Tillage and Crop Residue Effects on Soil Carbon and Carbon Dioxide Emission in Corn–Soybean Rotations

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ABSTRACT

Soil C change and CO_2 emission due to different tillage systems need to be evaluated to encourage the adoption of conservation practices to sustain soil productivity and protect the environment. We hypothesize that soil C storage and CO_2 emission respond to conservation tillage differently from conventional tillage because of their differential effects on soil properties. This study was conducted from 1998 through 2001 to evaluate tillage effects on soil C storage and CO_2 emission in Clarion–Nicollet–Webster soil association in a corn [*Zea mays* L.]–soybean [*Glycine max* (L.) Merr.] rotation in Iowa. Treatments included no-tillage with and without residue, strip-tillage, deep rip, chisel plow, and moldboard plow. No-tillage with residue and strip-tillage significantly increased total soil organic C (TC) and mineral fraction C (MFC) at the 0- to 5- and 5- to 10-cm soil depths compared with chisel plow after 3 yr of tillage practices. Soil CO_2 emission was lower for less intensive tillage treatments compared with moldboard plow, with the greatest differences occurring immediately after tillage operations. Cumulative soil CO_2 emission was 19 to 41% lower for less intensive tillage treatments than moldboard plow, and it was 24% less for no-tillage with residue than without residue during the 480-h measurement period. Estimated soil mineralizable C pool was reduced by 22 to 66% with less intensive tillage treatments compared with moldboard plow. Adopting less intensive tillage systems such as no-tillage, strip-tillage, deep rip, and chisel plow and better crop residue cover are effective in reducing CO_2 emission and thus improving soil C sequestration in a corn–soybean rotation.

SOIL C DYNAMICS play a crucial role in sustaining soil quality, promoting crop production, and protecting the environment (Bauer and Black, 1994; Doran and Parkin, 1994; Robinson et al., 1996), because of their effects on soil gas emission, water retention, nutrient cycling, and plant root growth (Sainju and Kalisz, 1990; Sainju and Good, 1993). Increased atmospheric carbon dioxide (CO_2) has been considered a major contributor to global warming. Carbon loss from soil to the atmosphere as CO_2 or other gases has been enhanced due to inappropriate tillage practices (Reicosky et al., 1997). However, soil can function as a net sink for sequestering atmospheric CO_2 through appropriate soil and crop management (Lal et al., 1995; Paustian et al., 1995).

From a long-term (>10 yr) perspective, soil can be managed to increase total soil organic C (TC) storage by implementing conservation tillage practices and annual cropping systems (Havlin et al., 1990; Franzluebbers et al., 1995; Halvorson et al., 2002). However, short-term (≤10 yr) tillage effects on soil C dynamics are complex and often variable. Franzluebbers and Arshad (1996) reported that there may be little to no increase

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in soil organic C in the first 2 to 5 yr after changing to conservation management, but a large increase in TC occurred in the next 5 to 10 yr. In addition, Duiker and Lal (1999) found that there was a linearly positive response of soil organic C to residue application rate regardless of tillage system after 7 yr.

Carbon dioxide is produced in the soil through the metabolism of plant roots, microflora, and fauna, and to a small extent, by chemical oxidation of carbon-bearing materials (Lundegardh, 1927). The rate of soil CO_2 emission is normally controlled by several factors, such as CO_2 concentration gradient between the soil and the atmosphere, soil temperature, soil moisture, pore size, and wind speed (Raich and Schlensinger, 1992). In addition, soil CO_2 emission is affected by agricultural practices such as tillage and residue management and varies with climatic conditions (Fernandez et al., 1993; Burton and Beauchamp, 1994; Osozawa and Hasegawa, 1995; Yavitt et al., 1995). The measurement of soil CO_2 emission could provide a more sensitive indication of soil C sequestration than low-resolution data such as total or organic C values (Fortin et al., 1996; Grant, 1997).

Tillage accelerates soil CO_2 emission by improving soil aeration, increasing soil and crop residue contact, enhancing plant nutrient availability (Logan et al., 1991; Angers et al., 1993), and increasing exposure of soil organic C in inter- and intra-aggregate zones to microbes for rapid oxidation (Reicosky and Lindstrom, 1993; Beare et al., 1994; Jastrow et al., 1996). The magnitude of CO_2 loss from the soil due to tillage practices is highly related to the frequency and intensity of soil disturbance caused by tillage. Although tillage effects on soil CO_2 emission are complex and often vary (Mosier et al., 1991; Lauren and Duxbury, 1993), conservation tillage is regarded as one of the most effective agricultural practices for reducing soil CO_2 emission to the atmosphere from agricultural soils (Kern and Johnson, 1993; Reicosky and Lindstrom, 1993; Lal and Kimble, 1997).

Conservation tillage systems such as no-tillage, strip-tillage, and chisel plow are increasingly used for crop production in the Midwest during the past decade due to their profitability and environmental advantages over moldboard plow. For example, no-tillage production in the Midwest was used in >22% of all cropland area in 2002 (Conservation Technology Information Center, 2003), which almost doubled the amount in 1992. In contrast, conventional tillage systems accounted for 35% of all croplands in the Midwest. Deep rip is an effective and popular tool used to overcome soil compaction. Although deep rip is not a conservation tillage system, it still results in less soil disturbance and mixing and thus

greater crop residue coverage on the soil surface than moldboard plow. There are few studies that quantify the effects of these main tillage alternatives with different intensities on soil CO_2 emission and C storage compared with more intensive tillage systems (i.e., moldboard plow) in the Midwest where a corn [*Zea mays* L.]–soybean [*Glycine max* (L.) Merr.] rotation has been the primary cropping system for decades. Even though moldboard plow use has been limited recently in the Corn Belt region, the inclusion of it in this study is to show the extremist intensive tillage system effect on soil C dynamics as we evaluate a suite of tillage systems differing in their intensities in soil disturbance at different depths.

