Tillage and crop rotation impacts on greenhouse gas fluxes from soil at two long-term agronomic experimental sites in Ohio

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Abstract: Soils may be a source or sink of greenhouse gases (carbon dioxide [CO_2], nitrous oxide [N_2O], and methane [CH_4]) that lead to global warming and climate change. While it is known that greenhouse gases are naturally cycled through soil and are part of the carbon (C) and nitrogen (N) cycles, it is not fully understood what effect crop production practices have on this cycling. Therefore, a study was conducted at the longest, continually maintained no-tillage plots in the world at Wooster (50 years no-till), near Wooster, Ohio, and Hoytville (49 years no-till), near Custar, Ohio, that represent two contrasting Ohio soils. Fluxes of greenhouse gases were measured by gas chromatography (GC) biweekly and following rainfall events greater than 1.2 cm (0.5 in) during the growing season of the corn (*Zea mays* L.), starting in July of 2011 until October of 2011, and then from May of 2012 to July of 2012. Samples were obtained at both sites in plots with rotations of corn after corn (CC) and corn after soybean (*Glycine max* L.) (CS), and when soils were managed using no-tillage (NT) and chisel or minimum conservation tillage (MT). Comparisons statistically significant at the $p < 0.10$ level are as follows. For CO_2 , the CS rotation yielded lower emissions than the CC at both sites, due to less biomass cycling. For N_2O , the CS rotation yielded lower emissions than the CC at both sites due to less total N fertilizer input in the CS than the CC rotation. The NT system resulted in lower N_2O emissions than the MT system at Hoytville, but not at Wooster. For CH_4 , soil in the long-term plots often acted as sinks. Global warming potentials were lower for Hoytville than Wooster and lower for rotation of CS than CC at both Hoytville and Wooster. Overall, after about 50 years, it is evident that the use of no-tillage combined with crop rotations can lead to improved environmental (i.e., greenhouse gas emissions and global warming potential) benefits.

Key words: No-tillage—crop rotation—greenhouse gases—methane—nitrous oxide—carbon dioxide

Global climate change, experienced as an increase in the average measured temperature of the earth's near surface air and oceans, is increasingly recognized as a threat to our planet's sustainability (Hsu et al. 2010). Temperature increase is mainly attributed to greenhouse gases accumulating in the atmosphere. Greenhouse gases (GHG), such as water, carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) absorb solar energy and trap it so that it cannot be emitted back into the atmosphere, thus raising the temperature of the earth's atmosphere (Hsu et al. 2010; Pant 2009). Due to the overall size and the nature of agricultural activities, agriculture now supplies from 3%

to 4% of the anthropogenic CO_2 , 30% to 80% of the anthropogenic N_2O , and 10% to 60% of the anthropogenic CH_4 emissions to the atmosphere (Flessa et al. 2002; Grant et al. 2004; Hsu et al. 2010; Konyar 2001; Pant 2009). Overall, agriculture contributes 14% of anthropogenic GHG emissions to the atmosphere (USEPA 2006).

Carbon dioxide emissions from soil mostly come from decomposition of soil organic matter such as residues and litter (Lal 1997). Microbial populations, using reduced carbon (C) compounds as an energy source account for the largest percentage of agricultural CO_2 emissions from the soil directly. However, this CO_2 often has a neutral effect on atmo-

spheric CO_2 levels unless it takes C stored in soil for thousands of years and converts it to CO_2 . When a soil is at equilibrium in regards to soil organic C concentrations, the soil is neither a source nor sink of CO_2 .

Nitrous oxide is mainly produced through denitrification processes in the soil. Denitrifying bacteria are most commonly facultative anaerobes and can survive under aerobic conditions in soil as well as where O_2 is devoid. Some research has shown that conservation tillage, especially no-tillage, results in greater amounts of N_2O emissions than do intensive tillage systems (Flessa et al. 2002; Grant et al. 2004; Halvorson et al. 2006; Koga et al. 2006). This is attributed to the residue left by conservation tillage keeping the soil wetter and providing energy to the denitrifying microorganisms. However, other research indicates that no-tillage produces less N_2O than does conventional tillage (i.e., moldboard plow or chisel tillage) (Omonode et al. 2011). This was attributed to conventional tillage causing more soil organic C decomposition due to higher levels of soil-residue mixing and higher soil temperatures. No-tillage (NT) or chisel or minimum conservation tillage (MT) can also maintain higher soil moisture levels and surface soil organic matter than where more intensive tillage practices are used. These conditions can lead to both increased nitrate (NO_3^-) levels and more anaerobic microsites that, in turn, lead to increase N_2O production.

