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Soil CO_2 flux from a norfolk loamy sand after 25 years of conventional and conservation tillage

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Abstract

Tillage affects the ability of coarse-textured soils of the southeastern USA to sequester C. Our objectives were to compare tillage methods for soil CO_2 flux, and determine if chemical or physical properties after 25 years of conventional or conservation tillage correlated with flux rates. Data were collected for several weeks during June and July in 2003, October and November in 2003, and April to July in 2004 from a tillage study established in 1978 on a Norfolk loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudults). Conventional tillage consisted of disking to a depth of approximately 15 cm followed by smoothing with an S-tined harrow equipped with rolling baskets. Conservation tillage consisted of direct seeding into surface residues. Flux rates in conservation tillage averaged 0.84 g CO_2 m^{-2} h^{-1} in Summer 2003, 0.36 g CO_2 m^{-2} h^{-1} in Fall 2003, 0.46 g CO_2 m^{-2} h^{-1} in Spring 2004, and 0.86 g CO_2 m^{-2} h^{-1} in Summer 2004. Flux rates from conventional tillage were greater for most measurement times. Conversely, water content of the surface soil layer (6.5 cm) was almost always higher with conservation tillage. Soil CO_2 flux was highly correlated with soil water content only in conventional tillage. In conservation tillage, no significant correlations occurred between soil CO_2 flux and soil N, C, C:N ratio, pH, bulk density, sand fraction, or clay fraction of the surface 7.5 cm. In conventional tillage, sand fraction was positively correlated, while bulk density and clay fraction were negatively correlated with soil CO_2 flux rate, but only when the soil was moist. Long-term conservation tillage management resulted in more uniform within- and across-season soil CO_2 flux rates that were less affected by precipitation events.

Keywords: Soil carbon dioxide flux; Soil C; Long-term conservation tillage; Soil water

1. Introduction

Many southeastern USA soils have low water- and nutrient-holding capacity, because of sandy texture and low organic matter concentration. Sequestering C in these soils could therefore increase productivity potential. Conservation tillage is widely regarded as a method to increase soil C, but with typical crop rotations, increases are slow and often limited to the surface few centimeters. Hunt et al. (1996) found C increased at a rate of only 0.61% per year during the first 14 years in the surface 5 cm of a Norfolk loamy sand soil managed with conservation tillage, and there was no change in soil C concentration deeper in the profile. Similarly, Reeves and Delaney (2002) found organic C levels of a Compass loamy sand soil were higher in conservation tillage than in conventional in the surface 5 cm of soil at the end of 4 years, but most of the difference between the tillage systems was in the surface 1 cm.

Tillage often increases short-term CO_2 flux from the soil (Reicosky and Lindstrom, 1993) due to a rapid physical release of CO_2 trapped in the soil air spaces. Prior et al. (2000) found that the amount of CO_2

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Table 1
Descriptive statistics for soil chemical and physical properties of the surface 7.6 cm of a Norfolk soil after 25 years of a tillage experiment

Soil property	Conventional tillage		Conservation tillage	
	Mean	Coefficient of variation (%)	Mean	Coefficient of variation (%)
N (g kg^{-1})	0.8[a]	11	1.2	20
Organic carbon (g kg^{-1})	9.5	11	16.7	28
C:N ratio	12.5	5	14.0	17
pH	7.4[a]	4	7.6	3
Bulk density (g cm^{-3})	1.4	6	1.6	6
Sand fraction (%)	76.1	6	70.5	11
Clay fraction (%)	3.8	56	2.3	39

Twenty samples were collected from each of three replicates for each tillage practice ($n = 60$).
[a] Indicates conventional tillage differed from conservation tillage ($P \leq 0.05$).

released into the atmosphere differed with different tillage systems and the amount lost was related to the amount of soil disturbance. In the weeks following tillage, keeping crop residues on the soil surface reduces CO_2 flux rates compared to incorporation (Reicosky and Lindstrom, 1993). Dao (1998) determined soil CO_2 flux following wheat in the 11th year of a tillage study and found the cumulative CO_2 evolved from soil in a 2-month period was much higher for moldboard plowing than for no-tillage.

