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Carbon and Nitrogen Storage are Greater under Biennial Tillage in a Minnesota Corn–Soybean Rotation

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ABSTRACT

Few studies have examined the impacts of rotational tillage regimes on soil carbon (C) and nitrogen (N). We measured the C and N content of soils managed under corn (*Zea mays* L.)–soybean (*Glycine max* L.) rotation following 10 and 15 yr of treatments. A conventional tillage (CT) regime employing moldboard and chisel plowing in alternate years was compared with both continuous no-till (NT) and biennial tillage (BT), which employed chisel plowing before soybean only. While masses of C and N in the upper 0.3 m under both BT and NT were higher than CT, only the BT treatment differed from CT when the entire sampled depth (0.6 m) was considered. Decreased C inputs, as indicated by reduced grain yields, may have limited C storage in the NT system. Thus, while more C was apparently retained under NT per unit of C input, some tillage appears necessary in this climate and cropping system to maximize C storage. Soil carbon dioxide (CO_2) fluxes under NT were greater than CT during a drier than normal year, suggesting that C storage may also be partly constrained under NT due to wetter conditions that promote increased soil respiration. Increased temperature sensitivity of soil respiration with increasing soil moisture was also observed. These findings indicate that long-term biennial chisel plowing for corn–soybean in the upper mid-west USA can enhance C storage, reduce tillage-related fuel costs, and maintain yields compared with more intensive annual tillage.

Reduced tillage agriculture has been promoted since approximately 1960 as a means of conserving water, fuel, and soil, as well as enhancing fertility and intensifying crop production (Six et al., 2002). More recently, no-till (NT) and other conservation tillage practices have been examined in the context of rising global atmospheric concentrations of CO_2 and other greenhouse gases (GHGs) (Kern and Johnson, 1993). Some studies have suggested that the GHG contribution of agriculture as a whole can be mitigated by widespread adoption of reduced tillage (Lal and Kimble, 1997). However, the effectiveness of reduced tillage in mitigating the GHG impact of individual agro-ecosystems can vary substantially depending on factors including climate, drainage, texture, and antecedent soil C content (Paustian et al., 1995; Wander et al., 1998). Studies across a range of conditions are required to assess the broader GHG impacts of reduced tillage.

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Studies examining tillage effects on soil C have generally compared NT with one or more distinct tillage operations, for example, annual moldboard or chisel plowing. Very few studies have compared treatments that utilize more than one type of tillage operation or examined intermittent no-till within a multi-year rotation (Omonode et al., 2006; Yang and Wander, 1999). Rotational tillage may be particularly useful in crop rotations where residue characteristics vary substantially between crops. Rotational regimes allow tillage intensity to be more finely adjusted so that benefits can be more optimally balanced against risks on a site-specific basis. For example, continuous no-till for corn cultivation in the north central USA may not be feasible due to delayed seedling emergence and decreased corn yields (Cox et al., 1990). Rotational tillage sequences may overcome these problems while minimizing unnecessary tillage.

While more than 60 studies examining long-term tillage effects on soil C have been conducted in the past three decades (West and Post, 2002; VandenBygaart et al., 2003), the overwhelming majority of studies have employed sampling to soil depths not exceeding 0.4 m. Studies using deeper sampling generally have reported no difference in soil C under reduced compared with conventional tillage across the entire sampled depth (Dolan et al., 2006; Carter, 2005; Jarecki and Lal, 2005; Deen and Kataki, 2003; Machado et al., 2003; Yang and Wander, 1999; Angers et al., 1997; Powlson and Jenkinson, 1981). While accumulation of soil C and N close to the surface may have several agronomic and environmental benefits, the vertical redistribution of C by itself does not constitute GHG mitigation.

Reduced tillage can alter soil moisture and temperature (Cox et al., 1990). Moisture and temperature, in turn, are strong regulators of soil respiration (Linn and Doran, 1984; Katterer et al., 1998). Several studies have focused on short-term responses of soil CO_2 emissions occurring within hours or days following tillage operations (Reicosky and Lindstrom, 1993; Rochette and Angers, 1999). Less consideration has been given to differences in soil CO_2 emissions that may persist during the remainder of the growing season possibly as a result of long-term tillage management (Franzluebbers et al., 1995).

The objective of the current study was to examine changes in soil C and N resulting from more than a decade of rotational tillage management in a corn–soybean rotation in southeastern Minnesota. Particular attention was given to the vertical distribution of soil C and N, and how consideration of varying soil profile depths affected estimates of C and N storage. During the course of two

Abbreviations: BT, biennial tillage; CT, conventional tillage; GHG, greenhouse gas; NT, no-till; WFPS, water-filled pore space.

consecutive growing seasons, we also measured soil CO_2 fluxes, moisture content, and temperature to examine how these factors may mediate any observed differences in soil C or N.

MATERIALS AND METHODS

Site Description and Experimental Design

Plots were located at the University of Minnesota's Research and Outreach Station in Rosemount, MN (44° 45′ N, 93° 04′ W). Soil at the site was a Waukegan silt loam (fine-silty over sandy or sandy-skeletal mixed, superactive mesic Typic Hapludoll) containing 22% sand, 55% silt, and 23% clay, with pH (1:1 H_2O) of 6.0 to 6.6, and slope <2%. The loess-derived silt loam is underlain starting at 0.6 to 0.8 m by outwash sands. Annual 30-yr mean precipitation is 879 mm, and annual mean temperature is 6.4°C. The site was planted in alfalfa (*Medicago sativa*) before 1987 and corn from 1987 to 1990 before establishing a corn–soybean rotation. In 1990, a 7.3-ha section of field (360 by 200 m) was subdivided into 36 plots (27.4 by 61 m) arranged in a 3-plot by 12-plot matrix with 3- to 10-m buffer zones between plots. Treatments examined in the current study were applied to 18 of the plots, representing six replicates of three tillage treatments. Treatments were assigned to plots using a completely randomized design. Every year, three plots of each tillage treatment were planted in corn and the other three in soybean. Tillage treatments consisted of: (i) Conventional tillage (CT) employing fall moldboard plowing following corn, fall chisel plowing or disk-ripping following soybean, with spring preplant cultivation before both corn and soybean, (ii) biennial tillage (BT) employing fall chisel plowing or disk-ripping following corn, no fall plowing following soybean, with spring cultivation before soybean only, and (iii) no-till (NT) employing no fall tillage or spring cultivation. Moldboard plowing was typically done to a depth of 0.18 m. Chisel plowing utilized 0.2-m deep shanks with 0.3-m spacing. Chisel plowing was replaced by disk ripping in 2000. Disk ripping utilized 0.3-m deep shanks with 0.76-m spacing, and two sets of 0.15-m deep disks. Corn stalks were chopped after harvest each fall before tillage, and no residue was removed. Urea was surface applied during corn years at 100 to 120 kg N ha^{-1} in the spring when plant height was approximately 0.3 m, and when 10 mm of rainfall was expected within the following 12 to 24 h.

