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

Mahdi M. Al-Kaisi* and Xinhua Yin

ABSTRACT

Soil C change and CO2 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 CO2 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 CO2 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 pool at the 0- to 5- and 5- to 10-cm soil depths compared with chisel plow after 3 yr of tillage practices. Soil CO2 emission was lower for less intensive tillage treatments compared with moldboard plow, with the greatest differences occurring immediately after tillage operations. Cumulative soil CO2 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 CO2 emission and thus improving soil C sequestration in a corn–soybean rotation.

Soil 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 (CO2) has been considered a major contributor to global warming. Carbon loss from soil to the atmosphere as CO2 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 CO2 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 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 CO2 emission is normally controlled by several factors, such as CO2 concentration gradient between the soil and the atmosphere, soil temperature, soil moisture, pore size, and wind speed (Raich and Schlesinger, 1992). In addition, soil CO2 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 CO2 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 CO2 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 CO2 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 CO2 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 CO2 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

Abbreviations: MFC, mineral fraction C; POMC, particulate organic matter C; TC, total soil organic C.
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 CO₂ 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 extremest 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 CO₂ 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 Canistoe (fine-loamy, mixed, calcareous, mesic Typic Hapludolls) 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 treatment 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 CO₂ 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 was no-tillage without corn residue cover on the soil surface, where the surface residues were completely removed by hand from inside the CO₂ measurement chambers. The CO₂ measurement chambers were installed on all plots immediately after tillage operations and kept in the same place for the entire duration of CO₂ 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 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 (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 (kg C m⁻³) 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-m² frame thrown randomly on each plot three times to collect the aboveground crop residue. Residue samples were oven-

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.

### 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

\[
  v = V_{\text{max}} \times \frac{S}{(K_m + S)}
\]

where \(v\) is the reaction velocity, \(V_{\text{max}}\) 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–Menten equation can also be used to describe the relationship between cumulative soil CO₂ emission and time. To calculate the amount of mineralizable C (i.e., the maximum cumulative soil CO₂ emission) due to different tillage systems, the Lineweaver–Burk transformation (Tabatabai, 1994) of the Michaelis–Menten equation was used

\[
  \frac{1}{c} = \frac{1}{C_{\text{max}}} + \frac{K_m}{C_{\text{max}}} \times \frac{1}{T}
\]

where \(c\) (kg CO₂ ha⁻¹) is cumulative soil CO₂ emission at a specific time after tillage operations, \(T\) is the time (h) after tillage operations, \(C_{\text{max}}\) (kg CO₂ ha⁻¹) is the potential maximum amount of cumulative soil CO₂ emission under a specific tillage system, and \(K_m\) is the Michaelis constant, which equals to the time (h) at half-maximum cumulative soil CO₂ 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 CO₂ 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 CO₂ 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 \(\times\) 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 was 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 CO₂ emission rate as the dependent variable and soil temperature or...
moisture content as the independent variable. Linear and quadratic regression analyses were also performed between cumulative soil CO2 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 CO2 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 0- 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.

<table>
<thead>
<tr>
<th>Tillage system</th>
<th>TC soil depth, cm</th>
<th>MFC soil depth, cm</th>
<th>POMC soil depth, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0–5</td>
<td>5–10</td>
<td>10–15</td>
</tr>
<tr>
<td>No-tillage</td>
<td>17.05 a‡</td>
<td>16.93 a</td>
<td>18.69 a</td>
</tr>
<tr>
<td>Strip-tillage</td>
<td>16.89 a</td>
<td>17.56 a</td>
<td>18.54 a</td>
</tr>
<tr>
<td>Deep rip</td>
<td>12.26 b</td>
<td>13.00 b</td>
<td>19.40 a</td>
</tr>
<tr>
<td>Chisel plow</td>
<td>12.88 b</td>
<td>12.47 b</td>
<td>18.29 a</td>
</tr>
<tr>
<td>Moldboard plow</td>
<td>11.37 b</td>
<td>12.43ab</td>
<td>14.31 b</td>
</tr>
</tbody>
</table>

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

Tillage Effects on Total Carbon Input from Crop Residue

Total C input from aboveground corn 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.

<table>
<thead>
<tr>
<th>Tillage system</th>
<th>Corn</th>
<th>Soybean</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mg ha</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No-tillage</td>
<td>5.47 a</td>
<td>2.76 a</td>
<td>8.23 a</td>
</tr>
<tr>
<td>Strip-tillage</td>
<td>5.02 a</td>
<td>2.44 a</td>
<td>7.46 a</td>
</tr>
<tr>
<td>Deep rip</td>
<td>5.86 a</td>
<td>2.84 a</td>
<td>8.70 a</td>
</tr>
<tr>
<td>Chisel plow</td>
<td>5.65 a</td>
<td>2.64 a</td>
<td>8.29 a</td>
</tr>
<tr>
<td>Moldboard plow</td>
<td>5.86 a</td>
<td>2.90 a</td>
<td>8.76 a</td>
</tr>
</tbody>
</table>

† 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 \( P < 0.05 \).
residue results in greater CO₂ 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 CO₂ emission to the atmosphere in a corn–soybean rotation.