Soils can be a source for CH_4 with most production due to methanogenic bacteria in flooded soils such as those in rice paddies (Cole et al. 1997; Ishizuka et al. 2005). Soils can also be sinks of CH_4 when methanotrophic bacteria take up CH_4 to oxidize it for energy production (Adhya et al. 1998). There is evidence that tillage reduces this oxidation in soils leading to less CH_4 removal (Adhya et al. 1998). If this is the case, NT should be more beneficial because it can increase CH_4 oxidation and thus serve as a sink for atmospheric CH_4 . This was observed for a no-tillage chronosequence in Ohio (Jacinthe et al. 2014).

Although research has been performed on the effects of tillage on GHG emissions

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(MacKenzie et al. 1997; Omonode et al. 2011; Venterea et al. 2005; Jacinthe and Dick 1997), most has focused on comparing traditional plow tillage with conservation tillage. As traditional plow tillage is becoming less used in Ohio and elsewhere in North America, a comparison of the now more common conservation tillage practices, such as chisel tillage with no-tillage is considered more relevant.

Crop rotation is another production variable that impacts GHG emissions. With the advent of greater use of corn (*Zea mays* L.) as a feedstock for biofuels production as well as the traditional uses as an animal feed and other end uses, corn is increasingly being continuously grown without rotation with other crops. This results in more total fertilizer input to soil. Also, crop rotation effects on GHG emissions are normally limited to looking at the difference between different crops rather than emissions from the same crop in a rotation, e.g., emissions from a cornfield where the previous year's crop was corn in comparison to when the previous year's crop was soybean (*Glycine max* L.) or other crops.

Soil properties, such as texture, are known to affect biological processes like N_2O production. However, texture was not found to significantly affect N_2O emissions during the wheat-growing season from 18 Chinese paddy soils (Huang et al. 2002). In contrast, Jarecki et al. (2008) found that cumulative N_2O emissions were greater from a sandy loam soil than from a clay soil. The authors speculated it was due to the higher cation exchange capacity (CEC) in the clay soil reducing nitrogen (N) availability through increased adsorption of NH_4^+ . Similarly, a loam soil was found to emit more of the applied fertilizer as N_2O than did a clay soil (Weitz et al. 2001).

In this study, we evaluated the effects of crop rotation and tillage on GHG fluxes from two contrasting soils in Ohio under similar climactic situations.

Materials and Methods

Site Characteristics. Two long-term experimental sites in Ohio were used for this research. The overall soil and terrain properties of the Wooster and Hoytville sites have been previously described (Dick et al. 1986a; Dick et al. 1986b; Dick et al. 1991). However, it is important to note that these soils are contrasting in texture with the Wooster site soil

being a silt loam (14% clay) and the Hoytville site soil being a silty clay loam (31% clay). While three tillage treatments (NT, MT, and plow-tillage [PT]) and three crop rotations (continuous corn after corn [CC], corn after soybean [CS], and corn after oats (*Avena sativa* L.) and meadow hay [COM]) were present on the fields; only soil from plots of the NT and MT treatments and the CC and CS crop rotations were sampled.

Crop rotations at both sites consist of a CC rotation and a CS rotation. The corn hybrid and soybean varieties grown differed over the years and were selected to maximize yield on each soil type. The plots were set up in a completely randomized block design with three replicates. Every crop was grown each year so that every year there was a corn crop following either a corn crop or a soybean crop. Temperature and precipitation data at each site are provided in figure 1.

Tillage operations were either MT (i.e., chisel plow) or NT. The chisel plow was equipped with 15 slightly curved shanks 13 cm (5 in) in width and pulled through the soil to a depth of 15 to 20 cm (6 to 8 in). This method prepares the seedbed for planting while leaving much of the residues on the soil surface. The amount of residue on the soil surface exceeded 30% cover (as deemed necessary to be conservation tillage), but by the end of the growing season the residue had mostly disappeared from the soil surface. Tillage was conducted from opposite directions every other year at both Wooster and Hoytville to avoid creating any rills in the soil and reduce tillage erosion. A tandem disc (3 m [10 ft] width) or field cultivator (4.5 m [15 ft] width) was used to prepare the final seedbed prior to planting. Primary tillage (i.e., chisel tillage) occurred in the fall at the Hoytville site, with secondary tillage in the spring. For the Wooster site, both primary and secondary tillage occurred in the spring. Corn was planted on June 4, 2011, and May 6, 2012, at the Wooster site, and June 6, 2011, and April 24, 2012, at the Hoytville site. Soil characteristics for the Wooster and Hoytville sites are summarized in table 1.