Soil Carbon and Nitrogen

In mid-June of 2000 and 2005, soil cores to a depth of 0.60 m were taken from all plots. In 2000, a hand-held soil corer (19 mm ID) was used. In 2005, cores were collected using a hydraulic sampler (37 mm ID) equipped with a high-relief bit to minimize soil compaction (Giddings, Windsor, CO). The mean ratio of extruded soil core length to sampler insertion depth was >0.97. Ten cores were taken from randomly selected locations centered between rows of each plot. Each core was segregated into the following depth intervals: 0 to 0.05, 0.05 to 0.1, 0.1 to 0.2, 0.2 to 0.3, 0.3 to 0.45, and 0.45 to 0.6 m. A single composite sample for each depth interval was generated by combining the respective interval from each of the 10 cores. The total (wet) mass of each composite was determined before subsampling for gravimetric water content determination by drying at 105°C. The entire content of each composite was air-dried and ground using a mechanical grinder (Nasco, Fort Atkinson, WI). A portion of the total ground sample was sieved through 2 mm. Subsamples (~20 g) were then further ground by ball milling, and analyzed for total C and N content using an elemental analyzer (Model NA 1500 NC, Carlo Erba/Fisons Instruments, Milan, Italy). Soil pH was <7.0 and no free carbonates were present in the upper 0.6 m, so total C was assumed to equal organic C. Bulk density was determined from dry soil mass contained in each depth interval composite sample.

Carbon Dioxide Fluxes

During each of two consecutive growing seasons (2003 and 2004), soil CO_2 flux (F_{CO2}) was measured in nine plots planted in corn following soybean, that is, a different set of plots were studied each year. Measurements were made on 100 separate dates, at a frequency of approximately twice per week during 28 May through 20 Nov. 2003, 26 Apr. through 15 Dec. 2004, and 4 Feb. through 7 Apr. 2005. Data collected in early 2005 were treated statistically as a continuation of the 2004 growing season. Planting occurred on 20 May 2003 and 10 May 2004, corn was harvested on 14 Oct. 2003 and 10 Nov. 2004, and tillage occurred on 3 Nov. 2003 and 17 Nov. 2004.

For each measurement, vented stainless steel chamber tops with an internal volume of 0.015 m^3 (15 L) (500 mm $\times$ 290 mm $\times$ 102 mm high) were sealed to stainless steel flanged chamber bases that enclosed an area of 0.145 m^2 (500 cm $\times$ 290 cm). Bases were installed for the duration of the season, centered between rows. Gas samples were collected at regular intervals of 0, 30, and 60 min by inserting the needle of a 12-mL polypropylene syringe through a septum in the chamber top and slowly withdrawing 9 to 12 mL. Samples were immediately transferred to 9-mL glass vials sealed with butyl rubber septa (Alltech, Deerfield, IL). We used either pre-evacuated vials, or unevacuated vials containing "ambient" (lab) air. In the latter case, sample concentrations were adjusted for dilution with ambient air concentrations, as determined in four replicate ambient vials analyzed with each set of sample vials (Venterea et al., 2005). Standards were prepared using the same set of prepared vials. Pressurized vials were vented immediately before analysis to equalize all vials to ambient pressure. We found excellent agreement (within 5%) in flux values obtained from the same chamber using either pre-evacuated or unevacuated vials.

Gas samples were analyzed within 3 d of collection by gas chromatography (GC) using a headspace autosampler (Teledyne Tekmar, Mason, OH) connected to a GC (Model 5890, Hewlett-Packard/Agilent, Palo Alto, CA) equipped with a thermal conductivity detector (TCD). The TCD was calibrated with each set of samples using analytical-grade 600, 1000, and 3000 ppm CO_2 standards (Scott Specialty Gases, Plumsteadville, PA). Gas fluxes were calculated from the rate of change in chamber concentration, chamber volume, and soil surface area and were corrected for air temperature using ideal gas relations. For routine sampling, fluxes were measured between 1100 and 1400 local time (LT) when soil temperatures were expected to be close to their daily mean values. On four days during 13 July to 29 July 2004, CO_2 fluxes and corresponding soil temperatures were measured three times per day, at approximately 0700, 1200, and 1700 LT.

Soil Temperature, Moisture, and Ancillary Variables

Soil temperature (T_{50}) was measured during F_{CO2} chamber deployment periods using soil temperature probes (Fisher, Hampton, NH) inserted 50 mm into the soil within 1 m of each chamber. Air temperature was measured using a thermocouple placed in the shade of the corn canopy when present. Air temperature and daily precipitation data were also obtained from a weather station l km from the plots. Soil water content in the upper 100 mm was determined in samples collected within 1 h of each flux measurement period using a steel core sampler (18.3 mm ID) inserted to 100-mm depth. Two or three cores from each plot were combined before drying for 12 to 24 h at 105°C. Bulk density in the upper 100 mm was determined at intervals of 4 to 12 wk by collecting soil cores (18.3 mm ID) from the interrow region followed by drying at 105°C. Bulk density values interpolated between sampling dates were used to estimate water-filled pore space (WFPS) corresponding to each flux and soil water content sampling date.

Data Analysis and Statistics

Soil C and N concentrations for each of the six depth increments were converted to mass units (Mg C or N ha^{-1}) using the measured bulk density values and interval depths. Mass data over all depths were summed to calculate total C and N contained in the upper 0.60 m. Total C and N contained in the upper 0.05-, 0.10-, 0.20-, 0.30-, and 0.45-m depths were calculated for comparison. Over the entire sampled depth, there were no significant differences ($p = 0.32$) by tillage in total soil mass collected, so equivalent mass corrections were not made (Ellert and Bettany, 1995). Concentration, mass, and bulk density data from each depth interval were evaluated by analysis of variance (ANOVA) with multiple observations in time (i.e., 2000 and 2005) using ANOVA and GLM procedures in SAS (SAS Institute, 2001) and least significant differences (LSD) means separation. Rates of C and N storage (Mg C or N ha^{-1} yr^{-1}) under BT and NT relative to CT were calculated from the difference in mean C or N mass between respective treatments divided by years since establishment of treatments, following West and Post (2002). The same approach was used to calculate storage rates under BT relative to NT. We use the term "relative storage" to indicate that these rates do not represent absolute rates of mass change over time within each treatment, since comparisons are between treatments at a given time and not between initial and final conditions.

Two separate analyses of the F_{CO2}, WFPS, and T_{50} data were performed on data sets obtained during 2003 and 2004 to 2005, respectively, each using ANOVA with multiple observations in time (i.e., individual sampling dates). Total soil CO_2 emissions (E_{CO2}) were estimated assuming that mid-day fluxes represented daily means and that fluxes changed linearly between measurement dates. For all mean comparisons, appropriate LSD values were calculated manually using error mean squares obtained from ANOVA and tabulated critical t values (Gomez and Gomez, 1984). Regression analyses were conducted using Statgraphics (Statgraphics, 2001). Unless stated otherwise, significance criteria of $p < 0.05$ were used.

