
CCC		3.00	0.76	6.00	1.01	9.00	1.72	13.56	1.27	196.94	19.92	8.09	0.33	3515.06	156.59	436.47	24.29	16.97	1.26
CS		1.10	0.17	2.57	0.24	3.67	0.35	8.59	1.13	146.52	7.76	7.47	0.27	3503.31	115.83	459.48	15.40	18.98	0.62
CSW		1.55	0.40	3.46	0.68	5.03	0.87	9.87	0.90	164.48	8.55	7.56	0.31	3560.91	86.90	440.49	14.20	17.06	0.59
SSS		0.53	0.04	1.44	0.13	1.98	0.16	17.50	4.00	134.31	12.97	6.56	0.22	3352.00	149.92	488.31	18.77	17.13	0.85
	T [2]	1.37	0.21	3.37	0.43	4.75	0.57	11.12	1.14	150.71	7.27	7.52	0.18	3490.98	81.57	461.17	11.77	17.76	0.48
	NT	1.61	0.43	3.09	0.59	4.70	0.97	11.12	1.30	168.63	9.03	7.42	0.29	3525.13	83.23	443.18	13.02	17.46	0.61
Rotation × Tillage																			
CCC [3]	T	2.45	0.56	5.03	0.50	7.48	0.74	13.50	1.65	195.25	11.74	8.44	0.56	3348.63	203.94	419.06	35.47	16.31	1.96
CCC	NT	3.56	1.48	6.97	1.97	10.53	3.43	13.63	2.18	198.63	41.38	7.75	0.32	3681.50	233.17	453.88	35.96	17.63	1.82
CS	T	1.04	0.33	1.72	0.06	2.77	0.36	12.13	3.13	145.31	21.48	8.00	0.31	3873.25	189.36	502.13	32.55	19.94	0.50
CS	NT	0.98	0.39	2.66	0.47	3.64	0.83	9.50	1.58	161.00	11.33	7.00	0.54	3697.63	137.35	459.00	20.55	18.50	1.72
CSW	T	0.81	0.17	1.96	0.31	2.85	0.46	9.69	0.84	168.63	24.50	7.63	0.38	3625.88	195.37	445.19	34.74	17.19	0.90
CSW	NT	1.88	1.22	1.53	0.44	3.41	1.51	12.06	3.82	195.19	27.81	7.06	0.66	3614.94	141.44	429.88	33.57	15.81	1.82
SC	T	1.28	0.41	3.33	0.50	4.60	0.78	5.75	1.45	125.38	16.29	7.19	0.47	3270.19	205.04	459.50	32.93	18.25	0.63
SC	NT	1.09	0.35	2.58	0.46	3.67	0.68	7.00	1.75	154.38	10.47	7.69	0.79	3172.19	242.28	417.31	31.24	19.25	1.90
SWC	T	1.47	1.01	4.14	0.39	5.61	0.87	6.87	1.15	128.75	5.88	7.31	0.37	3469.81	264.08	451.63	33.86	17.75	1.31
SWC	NT	_ [4]	_	_	_	_	_	9.56	2.81	139.00	6.67	7.31	0.73	3491.44	345.90	426.56	53.94	16.13	1.68
SSS	T	0.51	0.04	1.19	0.08	1.70	0.07	18.38	5.13	125.38	9.36	6.50	0.35	3320.88	277.88	499.50	16.49	16.13	1.16
SSS	NT	0.55	0.08	1.69	0.18	2.25	0.26	16.62	6.93	143.25	25.38	6.63	0.31	3383.13	164.38	477.13	35.91	18.13	1.16
WCS	T	2.06	0.58	6.20	2.02	8.26	2.38	11.56	1.60	166.31	17.11	7.56	0.39	3528.25	162.95	451.19	30.26	18.75	1.61
WCS	NT	_	_	_	_	_	_	9.50	2.19	189.00	21.30	8.50	1.59	3635.13	253.66	438.50	42.11	16.75	1.60

[1] SEM, standard error of the mean values;

[2] T, chisel till; NT, no-till;

[3] CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SC, soybean-corn; SWC, soybean-wheat-corn; SSS continuous soybean; WCS, wheat-corn-soybean;

[4] _, no samples taken.

Table B.8. Mean values of boron (B, mg kg^{-1}), iron (Fe, mg kg^{-1}), manganese (Mn, mg kg^{-1}), copper (Cu, mg kg^{-1}), zinc (Zn, mg kg^{-1}), and aluminum (Al, mg kg^{-1}), determined by crop rotation (R) and tillage (T) and for each R and T combination.