The objectives of this study are to evaluate (i) the short-term response of soil organic C pools to different tillage systems, (ii) immediate and short-term effects of a suite of tillage systems with different intensities in soil disturbance on soil CO_2 emission, and (iii) the influences of tillage systems on mineralizable C pools.

MATERIALS AND METHODS

Site Description

This study was conducted in 1998 through 2001 on a Clarion–Nicolet–Webster soil association at the Iowa State University Agronomy Research Farm, west of Ames, IA (42°39′ N lat; 95°47′ W long). The Clarion–Nicolet–Webster soil association includes Canisteo (fine-loamy, mixed, calcareous, mesic Typic Haplaquolls) and Clarion (fine-loamy, mixed, mesic Typic Hapludolls) soil series. The surface horizon (0–15 cm) of this site is generally dark colored with 29.0 kg m^{-3} of soil organic C. The crop rotation for the past decade was a corn–soybean rotation with chisel plow.

Experimental Design and Implementation

This study included no-tillage, strip-tillage, deep rip, chisel plow, and moldboard plow treatments, and it was established in a corn–soybean rotation in the fall of 1997. The study consisted of three replications with a randomized complete block design. Typically, no-tillage was defined as no preplant tillage. The crop in no-tillage was planted using a planter with a single coulter to cut through residues and loosen soil ahead of standard planter units. Tillage description, tillage depth, and width of disturbed soil zone due to tillage operations are presented in Table 1. The strip-tillage plots were tilled with a strip-tillage unit that consists of an anhydrous knife centered between two cover disks and a coulter for residue cleaning. The tilled zone was prepared in the proximity of previous season corn or soybean rows creating a tilled zone of 10 cm high. The chisel plow treatment was implemented using a commercially available model with straight shanks and twisted chisel plow sweeps at the bottom mounted on a tool bar. The shanks were mounted on four tool bars in a staggering order to ensure an effective spacing of 30 cm between shanks. The deep rip treat-

ment was performed by using a commercially available deep ripper with four straight shanks on a tool bar. The moldboard plow treatment resulted in a complete inversion of soil surface and nearly 100% incorporation of crop residue by using a commercially available model with four bottoms. In the spring before planting, all treatments except no-tillage and strip-tillage received one field-cultivation 10 cm deep. The field cultivator shovels were mounted on four tool bars in a staggering order to ensure an effective spacing between shovels of 30 cm. Tillage treatments were conducted during the fall immediately after harvest each season. The plot size for each treatment was 152 m wide by 272 m long. For the measurements of soil CO_2 emission, temperature, and moisture, the no-tillage treatment was divided into two different treatments. One treatment was no-tillage with crop residue cover on the soil surface and the other one was no-tillage without corn residue cover on the soil surface, where the surface residues were completely removed by hand from inside the CO_2 measurement chambers. The CO_2 measurement chambers were installed on all plots immediately after tillage operations and kept in the same place for the entire duration of CO_2 measurements.

Fertilizer rates were identical for all tillage treatments, but varied in placement methods. Before tillage operations in the fall, anhydrous ammonium was injected by using a mole knife with two cover disks in zones 76 cm apart at 135 kg N ha^{-1} for corn in all tillage treatments except no-tillage. For no-tillage treatment, anhydrous ammonium was injected in the fall by using a modified slot injector with minimum soil disturbance. No N fertilizer was applied for soybean regardless of treatment. Phosphorous and K were applied in the fall, as needed, according to soil test recommendations.

Soil and Crop Residue Sampling and Analysis

Before the establishment of this study, an initial composite soil sample was taken across the site for soil texture, pH, and organic C analyses. In the fall of 2000 after corn harvest, soil sampling for TC, mineral fraction C (MFC), and particulate organic matter C (POMC) was conducted at soil depths of 0 to 5, 5 to 10, and 10 to 15 cm for each plot. Soil samples were collected from the tilled area in the strip-tillage treatment. Ten to 12 soil cores were randomly collected from each plot with a soil probe of 1.9-cm diameter after removing visible crop residue from the soil surface. Soil cores from the same depth in each plot were mixed and placed in a soil-sampling bag and stored in a cooler at 4°C. Soil samples were kept at workable wet conditions to pass through a 2-mm sieve and left to completely air dry afterward. Total soil organic C equals the sum of MFC and POMC fractions. Soil particulate organic matter C fractionation was conducted (Cambardella and Elliott, 1992) to separate POMC associated with large stable soil aggregates (>53 μm) from MFC associated with soil micro aggregates (<53 μm or defined as silt + clay associated C fraction). Soil bulk density samples were taken at the same soil depth intervals as those used for soil organic C in the fall of 2000. Four samples per depth were taken to determine bulk density in each plot. Soil bulk density was determined using a core method with a copper cylinder of 5 cm in height and 5 cm in diameter, similar to that used by Culley (1993). Bulk density was used to convert soil organic C concentrations (g kg^{-1}) to mass per soil volume (kg m^{-3}).

In the fall of 2001, a crop residue sample was collected from each plot after corn harvest before any tillage operations were performed for the determination of total C concentration in crop residue. A crop residue sample was taken by using a 1-m^2 frame thrown randomly on each plot three times to collect the aboveground crop residue. Residue samples were oven-

Table 1. Tillage system, tillage depth, and width of disturbed soil zone due to tillage operations.

Tillage system	Shank or disk spacing	Tillage depth	Disturbed zone
	cm		
Strip-tillage	76	20	20
Deep rip	76	40–46	30–40
Chisel plow	30	22–25	20
Moldboard plow	76	25	46

dried at 64°C, cleaned from soil before weighing, and ground using a plant grinder with a 2-mm sieve (Wiley Mill, Model 2 Pulverized Carbon Steel, Arthur H. Thomas Co., Philadelphia, PA).