The dependence of soil CO_2 fluxes on soil temperature was evaluated by several indices. For data sets segregated by tillage treatment and growing season, Q_{10} factors were determined from

$$Q_{10} = \exp\left(\frac{10E_a}{RT_{50}T_r}\right) \quad [1]$$

where R is the universal gas constant (0.00831 kJ K^{-1} mol^{-1}), is the soil temperature at the 50-mm depth is expressed in K, T_r is the reference temperature (303.15 K = 30°C), and E_a (kJ mol^{-1}) is the apparent activation energy obtained by linear regression from the Arrhenius relation

$$\ln F_{CO2} = \ln A - \frac{E_a}{RT_{50}} \quad [2]$$

where A is a coefficient representing various rate factors (Rodrigo et al., 1997; Ellert and Bettany, 1992). Since Q_{10} values showed only small variation with temperature (coefficient of variation = 1.4–2.7%), mean Q_{10} values across temperatures are reported. For each data set analyzed above, the "Ratkowsky" parameter (b, [μg C m^{-2} h^{-1}]$^{0.5}$ °C^{-1}) was also determined from:

$$\sqrt{F_{CO2}} = b(T_{50} - T_{\min}) \quad [3]$$

where $T_{\min}$ is the minimum apparent temperature (°C) at which F_{CO2} is observed (Katterer et al., 1998). Temperature responses for each of the individual chamber locations sampled three times per day during July 2004 were calculated from linear regression as the increase in F_{CO2} per degree increase in soil temperature occurring on each day.

RESULTS

Soil Carbon and Nitrogen Concentrations and Bulk Density

Soil C and N concentrations were highly correlated across all measurements ($r^2 = 0.947$, $p < 0.001$), and differences by tillage were nearly identical for C and N (Tables 1 and 2). The 0.1- to 0.2-m interval was the only depth segment over which no significant differences due to tillage were evident. Only in the upper-most layer (0–0.05 m) did soil C and N concentrations under NT exceed CT to a significant degree. In contrast, concentrations under CT exceeded those under NT at depths below 0.2 m (for C) or 0.3 m (for N) in 2005. Soil C and N levels under BT also exceeded CT in the 0- to 0.05-m layer, but in general did not differ between BT and CT at lower depths. In the 0.05- to 0.1-m interval, and in all intervals below 0.2 m, C and N concentrations under BT were greater than under NT, although differences in N

Table 1. Soil carbon (C) content (mean ± standard error) at varying depth intervals in 2000 and 2005 in plots maintained under conventional tillage (CT), biennial tillage (BT), and no-till (NT) since 1990.†

	Total C					
	2000			2005		
Depth	**CT**	**BT**	**NT**	**CT**	**BT**	**NT**
m	g C kg^{-1}					
0–0.05	26 (0.91) a	30 (0.92) b	30 (0.94) b	25 (0.83) a	30 (0.63) b	29 (0.71) b
0.05–0.10	26 (1.3) b	29 (0.52) c	25 (0.61) ab	24 (0.61) ab	26 (0.61) b	23 (0.54) a
0.10–0.20	25 (1.11)	27 (0.81)	24 (0.72)	25 (0.72)	26 (0.93)	25 (1.3)
0.20–0.30	21 (1.7) abc	23 (0.73) c	20 (0.52) ab	22 (1.4) bc	23 (1.0) c	19 (1.1) a
0.30–0.45	13 (1.4) ab	16 (1.1) bc	11 (3.3) a	17 (1.4) c	17 (1.6) c	12 (0.73) a
0.45–0.60	9.2 (0.92) ab	11 (0.92) b	7.8 (0.24) a	11 (1.5) b	11 (1.1) b	7.2 (0.22) a

† Within each depth interval and across years, values with the same letter designation are not significantly different ($p < 0.05$).

Table 2. Soil nitrogen (N) content (mean ± standard error) at varying depth intervals in 2000 and 2005 in plots maintained under conventional tillage (CT), biennial tillage (BT), and no-till (NT) since 1990.†

	Total N					
	2000			2005		
Depth	CT	BT	NT	CT	BT	NT
m	g N kg^{-1}					
0–0.05	2.18 (0.08) a	2.56 (0.10) b	2.59 (0.09) b	2.20 (0.07) a	2.61 (0.03) b	2.62 (0.08) b
0.05–0.10	2.20 (0.14) ab	2.43 (0.07) b	2.22 (0.03) ab	2.13 (0.04) a	2.34 (0.07) ab	2.16 (0.11) ab
0.10–0.20	2.07 (0.12)	2.19 (0.11)	2.01 (0.04)	2.00 (0.05)	2.16 (0.04)	2.05 (0.10)
0.20–0.30	1.74 (0.12) abc	1.95 (0.08) c	1.57 (0.04) a	1.73 (0.12) abc	1.85 (0.06) bc	1.58 (0.09) ab
0.30–0.45	1.17 (0.13) ab	1.38 (0.08) b	1.02 (0.03) a	1.38 (0.12) b	1.44 (0.16) b	0.96 (0.07) a
0.45–0.60	0.65 (0.15) ab	0.93 (0.07) c	0.62 (0.07) ab	0.85 (0.12) bc	0.92 (0.09) c	0.55 (0.03) a

† Within each depth interval and across years, values with the same letter designation are not significantly different ($p < 0.05$).

were not always significant. Few significant differences in concentration by year within a tillage treatment were evident. In 2005, C in the BT plots at 0.05 to 0.1 m was lower than in 2000, while C in the CT plots at 0.3 to 0.45 m was higher than in 2000.

Soil C/N ratios generally did not vary by tillage treatment (data not shown). The only significant difference was in 2005 over 0.2 to 0.3 m, where soil C/N ratio under CT (12.8 ± 0.30) was greater than under NT (11.9 ± 0.30). In 2005, C/N ratio under NT (11.1 ± 0.15) was lower than in 2000 (11.8 ± 0.31) in the 0- to 0.05-m interval, but higher in 2005 (12.6 ± 0.46) than in 2000 (11.1 ± 0.15) in the 0.3- to 0.45-m interval. In the upper 0.2 m, bulk density under NT tended to be higher than CT and in some cases higher than BT, with the general trend being CT < BT < NT (Table 3). Below 0.2 m, no differences were evident.

Soil Carbon and Nitrogen Masses

Total integrated masses of C and N in the upper 0.2 to 0.3 m tended to be higher under NT compared with CT (Fig. 1). When depths below 0.3 m were also considered, differences between NT and CT disappeared. In the upper-most layer (0–0.05 m), the NT plots also contained more soil C (in 2000) and N (in 2000 and 2005) than BT. Differences between NT and BT disappeared when the upper 0.2 or 0.3 m was evaluated, and were reversed (i.e., BT > NT) when the upper 0.45 and 0.6 m were evaluated. Across the entire sampled depth (0.6 m) after 10 yr of treatments (in 2000), the BT plots contained more C and N than CT and NT, which did not differ from each other. After 15 yr (in 2005), the BT plots contained more C and N than the NT treatment, which did not differ significantly from CT. Differences between the 2000 and 2005 sampling events were only evident in the upper 0.1 m. Total masses of C and N contained in the upper 0.05 m under all treatments were higher in 2005 compared with 2000.

The lower 0.4 m of the profile (0.2- to 0.6-m interval) represented 55 to 56% of the total C contained in the upper 0.6 m under CT and BT compared with 48% under NT, averaged over both sampling dates. The NT plots on average contained 66.6 ± 1.8 Mg C ha^{-1} over 0.2 to 0.6 m, which was significantly less than CT (82.0 ± 4.7 Mg C ha^{-1}) and BT (89.5 ± 4.6 Mg C ha^{-1}).