Nitrogen was applied as liquid urea-ammonium nitrate at a rate of 202 kg N ha⁻¹ (180 lb N ac⁻¹) at Wooster and 224 kg N ha⁻¹ (200 lb N ac⁻¹) at Hoytville for the CC plots and 168 kg N ha⁻¹ (150 lbs N ac⁻¹) at Wooster and 190 kg N ha⁻¹ (170 lb N ac⁻¹) at Hoytville only to the corn plots of the CS rotation. Application dates for N fertilizer

were June 29, 2011, and June 11, 2012, at the Wooster site, and June 21, 2011, and June 6, 2012, at the Hoytville site.

Experimental Setup. Gas samples were collected from the individual plots at each site. Gas collection chambers were constructed of PVC pipe with an inner diameter of 30 cm (11.8 in), a height of 20.5 cm (8 in) above the soil, and a thickness of 1 cm (0.4 in) (Campbell 2012). The bottom edge of the chamber has an approximately 2.5 cm (1 in) beveled edge with the sharp edge on the inside of the PVC wall. This allows easier insertion into the soil with less compaction. The top edge of the chamber is lined with a gas resistant rubber gasket to help create a tighter seal with the lid. The chamber lid consists of a solid piece of PVC 1 cm (0.4 in) thick and 30 cm (11.8 in) in diameter with the same rubber sealing along the edge. In the center of the lid, a 1 cm (0.4 in) diameter grey butyl rubber septum is placed. A syringe is pushed through the septum to gather air samples from within the sealed chamber.

Gas collection chambers were placed approximately 2 to 3 m (6.5 to 9.8 ft) from the edge of the plot into the field in late June of 2011. Two chambers were used per plot, placed in between the center rows of each plot. The chambers were not removed once they were placed in the ground until the last sampling right before harvesting of the corn crop in late November. In 2012, chambers were again placed approximately 2 to 3 m (6.5 to 9.8 ft) from the edge of the plot into the field. Two chambers were used per plot, but this time one was placed in the center of the row and one was placed within the corn row. This was done to assess whether chamber placement affected the gas fluxes measured, but comparisons of flux data from in the row or between the rows showed no statistical differences (Campbell 2012). Thus, the effect of chamber placement was ignored when making calculations for the 2012 data. The chambers were placed in early May and sampled until mid-July when the drought conditions of 2012 resulted in almost no GHG emissions.

Chambers were sampled biweekly, and additional samplings were conducted following any rainfall event greater than 1.2 cm (0.5 in) total. Plants within the chambers were removed throughout the sampling period so that fluxes represent only those from soil. Initial samples were taken after the lid was sealed over the soil, i.e., at time zero. Samples

Figure 1

(a) Temperature (monthly average) and (b) precipitation (monthly total) data for the Wooster and Hoytville sites during the time of gas flux measurements.

were then taken from the chamber 30 and 60 minutes later in the same manner. After sampling was completed, the lids were removed and the soil in the chamber was exposed to natural weather conditions. Each gas sample

collected was placed into separate 15 mL (0.3 in³) labeled glass vials that were crimp-sealed with gray butyl rubber septa used as stoppers. Prior to sampling, the vials were evacuated to a pressure of <0.06 kPa.