The effect of tillage on CO_2 flux from the soil is dependent on the time of year measurements are made. Prior et al. (2004) found spring tillage did not increase CO_2 flux above that from undisturbed soil, while tillage in the fall resulted in higher flux than undisturbed soil. Rochette et al. (1991) found highest spatial variability for CO_2 flux in spring, while the variability declined throughout the season.

A tillage experiment that was established in 1978 (Hunt et al., 2004) was used to evaluate soil CO_2 flux from two tillage management systems. The objectives were: (1) to compare conventional tillage to conservation tillage for soil CO_2 flux; and (2) to determine whether soil physical and chemical properties within each tillage system were useful in explaining the spatial variability associated with CO_2 flux.

2. Materials and methods

2.1. Experimental design and management history

Data were collected in 2003 and 2004 during the 26th and 27th year of a tillage experiment on a Norfolk loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudults) at Clemson University's Pee Dee Research and Education Center near Florence, South Carolina, USA (latitude 34°18′N, longitude 79°44′W; elevation is 37 m above mean sea level). The site has two identical sets of plots that were initially used for irrigated versus non-irrigated comparisons but are now used for different crop rotation phases. Five replicates of conventional tillage and conservation tillage practices that have been maintained since the study was initiated in 1979. Within each set of plots, the same crop rotations were grown on each tillage system. Crops grown during the previous years included corn (*Zea mays* L.), winter wheat (*Triticum aestivum* L.), soybean [*Glycine max* (L.) Merr.], and cotton (*Gossypium hirustum* L.) (Karlen et al., 1996; Hunt et al., 1997, 2004). Soil C in the surface 5 cm, which was 5.8 g kg^{-1} in 1979, increased to 7.2 g kg^{-1} in conventional tillage, and 12.0 g kg^{-1} in conservation tillage at the end of 14 years (Hunt et al., 1997). Average soil C for the two tillage systems at the end of 26 years is shown in Table 1.

Conventional tillage consisted of disrupting the soil surface to a depth of approximately 15 cm with a disk harrow followed by smoothing with an S-tined harrow equipped with rolling baskets. For corn, cotton, and soybean, one-pass subsoiling and planting were done initially with a Brown-Harden Superseeder[1] (until mid-1980s) and later replaced with a Kelley Manufacturing Company (KMC, Tifton, GA, USA) in-row subsoiler and Case-IH model 800 planter (Case-IH Corporation, Racine, WI, USA). Conservation tillage involved one-pass in-row subsoiling and planting. No subsoiling was done before planting wheat in either tillage system. Beginning in 1996, each 45.6 m wide by 61 m long plot was split and a deep tillage component (subsoiled or

[1] Mention of any commercial product is for information only and does not imply an endorsement to this product by the USDA-ARS over any equally suitable product.

none) was evaluated along with surface tillage (Hunt et al., 2004). For those years (1996–2003) a 2-year corn–winter wheat/soybean rotation was grown on the plots. Each year corn was grown on one set of the plots and doublecropped wheat/soybean on the other. Wheat and soybeans were grown in 19 cm wide rows and planted with a John Deere model 750 drill (Deere and Company, Moline, IL, USA) and subsoiling (in the subsoiled plots only) was with a Tye paratill (AGCO Corporation, Duluth, GA) to a depth of 35 cm. From 1996 through 2000, corn was grown in 76 cm wide rows and planted with a six-row Case-IH model 800 planter. Beginning in 2001, corn was grown in 38 cm wide rows planted with a Monosem planter (AT.I. Inc., Lenexa, KS, USA) equipped with wavy coulters. Wheat was removed from the rotation in the fall of 2003 and all plots were planted with rye (*Secale cereale* L.) cover crop.