Rates of soil C and N storage under NT compared with CT (Fig. 2, left-hand plates) were maximal when the 0- to 0.2-m interval was evaluated, and approached zero when data from lower depths were also considered. During the first decade of treatments (1990–2000), storage rates for BT compared with CT increased with increasing depth, reaching 1.8 Mg C ha^{-1} yr^{-1} and 0.19 Mg N ha^{-1} yr^{-1} over the entire sampled depth. The relationship between depth of soil profile considered and storage rates under BT relative to CT was highly linear for 1990–2000 ($r^2 > 0.98$). Rates of C and N storage under both NT and BT relative to CT slowed during 2000–2005, as evidenced by lower storage rates for 1990–2005 compared with 1990–2000. Storage of C and N under BT relative to NT (Fig. 2, right-hand plates) were near-zero (and not significant) for soil profile depths <0.3 m, but were significant and substantial (>1.5 Mg C ha^{-1} yr^{-1} and >0.15 Mg N ha^{-1} yr^{-1}) over the 0.6-m depth.

Soil Carbon Dioxide Emissions and Climatic Factors

In 2003, F_{CO2}, E_{CO2}, and WFPS tended to be higher under reduced tillage (Fig. 3, Table 4). ANOVA in-

Table 3. Soil bulk density (mean ± standard error) at varying depth intervals in 2000 and 2005 in plots maintained under conventional tillage (CT), biennial tillage (BT), and no-till (NT) since 1990.†

	Bulk density					
	2000			2005		
Depth	CT	BT	NT	CT	BT	NT
m	Mg m^{-3}					
0–0.05	1.07 (0.04) a	1.03 (0.02) a	1.21 (0.04) b	1.30 (0.04) bc	1.29 (0.05) b	1.43 (0.05) c
0.05–0.10	1.20 (0.03) a	1.25 (0.03) ab	1.42 (0.03) c	1.31 (0.03) b	1.34 (0.03) b	1.47 (0.02) c
0.10–0.20	1.33 (0.02) ab	1.37 (0.02) bc	1.46 (0.03) c	1.29 (0.04) a	1.40 (0.02) bcd	1.43 (0.01) cd
0.20–0.30	1.40 (0.03)	1.36 (0.02)	1.42 (0.03)	1.40 (0.02)	1.39 (0.02)	1.43 (0.02)
0.30–0.45	1.40 (0.02)	1.38 (0.02)	1.39 (0.02)	1.35 (0.02)	1.34 (0.03)	1.31 (0.03)
0.45–0.60	1.43 (0.07)	1.43 (0.04)	1.37 (0.08)	1.39 (0.02)	1.40 (0.04)	1.42 (0.02)

† Within each depth interval and across years, values with the same letter designation are not significantly different ($p < 0.05$).

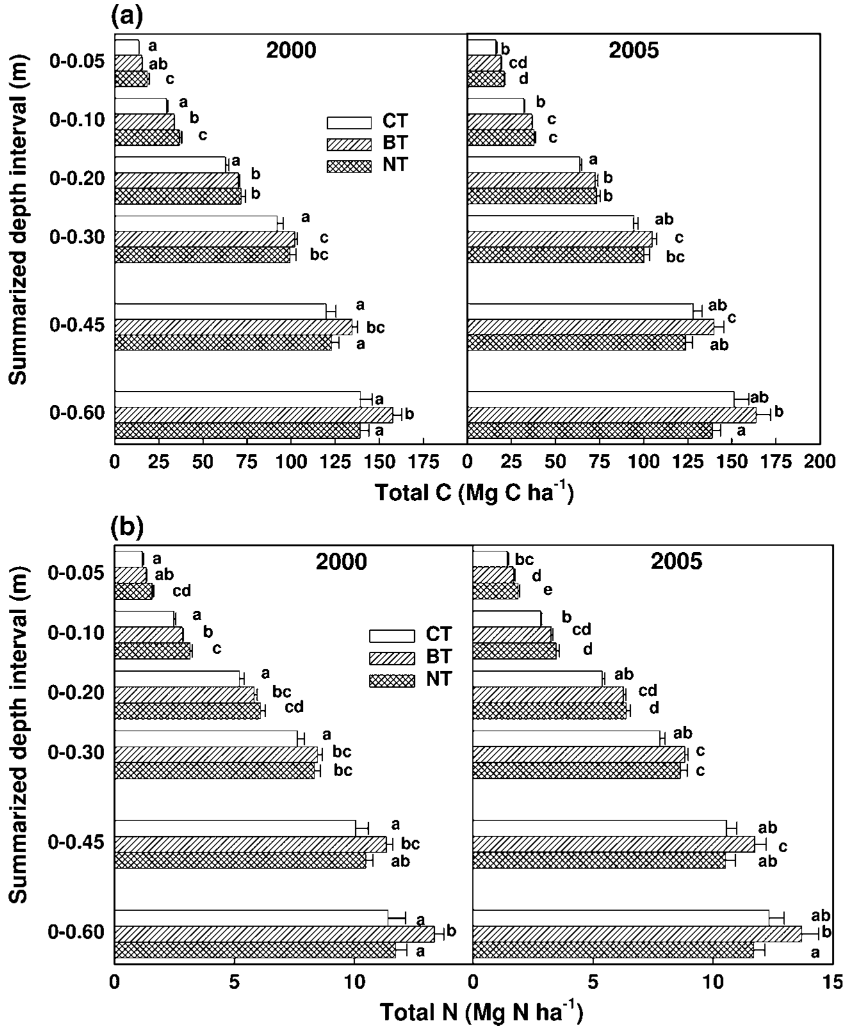

Fig. 1. (a) Soil carbon (C) and (b) soil nitrogen (N) summed over varying depth intervals, as determined in 2000 and 2005 in plots maintained under conventional (CT), biennial tillage (BT), and no-till (NT) (mean ± standard error). Within each depth interval and across years, bars with the same letter designation are not significantly different ($p < 0.05$).

dicated significant date-by-tillage interaction effects for F_{CO2}, WFPS, and T_{50}. Significant differences in daily mean F_{CO2} included NT > CT (occurring on five dates), NT > BT (on three dates), and BT > CT (on two dates) (Fig. 3a). Total emissions (E_{CO2}) increased in the order CT < BT < NT, with NT exceeding CT by 41%. Soil WFPS followed the same trends as F_{CO2} (Fig. 3b). Differences in WFPS included NT > CT (on 14 dates) and NT > BT (on 10 dates). Mean WFPS across all dates tended to be higher under NT compared with CT, neither of which differed significantly from BT at $p <$ 0.05. Early in the growing season, T_{50} tended to be higher under CT than NT or BT (Fig. 3c), although daily means after 4 July, and overall means across the entire season, did not differ significantly with tillage.