Gas Sample Analysis. Concentrations of CO₂, N₂O, and CH₄ were determined using a Varian CP3800 gas chromatograph (Palo Alto, California). The gas chromatograph was equipped with thermal conductivity (TCD), flame ionization (FID), and electron capture (ECD, ⁶³Ni) detectors for analyses of CO₂, CH₄, and N₂O, respectively. The carrier gas was ultra-high purity (UHP) He (Helium) set at a 20 mL min⁻¹ rate for the analysis of CO₂, CH₄, and UHP N₂ set at a 60 mL min⁻¹ rate for analysis of N₂O. The oven temperature was set to 90°C (194°F), detector temperatures were set to 150°C (302°F) for TCD and FID, and 300°C (572°F) for ECD. A precolumn of 0.3 m (0.9 in) length and 2 mm (0.07 in) inner diameter was placed before the analytical column of 1.8 m (5.9 ft) length and 2 mm (0.07 in) inner diameter. The columns were packed with Porapak Q of 80 to 100 mesh. The analytical column was baked at 150°C (302°F) for 10 minutes after every 20 samples that were run on the instrument. For calibration, gas standards from Altech (Deerfield, Illinois) and Air Liquide (Troy, Michigan) were run. Standards concentrations ranged from 100 to 1000 µL CO₂ L⁻¹, 1.7 to 100 µL CH₄ L⁻¹, and 0.1 to 1 µL N₂O L⁻¹.

Concentrations for each gas were determined in ppm from the gas chromatograph. From here, concentrations were turned into flux values of g CO₂-C m² d⁻¹, mg CH₄-C m² d⁻¹, and mg N₂O-N m² d⁻¹ using the following relationship:

$$F = \frac{\Delta C}{\Delta t} \times \frac{V}{A} \times k, \quad (1)$$

where $\Delta C/\Delta t$ equals the rate of gas accumulation inside of the chamber in ppm min⁻¹, V equals the volume of the chamber in L, A equals the area of the chamber in cm², and k equals the conversion factors needed for time (1,440 min d⁻¹) and volume (g L⁻¹ gas at STP).

The global warming potential (GWP) of each site was also determined using 100-year radiative forcing values, as determined by the

Table 1

Surface soil properties from the Wooster (0 to 3 cm) and Hoytville (0 to 5 cm) sites collected in 2005.

Site	Type	pH	Bulk density (Mg m ⁻³)	Total carbon (%)	Total nitrogen (%)	Sand (%)	Silt (%)	Clay (%)
Wooster	Silt loam	5.5	1.49	3.47	0.317	13.8	72.5	13.7
Hoytville	Clay	6.0	1.01	3.88	0.333	16.7	52.8	30.6

Intergovernmental Panel on Climate Change (IPCC) (Parry et al. 2007). The forcing values were 1 for CO₂, 25 for CH₄, and 298 for N₂O. This means that CH₄ is 25 times more effective at trapping radiative emissions in the atmosphere than CO₂ over a 100 year timespan. All of the greenhouse gas fluxes were converted to CO₂ equivalents in calculating the global warming value for each site.

Data Analysis. A repeated measures general linear model (GLM) analysis of variance test (ANOVA) with Tukey's multiple comparisons was performed at the $\alpha = 0.1$ significance level using MiniTab 15 software. A GLM-ANOVA procedure was used since it works with unbalanced factors and fixed and/or random factors, such as those used in this analysis.

Results and Discussion

Effects of Crop Rotation on Greenhouse Gas Fluxes. Greenhouse gas fluxes as affected by crop rotation at Wooster are presented in figure 2. For CO₂ and N₂O emissions, there were significant differences between the CC and the CS rotation (table 2), and the CC rotation resulted in higher emissions than did the CS rotation (figure 2a and 2c). The emission rates of N₂O were similar to the results reported by Venterea et al. (2005) and Parkin and Kaspar (2006). The CH₄ gas flux analysis revealed there was no significant difference between the CC and the CS rotation, while interactions of crop rotation with tillage and date were significant (table 2). The interaction of date and crop rotation showed that CH₄ emissions under the CC rotation were higher than the emissions under the CS rotation on some dates but reversed on other sample collecting dates (figure 2b).

For N₂O emissions, the total amount of N fertilizer applied to the CC plots totals more than that applied to the CS plots due to fertilizer applied every year for the CC rotation plots but only every other year for the CS rotation plots. This explains the higher N₂O emissions from the CC plots compared to the CS plots. The greater amount of residue also provides an energy (electron) source for denitrifiers in the soil as well as maintaining more water in the soil profile (Alvarez and Steinbach 2009). Both of these factors lead to increased N₂O emissions. Flessa et al. (2002) found that the greater the coverage of residue, the larger the emissions of N₂O from the soil. The interaction of crop rotation with date was also significant for N₂O emissions (table 2). On July

Figure 2

Greenhouse gas fluxes as affected by crop rotation from the Wooster site. The * shows a difference between corn following corn and corn following soybean at $p \leq 0.10$ at specific sample dates.