Corn, wheat, and soybean grain yields were determined by combine-harvesting 555 m^2 of each plot. Rye biomass was determined by collecting and weighing three 1 m^2 (spring of 2004) or 0.5 m^2 (summer of 2004) areas within each plot.

2.2. CO_2 flux measurements

Soil CO_2 flux and soil water content were measured in three of the five replicates in plots that were not subsoiled during 1996–2003. These data were collected during four periods of 2003 and 2004. For each measurement period, data collection began the day after conventional tillage plots were disked. Data were collected in Summer 2003 (17 days between wheat harvest and soybean establishment in June and July), in Fall 2003 (13 days between corn harvest and rye cover crop establishment in October and November), in Spring 2004 [8 days between killing rye cover crop (with disk tillage for the conventional plots or with glyphosate herbicide in the conservation plots) and corn establishment in April], and Summer 2004 (13 days between killing rye cover crop and soybean establishment during May–July). Measurements were made at a minimum of 5 points within each plot for both periods in 2003 and during April 2004, but only from a minimum of 3 points in Summer 2004. All measurements were collected between 08:00 and 12:00 Eastern Standard Time each season.

Soil CO_2 flux was measured with a LiCor 6000-09 (LiCor Biosciences, Lincoln, NE, USA) soil respiration chamber (962 cm^3 volume, 71.6 cm^2 soil-exposed area) connected to a LiCor 6250 CO_2 analyzer. Air in the chamber was at ambient CO_2 concentration before placing the chamber into the soil for each measurement. Each measurement was initiated when CO_2 concentration in the chamber increased at a constant rate, usually within 30 s of the chamber being placed on the soil surface. During Summer 2003 and on the first three dates that data were collected in Fall 2003, duration of measurement varied with soil CO_2 flux rate because the gas-exchange system software was programmed to terminate a measurement when CO_2 concentration in the chamber increased by 10 mg kg^{-1}. Because of the long time needed for each measurement with this protocol in plots with very low flux rates in Fall 2003, measurement duration was changed to 15 s (initiated after CO_2 concentration in the chamber increased at a constant rate) for the rest of the dates in Fall 2003 and all dates in 2004. Volumetric soil water content of the surface 6.5 cm was determined with a Delta-T soil moisture meter (Delta-T Devices, Cambridge, UK) at the same time and in the same area (within 30 cm) of each soil respiration measurement. Data were not collected on the day of tillage. To avoid CO_2 flux from respiration of the crop roots, measurements were between rows once crop plants emerged and discontinued shortly after crops were fully established. Planting dates were 14 days after tillage for soybeans in Summer 2003, 10 days after tillage for rye in Fall 2003, 19 days after tillage for corn in Spring 2004, and 15 days after tillage for soybeans in Summer 2004.

Data were analyzed using the GLM procedure of SAS (SAS Institute, 2002–2003) each day that measurements were collected to determine the tillage effect on soil CO_2 flux and soil water content. Means were considered significantly different if probability values from F-test were $\leq$0.05. Standard deviations were calculated for each mean on each day.

2.3. Spatial variability assessment

Soil physical and chemical characteristics were determined at 20 points within each plot in June of 2003 to assess relationships between these soil properties and soil CO_2 flux within each tillage system. Conventional tillage plots were disked on 9 June. On 10 June, a 4 × 5 grid (6.8 m wide, 24.3 m long, with 2.3 m and 6.1 m between grid points) was laid out in each plot. Bulk density was measured using the core method (Klute, 1986) at each grid point. At the same time, soil samples were collected from a 7.6 cm depth (five to ten 2.5 cm diameter cores) around each grid point. Samples were dried and ground. Soil N and organic C were measured using dry combustion and measurement by a LECO-2000 CNS analyzer (LECO Corp., Chicago, IL). Soil