In contrast to 2003, F_{CO2} during 2004–2005 did not differ by tillage treatment on any of the 61 sampling dates, and E_{CO2} values were similar (Fig. 4a, Table 4). ANOVA indicated significant date-by-tillage interaction effects for WFPS and T_{50}. However, differences in daily mean WFPS were much less frequent during the 2004 growing season compared with 2003 (Fig. 4b), and mean WFPS across all sampling dates in 2004–2005 did not differ by tillage treatment. In early spring 2005, WFPS tended to be greater in the NT and BT plots compared with CT, but this was not accompanied by significant differences in F_{CO2}. Soil temperatures during the 2004 growing season displayed significant differences with tillage treatment on specific dates (Fig. 4c), although the magnitude of the differences was small (LSD = 0.86°C), and overall means did not differ significantly. During early spring 2005, soil temperatures in the NT plots were consistently lower than in CT and BT.

There was significant variation in rainfall between the 2003 and 2004 growing seasons. In 2004, precipitation during March through October (724 mm) was similar to the 30-yr mean value (738 mm), while precipitation during the same period in 2003 (514 mm) was 40% lower (Fig. 3b and 4b). There were 45 measurable rainfall events during June through October of 2003 compared with 65 events during the same period in 2004. Interannual differences in T_{50} (Table 4) were mainly due to the inclusion of data from spring 2005, although the mean daily air temperature during June through August was lower in 2004 (19.0°C)

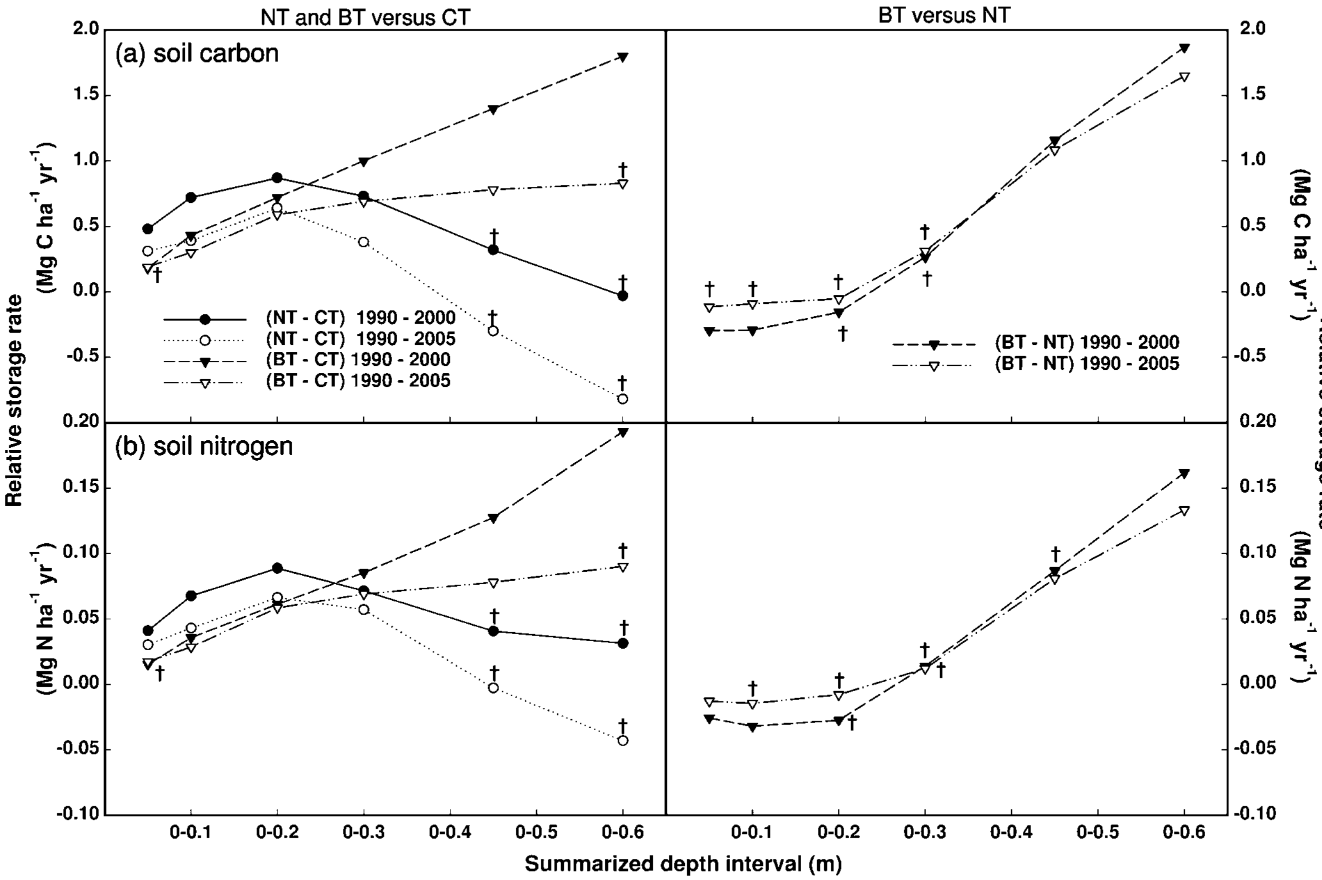

Fig. 2. Relative storage rates of (a) carbon (C) and (b) nitrogen (N) as function of summarized depth interval during 1990–2000 and 1990–2005. Left-hand plates represent storage rates under biennial tillage (BT) and no-till (NT) relative to conventional tillage (CT), and right-hand plates represent storage rates under BT relative to NT. Each point is calculated as the difference in means between treatments from corresponding data in Fig. 1. Symbols (†) indicate that differences in corresponding means are not statistically significant at $p < 0.05$.

than 2003 (20.6°C). These differences were reflected in higher mean WFPS in 2004 across all tillage treatments (Table 4). Interannual differences in WFPS increased with increasing tillage intensity. There was no significant correlation between F_{CO2} and WFPS across all data or when data were stratified by tillage treatment. When data were stratified by soil temperature, significant positive correlations emerged. For measurements where $T_{50} > 22.5$°C, representing ~18% of all measurements, WFPS explained 19% of the variance in F_{CO2}.

Soil temperature was positively correlated with F_{CO2} and explained 34% of the overall variance across all measurements based on linear regression of T_{50} versus F_{CO2}. There was significant year-to-year variation in Q_{10} and *b*. All parameters tended to be higher in 2004 than 2003, particularly in the CT treatment. When grouped by tillage treatment and growing season, temperature response parameters were significantly correlated with mean annual WFPS (Fig. 5a and 5b). Temperature responses based on individual chamber measurements over the course of the day also increased with WFPS (Fig. 5c).

DISCUSSION

Different patterns of relative C storage were evident when the upper versus lower segments of the soil profile were considered (Fig. 1 and 2). If sampling had been conducted only to 0.2 m, it would have appeared that the NT treatment had stored C at the rate of 0.8 Mg C ha^{-1} yr^{-1} during 1990–2000 relative to CT. This value is similar to the mean rate of 0.9 ± 0.6 Mg C ha^{-1} yr^{-1} obtained by West and Post (2002) based on previous studies in corn-soybean rotations. Sampling to 0.3 m would still have indicated significant C storage (0.4–0.7 Mg C ha^{-1} yr^{-1}) under NT relative to CT. However, when depths below 0.3 m were included no significant storage under NT was evident. Several other studies that employed sampling to depths well below the tillage zone have found similar lack of significant C storage under NT over the entire sampled zone (Dolan et al., 2006; Carter, 2005; Jarecki and Lal, 2005; Deen and Kataki, 2003; Machado et al., 2003; Yang and Wander, 1999; Angers et al., 1997; Powlson and Jenkinson, 1981).