Table 2Analysis of variance (ANOVA) for carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) fluxes from the Wooster site.

Factor	Degrees of freedom	Adjusted sum of squares	Adjusted mean square	F-test	p-value
CO ₂					
Rotation	1	1.565	1.565	4.35	0.039
Tillage	1	2.049	2.049	5.70	0.019
Date	12	54.234	4.520	12.56	<0.001
Rotation × tillage	1	0.727	0.727	2.02	0.158
Rotation × date	12	4.464	0.372	1.03	0.423
Tillage × date	12	11.555	0.963	2.68	0.003
CH ₄					
Rotation	1	0.001	0.001	0.19	0.664
Tillage	1	0.054	0.054	7.68	0.007
Date	12	0.911	0.760	10.81	<0.001
Rotation × tillage	1	0.021	0.021	2.93	0.089
Rotation × date	12	0.149	0.149	1.76	0.062
Tillage × date	12	0.665	0.055	7.89	<0.001
N ₂ O					
Rotation	1	832.500	832.500	26.37	<0.001
Tillage	1	5.770	5.770	0.18	0.670
Date	12	9,402.490	783.540	24.82	<0.001
Rotation × tillage	1	3.810	3.810	0.12	0.729
Rotation × date	12	3,348.780	279.060	8.84	<0.001
Tillage × date	12	2,165.900	180.490	5.72	<0.001

12, 2011, and June 19, 2012, N₂O emissions for the CC were higher than the N₂O emissions from the CS (figure 2c). Both of these dates released higher emissions than any other sampling date for either CC or CS. It should be noted that both of these dates were sampled following rainfall and were also about one month following fertilizer application.

Fertilizers, especially N fertilizers, are known to influence N₂O emissions when applied at different rates and types (Bouwman 1996; MacKenzie et al. 1997; Venterea et al. 2005). For example, NO₃⁻ from fertilizers or after nitrification of ammonium-based fertilizers become the substrate for denitrification reactions. This is one reason for the large spike seen in the N₂O emissions after N fertilizer additions to soil. Molodovskaya et al. (2012) also reported episodic behavior of intermittent, short-duration but high intensity peak fluxes of N₂O-N emissions. Fertilizer that is applied in the months prior to sampling is converted to NO₃⁻, and when the soil or microsites within the soil become saturated following rainfall, denitrification occurs. Nitrates are also produced when organic matter goes through the process of mineralization to release NH₄, followed by nitrification. In the early spring, when there is not yet a growing crop to take up the

NO₃⁻ and when soils tend to be wetter, the potential for N₂O production is high, and this was seen in our data.

Effects of Tillage on Greenhouse Gas Fluxes. Greenhouse gas fluxes as affected by tillage from Wooster are presented in figure 3. For CO₂ and CH₄ fluxes, there were significant differences between the MT and the NT (table 2). The interaction of tillage with date was significant for CO₂, CH₄, and N₂O. For CO₂, the emissions for MT were larger than emissions for NT on August 15, 2011 (figure 3a). The lower emissions of CO₂ coming from the NT plots suggest that less C was being lost from soil, and C sequestration was occurring as was noted by Kumar et al. (2012). In contrast, as the chisel plow runs through the soil it breaks up soil aggregates. The soil aggregates contain trapped C and nutrients that were previously unavailable to the atmosphere or microorganisms for decomposition. The newly exposed soil organic C is also oxidized leading to increased CO₂ emissions from the MT site and less or no C sequestration compared to NT.

For CH₄, soil generally acted as a sink and removed CH₄ from the atmosphere above the soil (figure 3b). This is the reason for the mostly negative flux values. The NT soil was less effective as a sink for CH₄

than MT on July 19, 2011, and June 14, 2012. On most other dates the reverse was true. Bronson and Mosier (1994) found that as the amount of mineral N (i.e., NH₄) in the soil was increased, the oxidation of CH₄ was inhibited and more could be emitted to the atmosphere. Thus the amount of CH₄ emitted may be a reflection of the mineral N status, especially NH₄, in the soil under MT or NT at various times of the year. Work by Jacinthe et al. (2014) has shown that the longer a soil is under NT, the more it acts as a sink for CH₄. There was also an interaction between tillage and rotation for CH₄. No-tillage soil was a more effective sink for CH₄ under the CC rotation, while the opposite was true for the CS rotation.