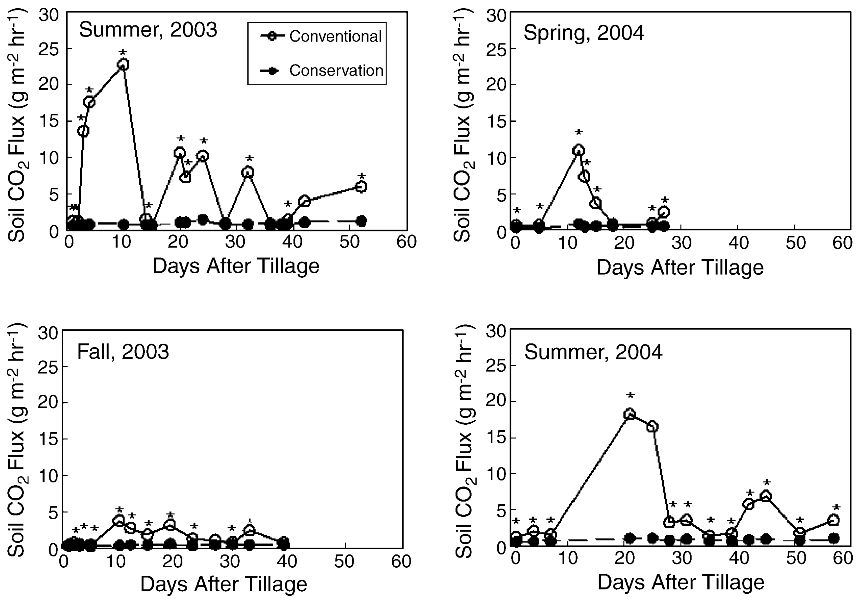

Fig. 1. Soil CO_2 flux in conventional tillage and conservation tillage during four seasons in 2003 and 2004 from plots established in 1978. An asterisk above a mean in conventional tillage indicates that conventional tillage had significantly higher flux than conservation tillage on that date.

pH was measured using a 1:1 soil/water ratio in deionized water. Sand and clay fractions were determined using a micro-pipette method (Miller and Miller, 1988). On 10 (the day after the tillage event), 11, 12, and 13 June, soil CO_2 flux data were collected at the 20 grid points within each plot.

Data were analyzed using the GLM procedure of SAS to determine the tillage effect on soil properties. Pearson correlation coefficients were calculated using SAS to determine the relationship between soil CO_2 flux on each of the 4 days and soil properties. All tests of significance were made with probability value of 0.05.

3. Results and discussion

3.1. Tillage effect on soil CO_2 flux

The CO_2 flux rates from conventional tillage were higher than those from conservation tillage during almost every measurement date in each season (Fig. 1). When the differences were not significant, soil in conventional tillage was quite dry (causing rates in conventional tillage to be low) or the variability among measurements was high.

These results differ from those of Prior et al. (2004) who reported that disturbing soil with tillage resulted in higher CO_2 efflux in the fall but not in the spring. In fact, differences in CO_2 flux between conventional and conservation tillage in this study tended to be greater in spring and summer than in fall (Fig. 1). Averaged across all dates, the difference in CO_2 flux between conventional and conservation tillage was 6.4 g m^{-2} h^{-1} in Summer 2003, 1.2 g m^{-2} h^{-1} in Fall 2003, 2.9 g m^{-2} h^{-1} in Spring 2004, and 4.4 g m^{-2} h^{-1} in Summer 2004. A major difference between this study and that of Prior et al. (2004) was that our study had a long history of tillage comparison, while their study was in fallow (with annual disking in spring) for 10 years before flux data were collected. Cropping history may have played a significant role in assessing tillage impacts on seasonal soil CO_2 flux.