The lack of significant total-profile C storage under NT relative to CT found here can be attributed to at least two factors. First, it is likely that decreased C inputs under NT offset any decreases in soil respiration that might have resulted from the lack of tillage operations. Reduced corn yields under no-till in the northern corn belt have been observed in several studies (e.g., Allmaras et al., 1964; Vetsch and Randall, 2000; Randall and Vetsch, 2006), including a long-term study in plots

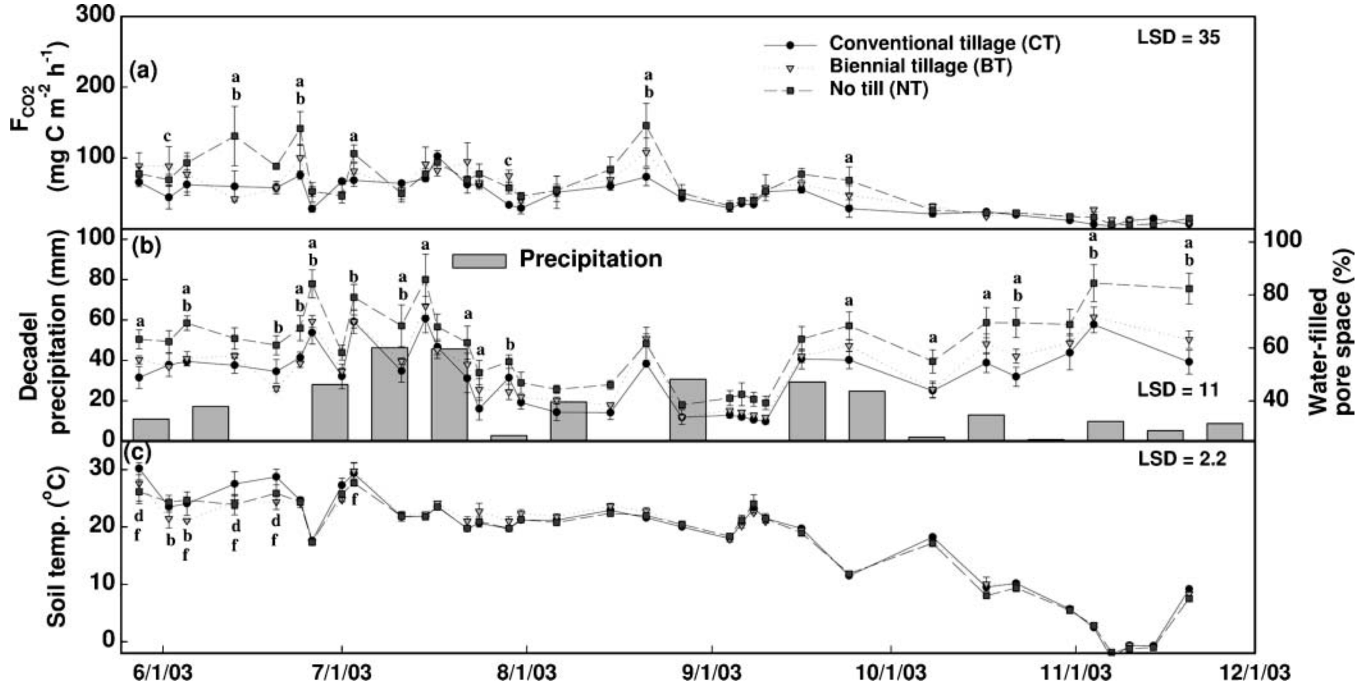

Fig. 3. Soil CO_2 fluxes (F_{CO2}) and ancillary variables in 2003 (mean ± standard error). (a) F_{CO2}, (b) cumulative 10-d precipitation and soil water-filled pore space, and (c) air and soil (50-mm depth) temperatures, under conventional (CT), biennial tillage (BT), and no-till (NT). LSD = least significant difference ($p < 0.05$). Significant differences are indicated by the symbols: *a*: NT > CT; *b*: NT > BT; *c*: BT > CT; *d*: CT > NT; *e*: BT > NT; *f*: CT > BT.

located 2 km from the current site (Linden et al., 2000). Corn yields in the current plots were about 88% of CT yields during 1992–1995 (Wallach and Linden, 1997) and 81% of CT yields during 2000–2005 (unpublished data), which is similar to the findings by Linden et al. (2000) that yield reductions increase with time under NT. Soybean yields have not varied by tillage in these plots. Thus, assuming that grain yields are reflective of C inputs (Wilts et al., 2004), the data suggest that more C was retained under NT per unit of C input, since there were no significant differences in soil C across the entire 0.6-m depth.

Corn yield reductions in the upper mid-west USA under no-till have been attributed to delayed planting and/or poor emergence due to lower spring soil temperatures and/or increased soil mechanical resistance in the upper 0.1 m under NT (Cox et al., 1990). Various practices to mitigate yield reductions, including row cleaners and starter fertilizers, have shown mixed success (Vetsch and Randall, 2000). In the current study, uniform fertilizer management and planting practices were used across tillage treatments to isolate the effects of tillage regime per se. It is possible that more intensive management of the no-till plots might have resulted in higher C inputs that in turn could have significantly altered C storage. Future studies should consider designs that attempt to optimize yields and C inputs under reduced tillage so that best-case comparisons can be made.

A second factor potentially constraining C storage under NT is suggested by the current soil CO_2 flux data. Increased respiration, apparently promoted by higher WFPS in surface soil under NT, has been previously found by Franzluebbers et al. (1995) in certain growing seasons of a sorghum-wheat-soybean rotation in south central Texas. In the drier than normal year (2003) of the current study, the NT system emitted ~0.7 Mg C ha^{-1} more via soil CO_2 flux than CT (Table 4), which is a substantial proportion of annual storage rates estimated from soil C data (Fig. 2). Soil microbial respiration can be limited by WFPS below a certain threshold level (Linn and Doran, 1984). These findings suggest that as organic matter, water retention, and bulk density increase in the upper 0.10 m under NT, so does the potential for increased soil respiration, at least during

Table 4. Surface CO_2 emissions (E_{CO2}), percent water-filled pore space (0– 100 mm) (WFPS), and soil temperature (50 mm) (T_{50}) (mean ± standard error) in plots maintained under conventional tillage (CT), biennial tillage (BT), and no-till (NT) since 1990.†

	E_{CO2}			WFPS			T_{50}		
	Tillage			Tillage			Tillage		
Year	CT	BT	NT	CT	BT	NT	CT	BT	NT
	mg C m^{-2}			%			°C		
2003	1.7 (0.09)a	2.0 (0.03)ab	2.4 (0.09)b	50 (1.3) a	53 (1.3) ab	61 (1.6) b	18.1 (0.86)	17.8 (0.82)	17.6 (0.83)
2004	3.6 (0.21)	3.6 (0.17)	3.7 (0.20)	65 (0.70)	64 (0.65)	67 (0.63)	13.5 (0.34)	13.3 (0.35)	13.0 (0.33)

† Within each year, means having the same letter designation are not significantly different ($p < 0.05$).