Crop Rotation (R)	Tillage (T)	B		Fe		Mn		Cu		Zn		Al	
		Mean	SEM [1]	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM
CCC		0.60	0.04	158.41	10.26	82.28	5.14	3.02	0.23	2.54	0.16	670.78	47.55
CS		0.68	0.02	125.84	6.24	75.06	4.00	2.89	0.14	2.52	0.08	627.88	24.08
CSW		0.66	0.02	125.95	5.54	66.34	2.07	2.73	0.06	2.76	0.09	638.67	20.51
SSS		0.70	0.02	113.81	8.52	80.75	4.33	3.16	0.20	2.66	0.23	586.38	36.09
	T[2]	0.67	0.02	120.71	4.95	76.04	2.97	2.85	0.09	2.56	0.09	624.25	18.52
	NT	0.65	0.02	136.94	5.54	70.29	2.27	2.90	0.10	2.72	0.08	641.15	21.13
Rotation × Tillage													
CCC[3]	T	0.59	0.07	156.44	15.79	88.81	1.57	2.93	0.36	2.40	0.24	680.19	78.85
CCC	NT	0.61	0.03	160.38	15.46	75.75	9.62	3.10	0.34	2.68	0.23	661.38	65.38
CS	T	0.66	0.03	122.50	10.58	83.44	10.13	3.12	0.31	2.53	0.16	606.38	35.16
CS	NT	0.66	0.02	131.63	11.94	73.38	8.12	2.93	0.27	2.61	0.23	603.63	40.22
CSW	T	0.67	0.03	120.81	13.77	66.06	7.19	2.66	0.15	2.64	0.20	628.75	46.33
CSW	NT	0.59	0.05	141.81	20.13	71.81	4.32	2.79	0.23	2.68	0.09	675.81	71.43
SC	T	0.70	0.05	114.31	11.18	72.19	7.77	2.70	0.25	2.43	0.16	639.06	48.08
SC	NT	0.72	0.03	134.94	17.70	71.25	7.68	2.81	0.35	2.51	0.10	662.44	75.13
SWC	T	0.69	0.04	103.00	5.40	73.81	7.08	2.69	0.18	2.39	0.23	624.81	65.73
SWC	NT	0.67	0.07	130.94	11.53	66.13	2.16	2.63	0.23	2.70	0.22	660.69	60.98
SSS	T	0.71	0.02	106.13	9.80	86.50	7.63	3.07	0.29	2.59	0.32	579.88	47.73
SSS	NT	0.69	0.03	121.50	14.25	75.00	2.68	3.24	0.32	2.74	0.38	592.88	61.42
WCS	T	0.68	0.04	121.75	11.23	61.50	3.47	2.80	0.08	2.97	0.27	610.69	33.91
WCS	NT	0.65	0.04	137.38	14.17	58.75	1.98	2.81	0.13	3.17	0.11	631.25	43.75

[1] SEM, standard error of the mean values;
[2] T, chisel till; NT, no-till;
[3] CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SC, soybean-corn; SWC, soybean-wheat-corn; SSS continuous soybean; WCS, wheat-corn-soybean;
[4] _, no samples taken.

Table B.9. Pearson correlation matrix among greenhouse gas emissions, yield index, and soil physical and chemical properties from Monmouth, IL. Variable include yield index (YdI), nitrous oxide (N_2O), carbon dioxide (CO_2), methane (CH_4), yield index (YdI), sand, silt, clay, average soil moisture (Ho), permanent wilting point (PWP), plant available water (PAW), bulk density (Bd), water aggregate stability (WAS), pH, cation exchange capacity (CEC), soil organic matter (SOM), carbon (C), nitrogen (N), carbon to nitrogen ratio (C/N), microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), soil ammonia intensity (NH_4), soil nitrate intensity (NO_3), total soil nitrogen intensity(TIN), available phosphorus (Pa), potassium (K), sulfur (S), calcium (Ca), magnesium (Mg), sodium (Na), boron, (B), iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), and aluminum (Al).