Soil organic C, MFC, POMC, and crop residue C concentrations were determined by dry combustion with a LECO CHN 2000 analyzer (LECO, St. Joseph, MI). Soil pH was measured using a 1:1 (soil/water) extraction. Before dry combustion, soil samples with pH > 7.1 were treated with 1 M HCl to eliminate any inorganic carbonate. On the other hand, TC was assumed to be equal to the soil total C if soil pH was not greater than 7.1.

Total C input from crop residue was estimated for the entire study period by including both corn and soybean seasons. Corn or soybean residue C input was estimated for each season separately by using crop grain yields that were measured each year for both corn and soybean. The total C input of each season was calculated as the quotient of grain yields by harvest index, then multiplied by the total C concentrations of crop residue (corn or soybean), respectively. The harvest index used in this computation was 0.59 for corn and 0.57 for soybean (Licht, 2003). Total C concentrations of corn and soybean were determined by using the corn and soybean residue samples collected in 2001.

Carbon Dioxide Emission Measurements

The short-term, tillage-induced soil CO_2 emission was measured in the fall of 2001 with a LI-6400 CO_2 analyzer (LI-COR, Lincoln, NE) immediately after tillage operations for each treatment. The LI-6400 CO_2 analyzer utilized a small chamber of PVC rings with 10 cm i.d. Immediately (1–2 min) after tillage operations in each tilled plot, five chambers were placed on the tilled soil surface and the measurements of CO_2 emission were taken along with soil moisture (with TRIME-TDR) and soil temperature. Soil temperature was measured by using a thermometer provided with the LI-6400 CO_2 analyzer. Soil moisture and temperature were measured in the top 5 cm. After completing the tilled soil CO_2 emission measurements, the same number of chambers was placed on the soil surface of the no-tillage plots, and CO_2 emission readings, along with soil moisture and soil temperature were taken. Measurements were taken using the same approach for all three replications. The tillage operations were conducted 7 Nov. 2001 and completed in the same day. The CO_2 emission measurements were repeated for the following time periods after tillage operations: 0, 2, 4, 8, 12, 24, 48, 96, 192, 288, and 480 h. The five chambers in each plot were kept at the same locations during the measurement period, regardless of treatment.[1]

Weather data were collected from a nearby weather station on the same research farm. Daily measurements included solar radiation, air temperature, precipitation, and wind speed. There was no precipitation during the 20-d period of CO_2 emission measurements.

Strip-tillage in this study tilled 27% of the total soil surface area of each plot; the other 73% of soil surface area remained in no-tillage. There was minimum residue removal and disturbance in the no-tillage areas due to strip-tillage. Because CO_2 emission from the strip-tillage treatment was measured in the tilled zones only, these measurements were adjusted to reflect the true field conditions of the entire plot in the strip-tillage treatment. The following formula was used: Adjusted soil CO_2 emission = 0.27 × CO_2 emission from the tilled zones + 0.73 × CO_2 emission from no-tillage treatment with residue.

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[1]All trade names and product lines are mentioned for the benefit of readers and do not imply endorsement by Iowa State University over comparable products.

Determination of Mineralizable Carbon under Different Tillage Systems

Michaelis and Menten (1913) reported the effect of substrate concentration on the velocity of enzyme-catalyzed reaction could be satisfactorily described in the following equation

$$v = V_{max} \times S/(K_m + S)$$

where v is the reaction velocity, V_{max} is the maximum reaction velocity, S is the substrate concentration, and K_m is the Michaelis constant. Numerically, K_m is equal to the substrate concentration at half-maximum reaction velocity.

According to the relationship of cumulative mineralized S vs. distillation time reported in a previous study (Pirela and Tabatabai, 1988), we believe the Michaelis–Mention equation can also be used to describe the relationship between cumulative soil CO_2 emission and time. To calculate the amount of mineralizable C (i.e., the maximum cumulative soil CO_2 emission) due to different tillage systems, the Lineweaver–Burk transformation (Tabatabai, 1994) of the Michaelis–Menton equation was used

$$1/c = 1/C_{max} + K_m/C_{max} \times 1/T$$

where c (kg CO_2 ha^{-1}) is cumulative soil CO_2 emission at a specific time after tillage operations, T is the time (h) after tillage operations, C_{max} (kg CO_2 ha^{-1}) is the potential maximum amount of cumulative soil CO_2 emission under a specific tillage system, and K_m is the Michaelis constant, which equals to the time (h) at half-maximum cumulative soil CO_2 emission.

Statistical Analysis

Statistical analyses of the data were conducted by using the SAS statistical package (SAS Inst., 2002). Values of TC, MFC, or POMC in all treatments and at all soil depth increments were analyzed as a single data set. Analysis of variance for TC, MFC, or POMC was conducted using the mixed procedure with repeated measures by treating tillage as a randomized factor and soil depths as a nonrandomized factor. Unlike tillage treatments that were randomly assigned to the plots in each replicate, soil depths were always arranged in the same order (0–5, 5–10, and 10–15 cm from the top to the bottom) in the soil profile regardless of replicate and tillage system. Therefore, soil depths were treated as repeated measures. For annual C input from crop residue, the mixed procedure was used. For soil CO_2 emission, an ANOVA procedure was used for each time measurement. Mean separations were achieved by using the adjusted Tukey's least significant difference (LSD) for TC, MFC, POMC, and annual C input from crop residue. For soil CO_2 emission, a protected LSD was used to separate treatment means. The probability level <0.05 was designated as significant.

Data presentations in the Results and Discussion are based on the order of statistical significance, which ranges from the highest order of interaction to the main effects. If there was a statistically significant interaction, then the main effects of the treatments involved in the interaction were not presented. For example, the tillage × depth interaction for TC content was the highest-order interaction that was statistically significant (Table 2); therefore, the results were presented in a format corresponding to this interaction regardless of the significance of main effects (tillage and depth). The same rule applied to other measurements.