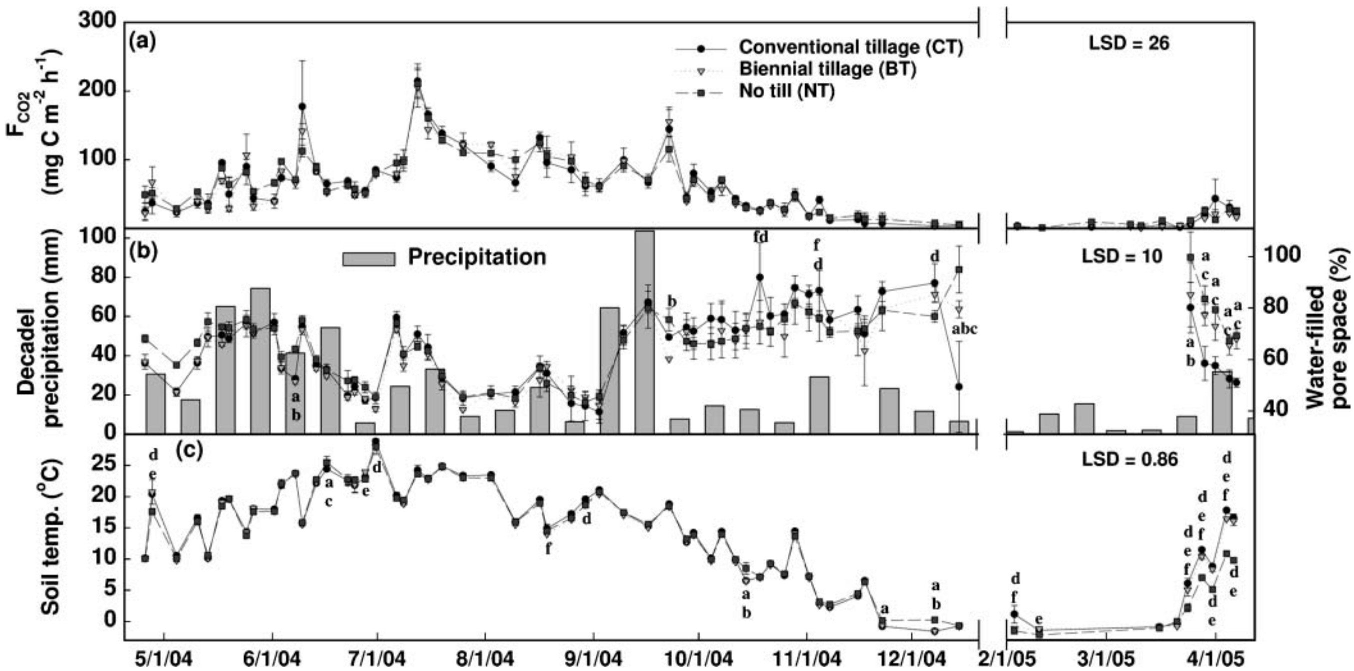

Fig. 4. Soil CO_2 fluxes (F_{CO2}) and ancillary variables in 2004 (mean ± standard error). (a) F_{CO2}, (b) cumulative 10-d precipitation and soil water-filled pore space, and (c) air and soil (50-mm depth) temperatures, under conventional (CT), biennial tillage (BT), and no-till (NT). LSD = least significant difference ($p < 0.05$). Significant differences are indicated by the symbols: *a*: NT > CT; *b*: NT > BT; *c*: BT > CT; *d*: CT > NT; *e*: BT > NT; *f*: CT > BT.

periods when soils remain wetter under NT. These dynamics would appear to result in some degree of self-regulation of C storage, so long as C inputs under NT relative to CT do not also increase with increasing soil moisture (as may occur for example in semiarid wheat cultivation, McAndrew et al., 1994). The lack of tillage-induced differences in WFPS during the normally wet year (2004) suggests that increased soil respiration under NT may be limited to periods of lower and/or less frequent rainfall, during which the mulching effects of higher surface residue under NT have more pronounced effects on soil moisture.

Our estimates of total CO_2 emissions (Table 4) are subject to considerable uncertainty due to temporal variations not captured by the sampling frequency employed. In particular, in 2003 and 2004 we did not measure changes in F_{CO2} that may have occurred within minutes to hours following tillage operations (Reicosky and Lindstrom, 1993). In the current study, these effects were likely small in relation to total CO_2 emissions occurring during the remainder of the year due to the low soil temperatures that prevailed in the days surrounding fall tillage operations (Al-Kaisi and Yin, 2005; Rochette and Angers, 1999). In fall 2005, we did not detect any tillage-induced increases in F_{CO2} measured immediately before, and then 1 and 3 h following moldboard plowing and disk-ripping, when soil temperatures were <5°C (data not shown).

The chamber method deployed here for F_{CO2} measures the sum of soil microbial and active root respiration sources. The above discussion assumes that observed differences in F_{CO2} derive mainly from differences in microbial respiration. The temporal pattern of differences in F_{CO2} in 2003 (Fig. 3a) shows no evidence that these differences were correlated with growth stage of the crop, which might be expected if differences in root respiration were the primary mechanism. Previous studies have found that total soil profile root length density (RLD) under CT can exceed that under NT (e.g., Qin et al., 2005). Higher RLD (and root respiration) under CT would also be expected in the current study if a correlation between grain yield and below-ground biomass is assumed. Thus, actual differences in microbial soil respiration in 2003 may have been greater than indicated by the F_{CO2} measurements. Similarly, in the 2004 data, which showed no tillage effects on F_{CO2}, actual differences in soil respiration may have been masked by differences in root respiration. Another potentially important role of roots relates to tillage effects on the vertical distribution of RLD. As discussed by Baker et al. (2006), higher RLD under CT compared with NT at depths below 0.20 m, attributable to lower early season soil temperatures and higher bulk density and mechanical resistance under NT, might partly explain the higher C content found below these depths under CT and BT in the current study.