For N₂O emissions to occur from soil, three things are needed: (1) a population of denitrifying microorganisms under anaerobic conditions; (2) a source of energy that is generally supplied by soluble organic C; and (3) a supply of NO₃⁻. In this study, the N₂O emission for NT was higher than N₂O emission for MT on July 12, 2011, while the emission for MT was higher than the emission for NT on June 19, 2012. Both of these dates released higher emissions than any other sampling date for either NT or MT. As previously noted, samples obtained

Figure 3

Greenhouse gas fluxes as affected by tillage from the Wooster site. The * shows a difference between chisel tillage and no-tillage at $p \leq 0.10$ at specific sample dates.

on these dates followed rainfall events and were also about one month following fertilizer application.

Effects of Crop Rotation on Greenhouse Gas Fluxes. Greenhouse gas fluxes as affected by crop rotation from Hoytville are presented in figure 4. For CO_2 and N_2O emissions, there were significant differences between the CC and the CS rotations (table 3), and the CC rotation yielded higher emissions than did the CS rotation (figure 4a and 4c). The CC rotation emitted around $0.4 \text{ g CO}_2\text{-C m}^{-2} \text{d}^{-1}$ ($3.6 \text{ lb CO}_2\text{-C ac}^{-1} \text{day}^{-1}$) on average with a max of $1.6 \text{ g CO}_2\text{-C m}^{-2} \text{d}^{-1}$ ($14 \text{ lb CO}_2\text{-C ac}^{-1} \text{day}^{-1}$) while the CS rotation emitted around $0.3 \text{ g CO}_2\text{-C m}^{-2} \text{d}^{-1}$ ($2.7 \text{ lb CO}_2\text{-C ac}^{-1} \text{day}^{-1}$) on average with a max of $1 \text{ g CO}_2\text{-C m}^{-2} \text{d}^{-1}$ ($8.9 \text{ lb CO}_2\text{-C ac}^{-1} \text{day}^{-1}$). This observation can be explained by the fact that the amount of residue produced by the CC rotation is greater than for the CS rotation. Soybeans produce much less residue than corn, and the CS rotation only has corn growing in the field every other year. The C in the residue is thus emitted as CO_2 at a higher rate for the CC plots than the CS plots. Similarly, as was observed at the Wooster site, the CC rotation had higher N_2O emissions than the CS rotation due to greater total fertilizer N input. The emissions were highly episodic similar to what was reported for the Wooster soil.

Effects of Tillage on Greenhouse Gas Fluxes. Greenhouse gas fluxes as affected by tillage from Hoytville are presented in figure 5. For CO_2 and N_2O emissions, there were significant differences between the MT and the NT (table 3). The interaction of tillage with date was also significant for CO_2 and N_2O . For CO_2 , the emissions for NT were larger than emissions for MT on July 22, 2011, and September 15, 2011 (figures 5a and 5c). For N_2O , the emission for MT was higher than for NT on July 22, 2011. This date released higher emissions than any other sampling date for either NT or MT. This is approximately one month following fertilizer applications and following rainfall. For N_2O , the interaction of crop rotation with tillage was significant (table 3). The MT treatment under the CC rotation emitted higher concentrations of N_2O compared with any other treatment (figure 6). The incorporation of the CC residue on the MT plots makes C more readily available to denitrifiers in the soil to use for energy. When fertilizer N is added, the availability of C energy, NO_3^- , and

Figure 4

Greenhouse gas fluxes as affected by crop rotation from the Hoytville site. There were no significant differences between rotations at specific sample dates.

denitrifiers made this treatment combination the most active in emitting N_2O .

Global Warming Potential. The Wooster site had a higher GWP than did the Hoytville site ($p = 0.028$) and the CC rotation had a higher GWP than did the CS rotation ($p = 0.075$) (table 4 and figure 7). The GWP is mostly a result of CO_2 and N_2O because the soil was actually a sink for CH_4 . The GWP for Hoytville was lower than the GWP for Wooster probably due to the differences of crop yields. Corn yields during the time this study was conducted tended to be better at Wooster (site average was 13.6 Mg ha^{-1} [$217 \text{ bu}^{-1} \text{ ac}$]) than Hoytville (site average was 11.3 Mg ha^{-1} [$180 \text{ bu}^{-1} \text{ ac}$]). This would lead to more roots and residues in the fields for decomposition and thus more CO_2 emissions from the Wooster site. However, the Wooster soils also received less amounts of N fertilizer that would lead to a lower GWP. This illustrates that calculating GWP using CO_2 as part of the equation is fraught with problems because it tends to dominate the calculation. A large CO_2 flux cycle due to cycling of photosynthetically fixed C without any net C sequestration in the soil may not really have any net GWP, but can greatly affect calculations of total GWP—at least on the short-term basis. Long-term studies are needed to more accurately incorporate all of the greenhouse gases into a GWP value.