Flux rates were relatively low ($\leq$1.2 g m^{-2} h^{-1}) in conventional tillage (Fig. 1) the day after tillage in all four seasons. Thus, most of the tillage-induced release of CO_2 from soil air spaces (Reicosky and Lindstrom, 1993; Prior et al., 2000) appears to have been completed by this time. Flux rates remained low until soil water content increased (Fig. 2) with the first rainfall event after disking (Fig. 3), at which time flux rates increased. Rates quickly fell as the soil dried (Fig. 1). Similar increases and decreases in flux rates occurred around subsequent rainfall events each season. Prior et al. (1997) found increases in soil CO_2 flux rates with rainfall events and Reicosky et al. (1999) reported a similar increase in soil CO_2 flux rates with a 25 mm irrigation event.

Flux rates in conventional tillage after the first rainfall in Summer 2003 and in both seasons of 2004

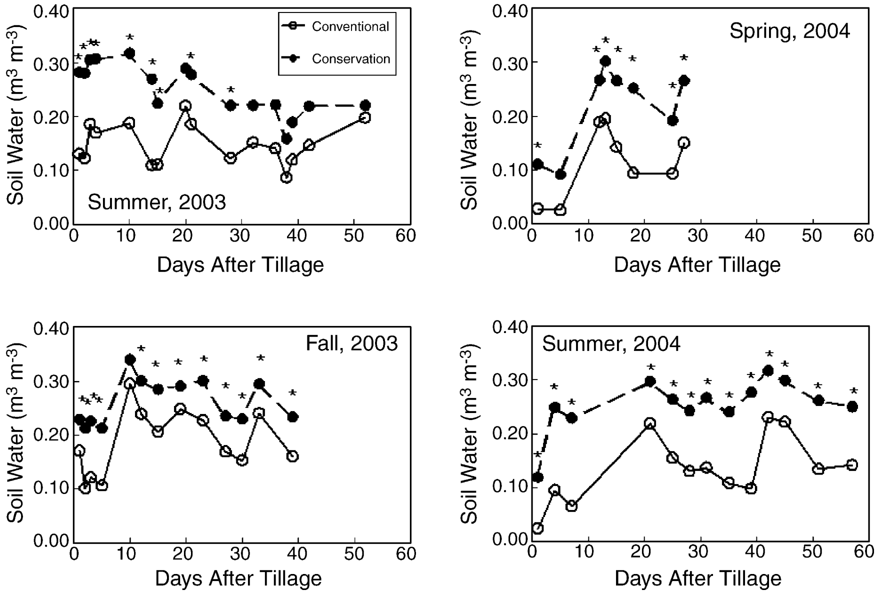

Fig. 2. Soil water content of the surface 5 cm in conventional and conservation tillage from plots established in 1978. An asterisk above a pair of means indicates tillage systems differed on that date.

(Fig. 1) were almost as high as the rates reported by Reicosky and Lindstrom (1993) immediately after a tillage event. It is not clear why rates were that high, but N content of the residue incorporated may have been partially responsible. Sarrantonio (2003) found soil CO_2 flux were higher on soil with a legume mulch than on soil with a cereal mulch. Prior et al. (1997) reported soil CO_2 flux rates were greater following soybean than following sorghum [*Sorghum bicolor* (L.) Moench.] and attributed the difference to a lower C:N ratio in the soybean residues. In our study, residues incorporated in Summer 2003 were from a drought-stricken wheat crop that had low yield (250 g m^{-2}) while residues incorporated prior to both 2004 periods were from a rye green manure that was fertilized with 30 kg N ha^{-1} (rye biomass was 25 g m^{-2} in Spring 2004 and