The maximum CO₂ 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, CO₂ 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 CO₂ emission are much smaller regardless of treatment unless there is a sharp change in soil temperature or moisture. Reicosky et al. (1997) reported that CO₂ 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 CO₂ 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 CO₂ emission immediately after tillage operation was not due to the increase in microbial activities, but rather due to the increase in soil aeration that was induced by tillage disturbance. Reicosky and Lindstrom (1993) also attributed greater CO₂ emission immediately after tillage practices to greater physical CO₂ emission from soil pores and solution.

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Beyond 2 h following tillage operations, no-tillage with residue produces a significantly lower CO₂ emission than moldboard plow at all the measurement times except the 192nd h (Fig. 1). Compared with moldboard plow, CO₂ emission is less from no-tillage without residue at all the measurement times except at Hour 192 and 288 after tillage operations. Similarly, strip-tillage produces lower CO₂ emission than moldboard plow at all measuring times except at Hour 192 and 288. Soil CO₂ 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 CO₂ emission than moldboard plow at Hour 8, 12, 24, and 480 after tillage operations. In addition, no-tillage without residue at Periodic soil CO₂ 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 CO₂ emission than moldboard plow during all measurement periods except Hour 96 to 192 and 192 to 288 periods after tillage operations. Cumulative CO₂ emission for the entire 21-d period following tillage are 41, 26, 21, and 24% greater than the CO₂ emission from no-tillage with moldboard plow at Hour 8, 12, 24, and 480 after tillage operations. In summary, lower CO₂ emission from no-tillage with residue than moldboard plow in our study could be

<table>
<thead>
<tr>
<th>Time period after tillage operations</th>
<th>0–2 h</th>
<th>2–4 h</th>
<th>4–8 h</th>
<th>8–12 h</th>
<th>12–24 h</th>
<th>1–2 d</th>
<th>2–4 d</th>
<th>4–8 d</th>
<th>8–12 d</th>
<th>12–20 d</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>kg ha⁻¹</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No-tillage with residue</td>
<td>2.31†</td>
<td>1.61c</td>
<td>3.40c</td>
<td>2.89d</td>
<td>3.00d</td>
<td>6.89d</td>
<td>20.62c</td>
<td>80.60a</td>
<td>90.86a</td>
<td>88.19c</td>
<td>300.36c</td>
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<tr>
<td>No-tillage without residue</td>
<td>2.09c</td>
<td>1.74c</td>
<td>4.56b</td>
<td>3.49bc</td>
<td>3.73d</td>
<td>11.79cd</td>
<td>36.63ab</td>
<td>101.12a</td>
<td>112.27a</td>
<td>118.94c</td>
<td>396.36b</td>
</tr>
<tr>
<td>Strip-tillage</td>
<td>3.46d</td>
<td>1.97bc</td>
<td>4.10c</td>
<td>3.28cd</td>
<td>4.32cd</td>
<td>11.35cd</td>
<td>31.96bc</td>
<td>96.45a</td>
<td>108.89a</td>
<td>111.73bc</td>
<td>377.57bc</td>
</tr>
<tr>
<td>Deep rip</td>
<td>4.37c</td>
<td>2.46ab</td>
<td>4.08bc</td>
<td>2.90cd</td>
<td>6.68bc</td>
<td>15.73bc</td>
<td>36.50ab</td>
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<td>108.54a</td>
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<td>Chisel plow</td>
<td>6.68b</td>
<td>2.82a</td>
<td>4.87b</td>
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<td>7.44b</td>
<td>18.63ab</td>
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<td>Moldboard plow</td>
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<td>5.96a</td>
<td>5.66a</td>
<td>12.41a</td>
<td>23.43a</td>
<td>59.09a</td>
<td>111.94a</td>
<td>111.36a</td>
<td>179.43a</td>
<td>511.34a</td>
</tr>
</tbody>
</table>

† 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 CO₂ 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 CO₂ emission by serving as a barrier for CO₂ 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, CO₂ emission is also low at these measurement times regardless of treatment. Our results generally agree with those by Reicosky et al. (1997, 1999), who observed that the relatively small temperature differences among tillage treatments probably had less influence on soil CO₂ 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 to 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-
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 CO2 emission and TC, MFC, or POMC. Overall, our results suggest that short-term measurement of CO2 emission during the dormant season can cumulative soil CO2 emission by 19 to 41% compared with no-tillage with residue than without residue covers.

Cumulative soil CO2 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 CO2 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–Menten equation applied to cumulative soil CO2 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 CO2 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 (Cmax) due to the effect of each tillage system. The Cmax 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 (Cmax) 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 CO2 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 CO2 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 CO2 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 CO2 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 CO2 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 CO2 emission and thus improving soil C sequestration in a corn–soybean rotation in Corn Belt soils. The benefit of less soil CO2 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.

**REFERENCES**


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