	YdI	N2O	CO2	CH4	Sand	Silt	Clay	Ho	PWP	PAW	BD	WAS	pH	CEC	SOM	C	N	C/N	MBC	MBN	NH4	NO3	TIN	Pa	K	Sul	Ca	Mg	Na	Bor	Fe	Mn	Cu	Zn	Al
YdI	1.00																																		
N2O	-0.19	1.00																																	
CO2	-0.01	**0.59**	1.00																																
CH4	0.03	**0.30**	0.03	1.00																															
Sand	0.12	0.15	0.24	0.07	1.00																														
Silt	0.10	**-0.26**	0.09	-0.09	-0.01	1.00																													
Clay	-0.13	0.23	-0.14	0.07	-0.20	**-0.98**	1.00																												
Ho	-0.13	0.14	0.03	-0.09	0.22	0.01	-0.05	1.00																											
PWP	**-0.42**	-0.13	**-0.45**	-0.06	-0.19	-0.18	0.23	**0.62**	1.00																										
PAW	0.13	**0.45**	**0.48**	0.14	-0.01	0.00	0.01	-0.16	**-0.54**	1.00																									
BD	-0.25	0.04	0.02	0.02	0.21	0.17	-0.21	**0.29**	-0.02	-0.13	1.00																								
WAS	-0.22	-0.10	-0.13	-0.09	-0.18	**-0.34**	**0.37**	0.24	**0.53**	**-0.32**	-0.02	1.00																							
pH	0.09	**-0.41**	**-0.53**	0.08	-0.21	0.24	-0.19	-0.15	0.15	**-0.29**	-0.04	**-0.26**	1.00																						
CEC	-0.18	**0.39**	**0.48**	-0.22	0.15	**-0.30**	**0.26**	0.21	0.11	0.24	-0.05	**0.28**	**-0.87**	1.00																					
SOM	0.02	**0.28**	**0.30**	-0.09	**0.30**	-0.11	0.05	**0.39**	0.23	0.12	0.13	**0.32**	**-0.56**	**0.59**	1.00																				
C	0.02	0.20	0.07	-0.12	0.22	-0.12	0.07	**0.49**	**0.44**	0.06	0.11	0.24	**-0.27**	**0.38**	**0.89**	1.00																			
N	-0.11	**0.28**	**0.27**	-0.15	**0.37**	-0.11	0.03	**0.35**	0.20	0.06	0.25	**0.32**	**-0.65**	**0.67**	**0.91**	**0.81**	1.00																		
C/N	0.18	-0.16	**-0.33**	0.00	-0.17	-0.05	0.09	**0.29**	**0.47**	-0.12	-0.17	-0.05	**0.53**	**-0.36**	0.07	**0.43**	-0.17	1.00																	
MBC	0.10	-0.08	-0.20	0.08	-0.11	0.05	-0.03	0.07	**0.32**	-0.22	-0.04	0.03	0.20	-0.08	0.22	**0.39**	0.11	**0.47**	1.00																
MBN	**0.31**	-0.15	**-0.30**	0.14	-0.21	**-0.27**	**0.31**	-0.06	0.13	**-0.28**	-0.13	0.09	0.21	**-0.31**	-0.13	0.00	-0.23	**0.34**	**0.34**	1.00															
NH4	**-0.26**	**0.44**	0.09	**0.39**	0.25	**-0.30**	0.24	0.12	0.07	0.00	0.10	0.17	-0.22	0.23	0.22	0.17	**0.34**	-0.22	-0.14	-0.17	1.00														
NO3	-0.20	**0.57**	0.12	**0.32**	**0.39**	-0.22	0.13	0.09	-0.13	**0.30**	0.01	0.00	-0.14	0.12	0.18	0.13	0.22	-0.16	-0.11	-0.09	**0.65**	1.00													
TIN	-0.24	**0.57**	0.12	**0.38**	**0.36**	**-0.27**	0.19	0.11	-0.05	0.19	0.05	0.07	-0.18	0.18	0.22	0.16	**0.29**	-0.20	-0.13	-0.13	**0.86**	**0.95**	1.00												
Pa	-0.19	0.07	0.01	0.13	-0.06	0.04	-0.03	0.18	0.22	0.14	-0.15	0.00	-0.07	0.17	0.19	0.24	0.20	0.14	0.10	-0.11	0.06	0.05	0.06	1.00											
K	**-0.25**	**0.38**	0.23	0.07	**0.26**	-0.20	0.15	0.19	-0.10	0.09	0.15	0.14	**-0.40**	**0.29**	**0.38**	0.18	**0.44**	**-0.36**	-0.19	**-0.33**	**0.53**	**0.39**	**0.49**	0.18	1.00										
