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

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ABSTRACT

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

1. Introduction

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

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

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

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

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

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

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

2. Materials and methods

2.1. Site characterization and experimental layout

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

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

2.2. Gas sampling procedures

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

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