Linear and quadratic regression analyses were conducted on the data set across treatments over the 0- to 480-h measurement period by using the natural logarithm of soil CO_2 emission rate as the dependent variable and soil temperature or

Table 2. Tillage effects on soil organic C in the soil profile after 3-yr management in a corn–soybean rotation.

Tillage system	TC soil depth, cm†				MFC soil depth, cm				POMC soil depth, cm			
	0–5	5–10	10–15	0–15	0–5	5–10	10–15	0–15	0–5	5–10	10–15	0–15
	Mg ha⁻¹											
No-tillage	17.05a‡	16.93a	18.60a	52.57a	12.04a	13.29a	14.72a	40.04a	5.01a	3.64a	3.88a	12.53a
Strip-tillage	16.89a	17.56a	18.54a	52.98a	12.24a	13.70a	14.89a	40.83a	4.66a	3.86a	3.65a	12.16a
Deep rip	12.26b	13.00b	19.40a	44.67ab	8.68b	10.21b	13.72ab	32.60b	3.58a	2.79a	5.69a	12.06a
Chisel plow	12.88b	12.47b	18.29a	43.64ab	8.94b	10.66b	14.72a	34.33ab	3.94a	1.81a	3.56a	9.31a
Moldboard plow	11.37b	14.23ab	14.31b	39.90b	8.64b	11.90ab	11.96b	32.50b	2.72a	2.33a	2.35a	7.40a

† TC, total soil organic C; MFC, mineral fraction C; POMC, particulate organic matter C.
‡ Values in column followed by the same letter are not significantly different at $P < 0.05$.

moisture content as the independent variable. Linear and quadratic regression analyses were also performed between cumulative soil CO_2 emission and TC, MFC, POMC, or the time following tillage practices over the entire 480-h measurement period for each treatment. In addition, linear regression analysis was conducted by using the inverse of cumulative soil CO_2 emission as the dependent variable and the inverse of time after tillage operations as the independent variable for each treatment for the entire 480-h measurement period according to the Lineweaver–Burk transformation of the Michaelis–Menton equation.

RESULTS AND DISCUSSION

Tillage Effects on Soil Organic Carbon

A significant soil depth × tillage interaction effect ($p = 0.004$) on TC is observed (Table 2). At the 0- to 5-cm soil depth, TC is approximately 32% greater in no-tillage and strip-tillage treatments compared with chisel plow. Soil TC is 36 to 41% greater with no-tillage and strip-tillage treatments compared with chisel plow at the 5- to 10-cm soil depth interval. However, no significant difference in TC at 10 to 15 cm is observed when no-tillage and strip-tillage compared with chisel plow. Our results generally suggest reducing tillage intensity in a corn–soybean rotation can enhance TC at the 0- to 15-cm soil depth.

Similar to TC, the soil depth × tillage interaction effect ($p = 0.003$) on MFC is significant (Table 2). Mineral fraction C at 0 to 5 cm is increased by 35 to 42% for no-tillage and strip-tillage compared with other tillage systems. Soil MFC at 5 to 10 cm is approximately 25 to 29% greater for no-tillage and strip-tillage than chisel plow. At 0 to 15 cm, other tillage systems had similar MFC compared with chisel plow. No significant tillage or soil depth × tillage effect on POMC was observed (Table 2), although numerical increases were frequently detected under no-tillage, strip-tillage, and deep rip treatments relative to chisel plow.

Monreal and Janzen (1993) reported that although soil organic C changes in response to management practices could be relatively rapid, it still took about 10 yr to obtain stable management effects. By the time our soil C measurements were made, it had been only 3 yr after no-tillage was initiated. Therefore, TC, MFC, and POMC levels likely have not reached a steady state in no-tillage, and the impact of no-tillage on increasing TC, MFC, and POMC would be greater with time.

Tillage Effects on Total Carbon Input from Crop Residue

Total C input from aboveground crop residue is significantly affected by tillage ($p = 0.02$) (Table 3). Total C input in 3 yr was 10% lower with strip-tillage than chisel plow. All other tillage systems have similar total C input as chisel plow. Therefore, TC and MFC increases at 0 to 10 cm with no-tillage; strip-tillage over chisel plow (Table 2) could not be attributed to the total C input from aboveground crop residue in such a short period. Rather, it might relate to decreased mineralization of soil organic matter due to less soil disturbance and cooler soil conditions in no-tillage and strip-tillage.

Tillage and Crop Residue Effects on Soil Carbon Dioxide Emission

Significant treatment effects on soil CO_2 emission are observed at almost all measuring times although CO_2 emission varied tremendously with time regardless of treatment (Fig. 1). At Hour 0 measurement time, no-tillage with and without residue, strip-tillage, deep rip, and chisel plow treatments reduced CO_2 emission by 79, 79, 60, 50, and 14%, respectively, compared with moldboard plow immediately after tillage operations. Although all CO_2 emission reductions with less intensive tillage alternatives are statistically significant, the greatest reductions in CO_2 emission are associated with those tillage systems having less soil disturbance, such as the two no-tillage treatments. Removal of crop residue from the soil surface under no-tillage did not alter CO_2 emission significantly compared with no-tillage with residue at the measurement time of Hour 0.

At the 2nd h measurement time, CO_2 emission from no-tillage with and without residue and strip-tillage are

Table 3. Tillage effects on C input from aboveground corn and soybean residue during the first 3 yr in a corn–soybean rotation.