Greater soil C below 0.2 m under CT compared with NT has also been reported by Lal et al. (1990), Lal (1997), Deen and Kataki (2003), and Angers et al. (1997), who found this pattern consistently in tillage studies in several different soils of varying texture under barley, wheat, soybean, and corn cultivation across eastern Canada. Angers et al. (1997) proposed that plowing-induced deterioration of soil structure at the bottom of the plow layer could inhibit aeration and C decomposition below this depth (~0.2 m). Angers et al. (1997),

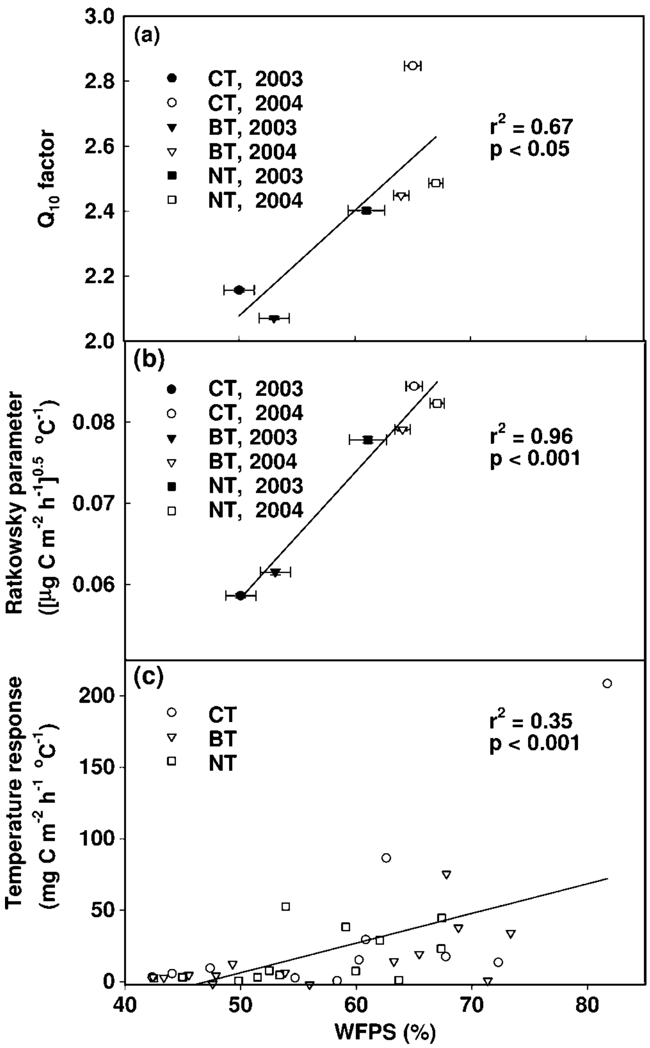

Fig. 5. Relationships between water-filled pore space (WFPS) and (a) Q_{10} factors, (b) Ratkowsky parameters, and (c) temperature responses. Data shown in (a) and (b) represent annual mean values (± standard error). Data shown in (c) are from individual chamber measurements made 13 July– 29 July 2004.

Lal (1997), and Machado et al. (2003) also discussed the role of tillage in stabilizing organic matter in the subsoil against decomposition by increasing its association with silt- and clay-sized mineral particles, which may then be transported downward. It is also possible that, in the current and previous studies, differences in C storage existing before the imposition of treatments (VandenBygaart and Kay, 2004) may have influenced data from depths below the tillage zone to a greater extent than data from above the tillage zone.

Higher storage under BT relative to CT can be attributed to the less frequent and intensive physical disruption caused by the disk-ripping/no-till rotation than the moldboard plowing/disk-ripping regime, combined with comparable C inputs (yields) under BT and CT. Soil inversion from moldboard plowing exposes a substantially greater volume of soil from deeper depths (0.1–0.2 m) to the surface than chisel plowing (Reicosky, 1998). More intensive and frequent wet-dry and freeze–thaw cycles that prevail closer to the soil surface degrade aggregate structure, thereby promoting microbial decomposition of residues that had been previously protected from microbial decomposition (Six et al., 2002). Unlike the NT system, corn yield reductions under BT have not been observed (Wallach and Linden, 1997). Randall and Vetsch (2006) similarly found increased corn yields under BT compared with NT in corn-soybean systems in Waseca, MN. This suggests that any differences in spring soil temperature or bulk density between CT and BT have not affected corn seedling emergence and yields, despite the lack of fall tillage or spring cultivation preceding corn planting under BT. While the pattern of increased CO_2 emissions and WFPS under BT in 2003 was less pronounced than for NT, it does suggest that increased soil respiration during certain periods may have constrained organic matter storage under BT.

Increasing Q_{10} factors for ecosystem or soil respiration with increasing soil moisture has been reported in forest systems (Reichstein et al., 2002, 2005) and to a lesser extent in agricultural soils (Kutsch and Kappen, 1997). In laboratory incubation studies using intact monoliths of forest mineral soil, Reichstein et al. (2005) observed variation in Q_{10} over the range of approximately 2.0 to 2.5 (similar to that observed here, Fig. 5a) during imposed wet-dry cycles. Reichstein et al. (2002) proposed that differential drying and inactivation of more labile substrates located closer to the surface could partly explain the phenomenon, due to higher temperature sensitivity of respiration of more labile substrates. Reichstein et al. (2002) also proposed that reduced canopy C assimilation and correspondingly reduced root respiration under dry conditions might also play a role, based on results of Boone et al. (1998) indicating greater temperature sensitivity of root and rhizosphere versus bulk soil respiration. Baath and Wallander (2003), however, found no differences in Q_{10} factors between rhizosphere and bulk soil respiration. Davidson et al. (2006) point out that Q_{10} factors do not necessarily reflect a consistent or inherent temperature response of systems that are influenced by multiple underlying processes, each of which may exhibit differing nonlinear temperature responses. Regardless of mechanism, the results obtained here suggest that increased temperature sensitivity with increasing soil moisture contributed to higher soil respiration rates under NT in the drier year, and thus that moisture-temperature interactions may play a role in limiting C storage under reduced tillage.

CONCLUSIONS

The depth of soil profile considered was critical to the assessment of C and N storage. No significant storage was evident under NT compared with CT when the entire sampled depth was considered. As emphasized by Baker et al. (2006), studies aimed at characterizing the GHG impact of tillage practices need to consider that limiting sampling to shallower depths can bias results in favor of reduced tillage. If sampling in the current study had been terminated at 0.3 m, it would have appeared that both reduced tillage treatments had stored similar amounts of C.

For corn cultivation in the north central USA, the potential for C storage under reduced tillage regimes appears to depend largely on overcoming limitations to yield reductions. The current soil CO_2 flux data also suggest that an inherent self-limitation resulting from increasing soil respiration with reduced tillage may also constrain soil C storage, at least under continuous NT. These dynamics may also be driven in part by increased temperature sensitivity of soil respiration with increasing soil moisture.

A BT regime intermediate in intensity between annual CT and continuous NT contained the greatest amount of C and N over 0.6 m after 10 and 15 yr of management. Thus, some amount of tillage appears necessary in this climate and cropping system to sustain yields and maximize C storage. Questions emerge from these findings related to optimizing the agronomic and environmental benefits of rotational tillage regimes. For example, could tillage frequency be reduced to less than a biennial regime with additional gains in soil C while also maintaining yields? Identifying the "optimal" level will depend largely on defining values for each of the various impacts of increased soil C and N, including GHG impacts (Sparling et al., 2006). Machinery and fuel costs, which can account for 20 to 25% of total production costs in corn–soybean systems (Katsvairo and Cox, 2000), also need to be considered. The BT regime in the current study would be expected to save approximately 50% in machinery costs compared with the CT regime. Reducing tillage frequency to once every 4 yr would save an additional 25%, with unknown effects on grain yields or soil C and N storage. Additional studies examining benefits of rotational tillage regimes, particularly in cooler climates and in rotational cropping systems, are required to answer these questions.

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