If GWP is calculated using only N_2O and CH_4 , the values for the silty clay loam soil Hoytville and silt loam Wooster site are similar. This was because the N_2O emissions for the two sites were similar and the CH_4 fluxes had only a small effect on the GWP calculated for each site.

The significantly larger GWP from CC rotations than CS rotations is due to the larger residue amounts being returned to the soil from the corn stalks than the soybean stalks, and more total fertilizer N applied in the CC than the CS rotation. It should be noted that there was no significant difference in GWP by tillage treatments in spite of individual gases showing tillage differences. This seems to be caused by large CO_2 emissions being countered by smaller N_2O emissions or vice versa.

Summary and Conclusions

The NT management system released less CO_2 than did MT, and the CS rotation released fewer CO_2 emissions than did the CC rotation at the Wooster site. At the Hoytville

Table 3Analysis of variance (ANOVA) for carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) fluxes from the Hoytville site.

Factor	Degrees of freedom	Adjusted sum of squares	Adjusted mean square	F-test	p-value
CO ₂					
Rotation	1	0.717	0.717	9.42	0.003
Tillage	1	1.309	1.309	17.21	<0.001
Date	9	12.754	1.417	18.62	<0.001
Rotation × tillage	1	0.010	0.010	0.14	0.714
Rotation × date	9	1.024	0.114	1.49	0.163
Tillage × date	9	1.173	0.130	1.71	0.098
CH ₄					
Rotation	1	0.001	0.001	0.02	0.881
Tillage	1	0.054	0.054	1.05	0.308
Date	9	0.233	0.026	0.50	0.872
Rotation × tillage	1	0.039	0.039	0.75	0.389
Rotation × date	9	0.141	0.016	0.30	0.972
Tillage × date	9	0.228	0.026	0.49	0.880
N ₂ O					
Rotation	1	25.375	25.375	4.50	0.037
Tillage	1	60.952	60.952	10.80	0.001
Date	9	271.342	30.149	5.34	<0.001
Rotation × tillage	1	30.624	30.624	5.43	0.022
Rotation × date	9	69.620	7.736	1.37	0.214
Tillage × date	9	142.414	15.935	2.82	0.006

Table 4

Analysis of variance for global warming potential at the Wooster and Hoytville sites.

Factor	Degrees of freedom	Adjusted sum of squares	Adjusted mean of squares	F-test	p-value
Site	1	130.433	130.433	511.18	0.028
Tillage	1	0.431	0.431	1.69	0.418
Rotation	1	18.344	18.344	71.89	0.075
Site × tillage	1	0.215	0.215	0.84	0.527
Tillage × rotation	1	0.918	0.918	3.6	0.309
Site × rotation	1	4.284	4.284	16.79	0.152

site, CO₂ emissions increased under NT due to faster cycling of nutrients while N₂O increased under MT. The overall emissions were decreased by practicing a crop rotation of CS versus CC. The clay soil of Hoytville had a lower GWP than did the silt loam of Wooster, but also has a recent history of lower yields. Crop rotation led to a lower GWP than monocropping of corn did, which would help to enforce the idea that this management practice is environmentally beneficial. Also, the benefits that have been found for the adoption of NT, when combined with crop rotations, suggest that the simultaneous adoption of both practices will lead to improved crop production and environmental benefits.

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Figure 5

Greenhouse gas fluxes as affected by tillage from the Hoytville site. The * shows a difference between chisel tillage and no-tillage at $p \leq 0.10$ at specific sample dates.

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Figure 6

Significant interaction ($p \leq 0.10$) of crop rotation and tillage for averaged daily nitrous oxide-nitrogen (N_2O-N) emissions from the Hoytville site during the sampling period of this study.

Figure 7

Global warming potential based on converting carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) to CO_2 -C equivalents as affected by site and crop rotation. Different letters over each bar in the same group (different crop rotations or different experimental sites) represent a significant difference at $p \leq 0.10$.

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