Tillage system	C input†		
	Corn	Soybean	Total
	Mg ha⁻¹		
No-tillage	5.47a‡	2.76a	8.23ab
Strip-tillage	5.02a	2.44a	7.46b
Deep rip	5.86a	2.84a	8.70a
Chisel plow	5.65a	2.64a	8.29a
Moldboard plow	5.86a	2.90a	8.76a

† Carbon input under columns of corn, soybean, and total refers to C input from 1 yr corn, 2 yr soybean, and all 3 yr, respectively.
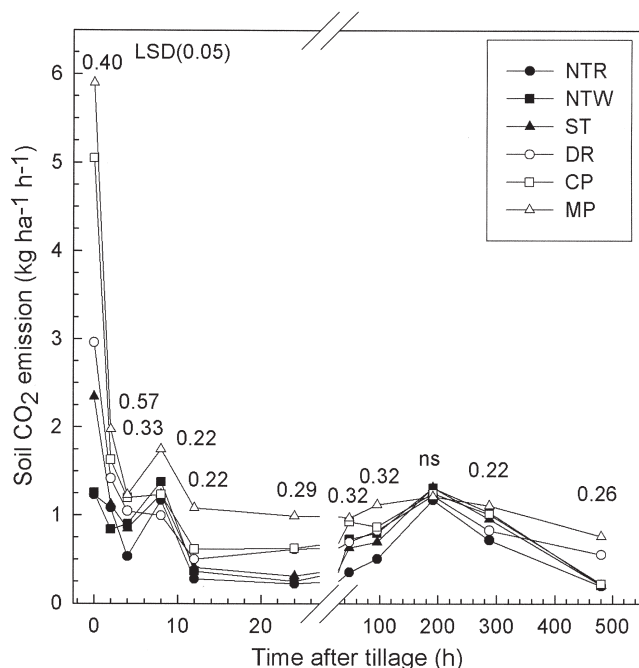‡ Values in column followed by the same letter are not significantly different at $P < 0.05$.

Fig. 1. Tillage and crop residue effects on soil CO_2 emission after 3 yr in a corn–soybean rotation. Least significant difference (LSD) at $P < 0.05$ for each measuring time is provided in the graph; NS, not significant at $P < 0.05$. NTR, no-tillage with residue; NTW, no-tillage without residue; ST, strip-tillage; DR, deep rip; CP, chisel plow; MP, moldboard plow.

residue results in greater CO_2 emission than no-tillage with residue at the measurement times of Hour 4, 48, and 288. Our results generally confirm the potential of reducing tillage intensity and increasing crop residue on the soil surface in reducing soil CO_2 emission to the atmosphere in a corn–soybean rotation.

The maximum CO_2 emission from all tilled treatments (strip-tillage, deep rip, chisel plow, and moldboard plow) is observed immediately after tillage operations (i.e., at Hour 0 measurement time) (Fig. 1). However, CO_2 emission from these tilled treatments decreases sharply by 52 to 68% within the first 2 h following tillage operations. In contrast, the two no-tillage treatments have only 12 to 33% reduction during the same period (2 h after tillage operations). After the first 2 h, changes in CO_2 emission are much smaller regardless of treatment unless there is a sharp change in soil temperature or moisture. Reicosky et al. (1997) reported that CO_2 emission decreased rapidly by 80% immediately after tillage operations on a harvested wheat field, which is greater than the reductions we observed in our study.

A sharp increase in CO_2 emission immediately after tillage operations may be attributed to the rapid increase in microbial activities in decomposing the labile soil organic matter pool. However, Jackson et al. (2003) and Roberts and Chan (1990) concluded that the increase in soil CO_2 emission immediately after tillage operation was not due to the increase in microbial activities, but it was rather due to the increase in soil aeration that was induced by tillage disturbance. Reicosky and Lindstrom (1993) also attributed greater CO_2 emission immediately after tillage practices to greater physical CO_2 emission from soil pores and solution.

Periodic soil CO_2 emission differs significantly among the treatments during most of these measurement periods (Table 4). For example, both no-tillage with residue and strip-tillage result in significantly less CO_2 emission than moldboard plow during all measurement periods except Hour 96 to 192 and 192 to 288 periods after tillage operations. Cumulative CO_2 emission for the entire 20-d period following tillage are 41, 26, 21, and 19% lower for no-tillage with residue, strip-tillage, deep rip, and chisel plow than with moldboard plow, respectively (Table 4). Cumulative CO_2 emission from no-tillage without residue is 23% lower than that with moldboard plow, but 24% greater than the CO_2 emission from no-tillage with residue over the 20-d period.

In summary, lower CO_2 emission from no-tillage with residue than moldboard plow in our study could be

43 to 58% less than from moldboard plow (Fig. 1), while chisel plow and deep rip treatments have statistically similar CO_2 emission as moldboard plow. The differences in CO_2 emission between the two no-tillage and moldboard plow treatments are significantly smaller at the 2nd h of measurement time than those at Hour 0 according to a paired t test.

Beyond 2 h following tillage operations, no-tillage with residue produces a significantly lower CO_2 emission than moldboard plow at all the measurement times except the 192nd h (Fig. 1). Compared with moldboard plow, CO_2 emission is less from no-tillage without residue at all the measurement times except at Hour 48, 192, and 288 after tillage operations. Similarly, strip-tillage produces lower CO_2 emission than moldboard plow at all measuring times except at Hour 192 and 288. Soil CO_2 emission is significantly less from deep rip than moldboard plow at Hour 8, 12, 24, and 288 measurement times. Similarly, chisel plow has significantly lower CO_2 emission than moldboard plow at Hour 8, 12, 24, and 480 after tillage operations. In addition, no-tillage without

Table 4. Tillage and crop residue effects on soil CO_2 emission after 3 yr in a corn–soybean rotation.