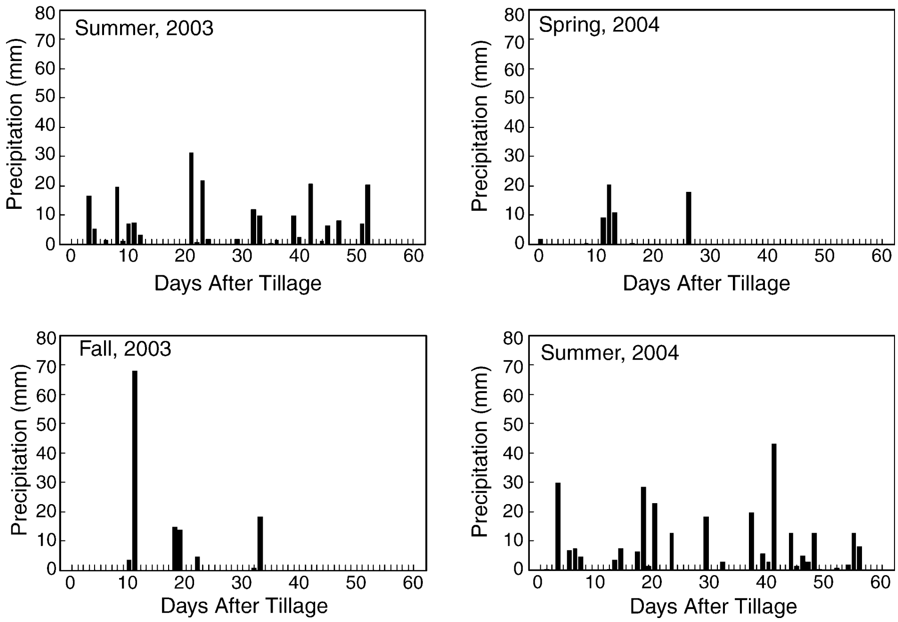

Fig. 3. Precipitation events during the periods soil CO_2 flux measurements were collected.

Table 2
Correlation coefficients for soil CO_2 flux and soil physical and chemical properties on 4 days after conventional plots were disked ($n = 60$ for each tillage method) in June 2003

Tillage	Days after tillage	Soil property						
		N	Organic C	Soil C:N ratio	pH	Bulk density	Sand fraction	Clay fraction
Conventional	1	0.22	0.15	−0.18	−0.15	−0.28[a]	−0.06	0.16
	2	−0.05	−0.10	−0.14	−0.08	−0.12	0.12	−0.14
	3	−0.15	−0.11	0.09	−0.04	−0.37[b]	0.44[b]	−0.49[b]
	4	−0.30[a]	−0.14	0.31[a]	−0.05	−0.30[a]	0.48[b]	−0.61[b]
Conservation	1	0.00	−0.14	−0.23	0.21	−0.05	0.17	−0.14
	2	−0.12	−0.13	−0.08	0.13	0.01	0.22	0.09
	3	−0.13	−0.08	0.02	0.17	0.02	0.09	0.20
	4	−0.12	−0.13	−0.07	0.16	0.05	0.22	0.24

[a] Indicates probability that correlation coefficient does not equal zero is significant at $P = 0.05$.
[b] Indicates probability that correlation coefficient does not equal zero is significant at $P = 0.01$.

639 g m^{-2} in Summer 2004). Flux rates were much lower with the first precipitation in Fall 2003 presumably because residues incorporated into the soil before those measurements were from a corn crop that had above average yield for the region (744 g m^{-2}).

Soil CO_2 flux rates after 25 years of conservation tillage management varied little among the four measurement periods, with a range in average CO_2 flux of ≤0.8 g CO_2 m^{-2} h^{-1}. Furthermore, in contrast to conventional tillage, the magnitude of CO_2 flux varied little following precipitation events (Figs. 2 and 3). This may have been partially due to higher soil water content with conservation tillage (Fig. 2). Averaged across all dates, soil water content under conservation tillage was higher than conventional tillage in all four periods. The difference in soil water content between tillage systems was 0.102 m^3 m^{-3} in Summer of 2003, 0.074 m^3 m^{-3} in Fall 2003, 0.120 m^3 m^{-3} in Spring 2004, and 0.230 m^3 m^{-3} in Summer 2004.