Sul	0.09	**0.31**	**0.46**	0.06	**0.39**	**0.29**	**-0.36**	-0.18	**-0.58**	**0.45**	0.20	-0.25	**-0.35**	0.18	0.04	-0.12	0.16	**-0.51**	**-0.33**	-0.18	0.13	**0.27**	0.24	-0.17	0.21	1.00									
Ca	0.07	0.09	-0.03	-0.16	0.04	**-0.33**	**0.31**	0.24	**0.58**	-0.18	-0.14	0.20	-0.02	**0.29**	**0.38**	**0.50**	**0.29**	**0.42**	**0.27**	0.09	0.16	0.03	0.09	0.21	0.09	**-0.38**	1.00								
Mg	-0.01	-0.05	-0.23	-0.07	-0.13	-0.21	0.23	0.09	**0.60**	-0.22	-0.20	0.05	**0.52**	-0.13	-0.05	0.21	-0.13	**0.58**	**0.27**	0.09	0.05	-0.05	-0.01	0.16	-0.20	**-0.54**	**0.72**	1.00							
Na	0.18	0.01	**0.28**	-0.05	0.14	0.16	-0.18	-0.23	**-0.39**	**0.35**	0.14	-0.01	-0.20	0.02	-0.05	-0.20	-0.03	**-0.33**	**-0.29**	0.15	-0.14	0.10	0.01	-0.06	-0.05	**0.42**	**-0.25**	**-0.33**	1.00						
Bor	0.14	-0.12	**-0.30**	-0.08	-0.19	0.06	-0.02	-0.07	**0.27**	-0.05	-0.13	-0.15	**0.69**	**-0.47**	-0.24	0.05	**-0.32**	**0.57**	0.24	0.25	-0.11	-0.08	-0.10	0.03	**-0.30**	**-0.39**	**0.43**	**0.74**	-0.14	1.00					
Fe	-0.25	**0.33**	**0.39**	0.02	-0.03	**-0.32**	**0.32**	0.19	0.01	0.24	0.04	0.22	**-0.79**	**0.68**	**0.50**	**0.29**	**0.49**	**-0.27**	-0.17	0.00	0.20	0.14	0.18	**0.26**	**0.26**	0.15	0.04	**-0.41**	0.21	**-0.55**	1.00				
Mn	-0.16	0.14	0.19	0.01	-0.20	0.19	-0.15	-0.25	**-0.25**	**0.36**	0.11	**-0.32**	0.03	0.15	**-0.34**	**-0.39**	-0.18	**-0.39**	-0.15	**-0.46**	0.06	0.02	0.04	0.16	-0.03	0.09	-0.12	0.04	0.07	0.02	-0.10	1.00			
Cu	-0.16	0.15	-0.07	-0.03	**-0.36**	-0.23	**0.30**	0.19	**0.64**	-0.04	-0.17	0.18	0.13	0.18	0.11	**0.30**	0.04	**0.45**	0.23	0.13	0.09	0.02	0.05	**0.41**	-0.22	**-0.50**	**0.65**	**0.72**	-0.12	**0.48**	0.13	0.15	1.00		
Zn	0.13	0.10	-0.01	0.08	-0.14	0.07	-0.04	**0.28**	0.21	-0.03	0.02	0.13	-0.05	0.08	**0.46**	**0.53**	**0.35**	**0.30**	0.24	0.11	0.10	0.07	0.09	**0.47**	0.11	-0.15	**0.46**	0.19	-0.16	0.18	0.22	-0.10	**0.42**	1.00	
Al	-0.05	0.02	**0.29**	0.01	0.13	0.03	-0.06	-0.15	**-0.49**	0.20	0.09	0.01	**-0.57**	**0.29**	0.05	**-0.27**	0.09	**-0.62**	**-0.42**	-0.11	0.02	0.05	0.04	-0.17	**0.27**	**0.53**	**-0.56**	**-0.83**	**0.41**	**-0.75**	**0.55**	-0.01	**-0.62**	**-0.30**	1.00

APPENDIX C: SUPPLEMENTAL TABLE FOR CHAPTER 4

Table C.1. Number of observations, season of sampling, and year of sampling originally included for each variable throughout the study (2013–2017) from Urbana, IL.

Variable	No. of Obs.	Season of Sampling [1]	Year(s) of Sampling
NH_4	192	Winter & Spring	2013-2017
NO_3	192	Winter & Spring	2013-2017
TIN	192	Winter & Spring	2013-2017
N_2O	192	Winter & Spring	2013-2017
CO_2	192	Winter & Spring	2013-2017
CH_4	192	Winter & Spring	2013-2017
Stand	144	Fall	2014-2016
Bio	54	Spring	2013-2017
Yield	239	Fall	2013-2017

[1] Spring, March–May; Summer, June–August; Fall, September–November; Winter, December–February.