	Time period after tillage operations										
Tillage system	0–2 h	2–4 h	4–8 h	8–12 h	12–24 h	1–2 d	2–4 d	4–8 d	8–12 d	12–20 d	Total
	kg ha^{-1}										
No-tillage with residue	2.31e†	1.61c	3.40c	2.89d	3.00d	6.89d	20.62c	80.60a	90.86a	88.19c	300.36c
No-tillage without residue	2.09e	1.74bc	4.56b	3.49bc	3.73d	11.79bcd	36.63ab	101.12a	112.27a	118.94bc	396.36b
Strip-tillage	3.46d	1.97bc	4.16bc	3.28bcd	4.32cd	11.35cd	31.96bc	96.45a	108.89a	111.73bc	377.57bc
Deep rip	4.37c	2.46ab	4.08bc	2.99cd	6.68bc	15.73bc	36.50ab	98.28a	98.47a	132.66b	402.20b
Chisel plow	6.68b	2.82a	4.87b	3.70b	7.44b	18.63ab	43.06ab	101.51a	108.54a	118.61bc	415.83b
Moldboard plow	7.87a	3.20a	5.96a	5.66a	12.41a	23.43a	50.09a	111.94a	111.36a	179.43a	511.34a

† Values in column followed by the same letter are not significantly different at $P < 0.05$.

partially attributed to slower decomposition of crop residue placed on the soil surface in no-tillage than when they were incorporated with moldboard plow (Curtin et al., 2000). Meanwhile, tillage operations may physically facilitate gas emission from the soil pores due to soil disturbance (Ellert and Janzen, 1999). Our results show trends similar to others (Reicosky et al., 1999; Dao, 1998; Jacinthe et al., 2002). Reicosky et al. (1999) reported that cumulative soil CO_2 emission from conventional tillage at the end of 80 h was nearly three times larger than from no-tillage. Additionally, crop residue on the soil surface with no-tillage contributes to the

reduction of soil CO_2 emission by serving as a barrier for CO_2 emission from soil to the atmosphere, having a lower crop residue decomposition rate due to minimum residue-soil contact, and lowering soil temperature (Reicosky et al., 1999).

Soil temperature at 5 cm during the 20-d measurement period ranged from −9 to 6°C (Fig. 2). Soil temperature changes from one measurement time to another are similar for all treatments. Soil temperature is below zero at Hour 24, 48, 96, 288, and 480 measurement times regardless of treatment. Accordingly, CO_2 emission is also low at these measurement times regardless of treatment (Fig. 1). This observation confirms that soil CO_2 emission is affected by soil temperature. Furthermore, tillage and crop residue effects on soil temperature are significant at 4 of 11 measurement times during the 20-d period (Fig. 2). Our soil temperature results generally agree with those by Reicosky et al. (1997), who observed that the relatively small temperature differences among tillage treatments probably had less influence on soil CO_2 emission than the differences in tillage-induced soil disruption.

Compared with soil temperature, fluctuations in soil moisture are much lower during the 20-d measurement period (Fig. 2). In general, the two no-tillage treatments result in significantly higher soil moisture than moldboard plow (data not presented). Chisel plow and strip-tillage treatments have similar moisture content during the first 12 h after tillage operations, but significantly higher moisture when compared with moldboard plow. Soil moisture is similar or higher under deep rip relative
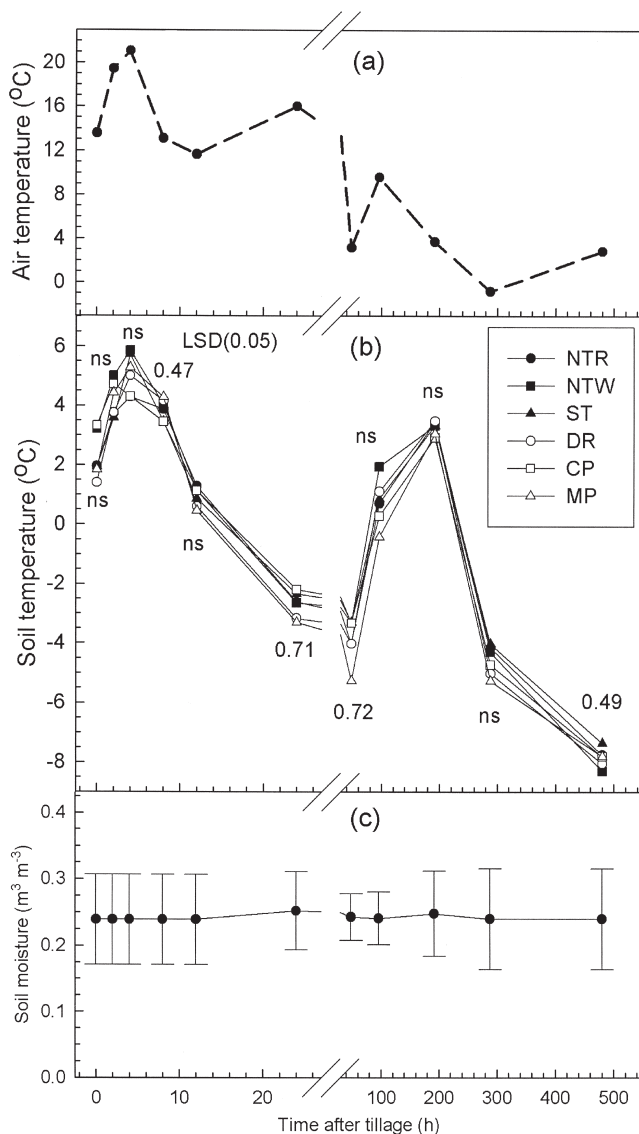