Average CO_2 flux rates in conservation tillage were higher in Summer 2003 and 2004 than in Fall of 2003 or Spring 2004. Soil CO_2 flux rates were 0.84 g CO_2 m^{-2} h^{-1} in Summer 2003, 0.86 g CO_2 m^{-2} h^{-1} in Summer 2004, 0.36 g CO_2 m^{-2} h^{-1} in Fall 2003, and 0.46 g CO_2 m^{-2} h^{-1} in Spring 2004. Differences in crop residues, as discussed for conventional tillage, may have contributed to some of the difference (in conservation tillage plots, wheat yield in 2003 was 280 g m^{-2}, corn yield in 2004 was 838 g m^{-2}, rye biomass in spring of 2004 was 39 g m^{-2}, and rye biomass in summer of 2004 was 715 g m^{-2}). Differences in seasonal temperature as has been reported previously (Buyanovsky et al., 1986) were presumably also important. Average air temperature during measurements were was 31.5 °C in Summer 2003, 33.4 °C in Summer 2004, 22.8 °C in Fall 2003, and 20.3 °C in Spring 2004.

3.2. *Relationship between soil CO_2 flux and soil properties in June 2003*

Soil physical and chemical properties of the surface 7.6 cm are shown in Table 1. Despite relatively large differences in mean values for some parameters, there were few significant differences between tillage systems due to large variation. Even though surface soil managed with conservation tillage averaged 7.2 g kg^{-1} more organic C than conventional tillage, the difference was not significant ($P = 0.12$). Conventional tillage had a lower total N content and pH than conservation tillage (Table 1).

Soil managed with conservation tillage had larger coefficients of variation for N, C, C:N ratio, and sand fraction than did soil managed with conventional tillage (Table 1). Evidently, mixing of the soil twice each year through disk tillage created a more homogeneous surface across the plots than with conservation tillage. The two tillage systems had similar mean and coefficient of variation for bulk density. The only soil property that had a larger coefficient of variation with conventional tillage was percent clay fraction. This may be due to loss of surface soil by erosion in parts of the conventional tillage plots and mixing of the sandy clay loam B horizon material with the surface in those areas where erosion occurred.

Soil CO_2 flux was not closely correlated with any of the soil chemical and physical properties in conservation tillage on any of the 4 days after tillage (Table 2). However, there was little variability in soil CO_2 flux on any date. For conventional tillage, significant correlation of CO_2 flux occurred with bulk density at the first day after tillage. None of the variables were significant at 2 days after tillage. Soil CO_2 flux averaged about 1 g m^{-2} h^{-1} during the first 2 days after tillage (Fig. 1).

On the evening of the second day after tillage, a 2.2 cm rainfall occurred and soil water content of the surface 7.5 cm increased from 0.122 to 0.185 $m^3 m^{-3}$ in conventional tillage (Fig. 2a). Following the rain, soil CO_2 flux averaged $>10\ g\ m^{-2}\ h^{-1}$ on the third and fourth day after tillage (Fig. 1). At 3 and 4 days after tillage, soil CO_2 flux was negatively correlated with bulk density and clay fraction, and positively correlated with sand fraction. These correlations may be related to the ability of the soil to exchange air with the atmosphere. Lower bulk density and higher sand content would provide more soil micro- and macropores, allowing for easier O_2 (for aerobic respiration by microorganisms on the crop residues) and CO_2 exchange between the soil and the atmosphere.

4. Summary

Soil CO_2 flux was generally greater in conventional tillage than in conservation tillage. After 25 years of conservation tillage, CO_2 flux rates within a season did not vary greatly, and differences among seasons were less than those in conventional tillage. Precipitation events and water content had much less of an influence on soil CO_2 rates in conservation than in conventional tillage. Even though a considerable amount of variability existed for the soil properties measured, none were closely related to soil CO_2 flux in conservation tillage. With conventional tillage, bulk density and soil texture were loosely related to flux rates when soil water contents were relatively high. Higher surface soil water content with conservation tillage than conventional tillage (along with high temperature in this region) may be limiting accumulation of C in this soil, even with high residue crops of corn and winter cereal in a two-year rotation.

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