Fig. 2. (a) Air temperature, (b) soil temperature, and (c) soil moisture in the top 5 cm of different tillage systems and residue covers from 7 to 26 Nov. 2001, after 3 yr in a corn–soybean rotation. For soil temperature, least significant difference (LSD) at $P < 0.05$ for each measurement time is provided; NS, not significant at $P < 0.05$. For soil moisture, an error bar for each measurement time is provided. NTR, no-tillage with residue; NTW, no-tillage without residue; ST, strip-tillage; DR, deep rip; CP, chisel plow; MP, moldboard plow.
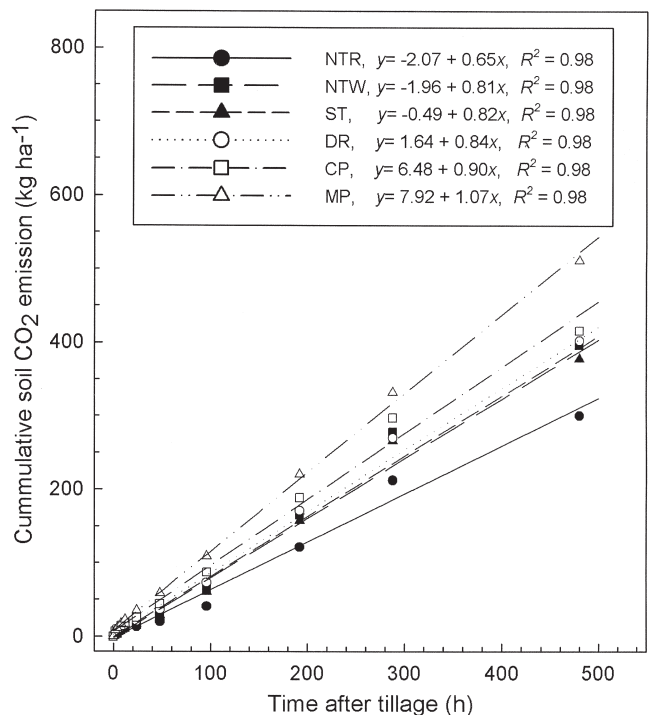

Fig. 3. Tillage and crop residue effects on cumulative soil CO_2 emission after 3 yr in a corn–soybean rotation. NTR, no-tillage with residue; NTW, no-tillage without residue; ST, strip-tillage; DR, deep rip; CP, chisel plow; MP, moldboard plow.

to moldboard plow. A significant difference in soil moisture is observed between the two no-tillage treatments only at Hour 192 and 288 measurement times, when no-tillage with residue has greater soil moisture. Overall, soil moisture effects on CO$_2$ emission seem to be minor during such a short period of time.

Regression Analysis of Carbon Dioxide Emission with Soil Temperature and Moisture

Linear regression analysis of the data set across all treatments over time reveals a statistically significant relationship between CO$_2$ emission and soil temperature. However, the contribution of soil temperature to variation in CO$_2$ emission is low ($R^2 = 0.23$). This can be attributed to low soil temperatures and narrow amplitude in temperature ranges during the measurement period. Soil CO$_2$ emission is not linearly related to soil moisture, where changes in soil moisture over the measurement period are not significant.

Because CO$_2$ emission is measured during November in our study, soil temperature was low and soil moisture was generally stable over time. These facts may explain why CO$_2$ emission is weakly correlated with soil temperature and not associated with soil moisture. Our results are different from those reported in previous studies (Kirschbaum, 1995; Follett, 1997), where CO$_2$ emission was

monitored for an entire growing season or calendar year. Both Kirschbaum (1995) and Follett (1997) reported that soil temperatures primarily governed seasonal variations in soil CO$_2$ emission, with high soil CO$_2$ emission during the summer when soil moisture and substrate C were adequate and low CO$_2$ emission during the winter when soil biological activity was minimal due to near-freezing soil temperatures. Therefore, given the timing of our study, soil CO$_2$ emission is most likely due to CO$_2$ exchange through soil pores rather than by microbial activity. These findings show the effects of tillage that is normally conducted in the fall on soil C loss in the Corn Belt region.

Regression of Cumulative Soil Carbon Dioxide Emission with Soil Organic Carbon Pools and Time

No significant linear or quadratic relationship between cumulative soil CO$_2$ emission and TC, MFC, or POMC is observed over the 480-h measurement period regardless of treatment (data not presented). This finding indicates that soil organic C substrate is not the limiting factor to soil CO$_2$ emission. Rather, soil CO$_2$ emission in such a short-term experiment may be governed by soil structural pore changes due to tillage and microbial community population and its activity. This is reason-
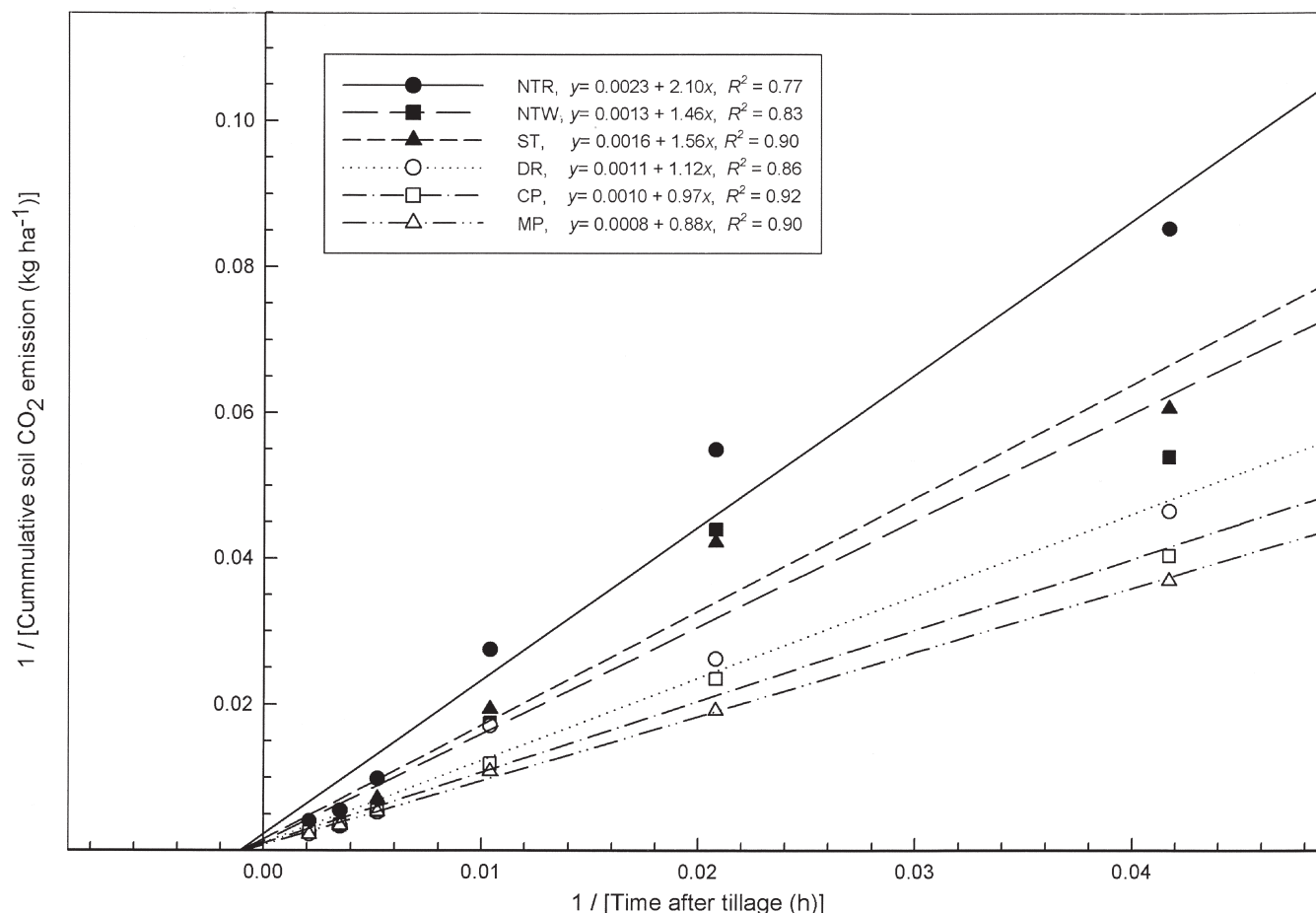

Fig. 4. Linear plot of the Michaelis–Menten equation for cumulative soil CO$_2$ emission. NTR, no-tillage with residue; NTW, no-tillage without residue; ST, strip-tillage; DR, deep rip; CP, chisel plow; MP, moldboard plow.

able because our measurements were taken for only a 3-wk period in early November, when farmers normally conduct the tillage operations. In addition, low soil temperatures and stable soil moisture during the measurement period may cause a decrease in microbial activity, thus reducing the significance of relationship between cumulative soil CO_2 emission and TC, MFC, or POMC. Overall, our results suggest that short-term measurement of CO_2 emission during the dormant season can be considered as an indicator of soil physical changes due to tillage disturbance and microbial activity rather than soil organic C pool levels.

Cumulative soil CO_2 emission and time after tillage operations is linearly related regardless of treatment (Fig. 3). Slope of the equation decreases as tillage intensity is reduced. Moldboard plow has the greatest slope and no-tillage with residue has the lowest slope. This finding suggests that cumulative soil CO_2 emission to the atmosphere can be lowered by adopting less intensive tillage systems compared with moldboard plow.

Determination of Mineralizable Carbon under Different Tillage Systems

The Lineweaver–Burk transformation of Michaelis–Menton equation applied to cumulative soil CO_2 emission vs. time after tillage operations is shown in Fig. 4 for each tillage system. There is a linear relationship between the inverse of cumulative soil CO_2 emission and the inverse of time after tillage operations regardless of tillage system. Inverse of the intercept of each linear relationship represents the size of potentially mineralizable C pool (C_{max}) due to the effect of each tillage system. The C_{max} value is lower with less intensive tillage systems compared with moldboard plow (Table 5). No-tillage with and without residue, strip-tillage, deep rip, and chisel plow reduced the size of mineralizable portion of the maximum C pool (C_{max}) by 66, 40, 51, 28, and 22% relative to moldboard plow, respectively. This trend suggests adopting less intensive tillage systems and maximizing residue coverage on the soil surface can reduce the amount of C mineralized due to tillage.

CONCLUSIONS

Reducing the intensity of tillage operations could increase soil C storage in a corn–soybean rotation from a short-term perspective. No-tillage with residue and strip-tillage significantly increase TC and MFC at the 0- to 5- and 5- to 10-cm soil depths compared with chisel plow after 3 yr of tillage practices. This short-term tillage effect is not attributed to the annual C input from above-

ground crop residue, but most likely is related to decreased mineralization rate of soil organic matter with no-tillage.

Soil CO_2 emission is generally lower with less intensive tillage alternatives relative to moldboard plow, with the greatest differences occurring at the time immediately following tillage operations. Over the 480-h measurement period, less intensive tillage alternatives lower cumulative soil CO_2 emission by 19 to 41% compared with moldboard plow. Carbon dioxide emission is 24% less with no-tillage with residue than without residue covers.

Relationship of soil CO_2 emission with TC, MFC, POMC, soil temperature, or moisture content is not observed or was weak over the short period of measurement. However, a positive linear relationship between cumulative CO_2 emission and time is observed. Estimated mineralizable C pool is reduced by 22 to 66% with less intensive tillage alternatives relative to moldboard plow. The decrease in mineralizable C pool may be partially responsible for the reduced soil CO_2 emission, especially from the no-tillage treatments.

Our results suggest that from a short-term perspective, adopting less intensive tillage alternatives such as no-tillage and strip-tillage and leaving more crop residue cover on the soil surface are effective in reducing soil CO_2 emission, and thus improving soil C sequestration in a corn–soybean rotation in Corn Belt soils. The benefit of less soil CO_2 emission or C loss along with other economic and environmental advantages such as higher production profitability and less soil erosion, associated with less intensive tillage and better crop residue management systems, should be taken into account when soil management decisions are made for conservation planning.

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Table 5. Maximum mineralizable soil C under different tillage systems estimated by the Lineweaver–Burk transformation of the Michaelis–Menten equation.

Tillage system	C_{max}, kg ha^{-1}
No-tillage with residue	435
No-tillage without residue	775
Strip-tillage	629
Deep rip	935
Chisel plow	1010
Moldboard plow	1294

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