Long-Term Tillage and Residue Management Influences Soil Carbon and Nitrogen Dynamics

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Abbreviations: CT, conventional tillage; HI, high input; LI, low input; MBC, microbial biomass carbon; MBN, microbial biomass nitrogen; NT, no-till; RT, reduced tillage; SOC, soil organic carbon.

As the atmospheric CO_2 concentration continues to rise at a rate of $1.7 \ \mu mol \ mol^{-1} \ yr^{-1}$ (Tans, 2009), there is strong scientific interest in finding ways to slow or reverse this trend. Adopting agricultural practices that increase the amount of C in the soil, thereby diverting it from the atmosphere, is a recognized mitigation strategy (Lal, 2008). Conservation tillage practices such as RT and NT produce less soil disturbance and physical fragmentation of crop residues than CT, which is expected to increase the SOC pool (Madgoff and Weil, 2004). According to Smith et al. (2007), the annual mitigation potential of tillage and residue management is estimated at 0.17 to 0.86 Mg CO₂ equivalent ha⁻¹ yr⁻¹ in cool dry climates and from 0.53 to 1.12 Mg CO₂ equivalent ha⁻¹ yr⁻¹ in cool moist climates.

Agricultural land in western Canada tends to be in semiarid regions (cool, dry climate), whereas farmland in eastern Canada receives more annual precipitation in the form of snow and rain (cool, moist climate). The effect of tillage on SOC in these two regions was evaluated by VandenBygaart et al. (2003), who reported that the net gain in SOC of NT agroecosystems compared with CT agroecosystems was 32 ± 15 g C m⁻² yr⁻¹ in western Canada and -7 ± 27 g C m⁻² yr⁻¹ in eastern Canada (VandenBygaart et al., 2003). This suggests a slower rate of SOC accrual in eastern Canada than predicted by Smith et al. (2007). One reason could be that wheat (*Triticum aestivum* L.)-based cropping systems dominate in western Canada, while those in eastern Canada are often corn based; cereal residues have higher lignin contents and probably decompose more slowly than corn residues (VandenBygaart et al., 2003). A review by Wilhelm et al. (2004) indicated that the SOC level in CT agroecosystems could be maintained with an annual input of <1 to 5.3 Mg ha⁻¹ of wheat residues, but CT agroecosystems under corn production would require 6 to

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 $14 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ of residues to maintain the SOC level. Reducing the tillage intensity and increasing the quantity of corn residues retained in continuously cropped agroecosystems could increase the SOC pool in soils of eastern Canada, but this hypothesis needs to be tested.

Rates of SOC accumulation are generally slow and it is challenging to detect changes in the SOC pool, especially in soils with high background levels of SOC. The C concentration in microbial biomass, floatable organic matter (light fraction), or macroaggregate-associated organic matter is considered to be a more sensitive indicator of change in the SOC pool (Six et al., 2002; Jastrow et al., 2007). An 11-yr field experiment in St. Lambert, QC, revealed no change in the total SOC pool due to tillage, but the MBC and particulate organic C and N concentrations were greater in the shallowly harrowed RT treatment than the CT treatment (Angers et al., 1993). Similarly, laboratory-based C and N mineralization rates may reflect the presence of labile organic compounds that were protected from microbial degradation under field conditions (Haynes, 2005). At four sites with a 7- to 12-yr history of NT management, Sharifi et al. (2008) reported a trend of greater mineralizable N in soils from NT than CT agroecosystems, although the effect of tillage was significant (P < 0.1) at only one site. After 35 yr of tillage treatments, the N mineralization rates from a silt loam soil followed the pattern NT > RT > CT, whereas there was no effect of tillage on N mineralization from a silty clay loam (Martens and Dick, 2003). Our working hypothesis was that tillage and crop residue management effects on SOC and N dynamics would be detected in the soil microbial biomass and potentially mineralizable C and N fractions of SOC.

The objectives of this study were (i) to evaluate the effect of long-term (16-yr) tillage and residue inputs on the SOC pool in a corn agroecosystem in eastern Canada, and (ii) to determine if labile fractions of SOC (microbial biomass and potentially mineralizable C and N) were affected by tillage and residue inputs.

MATERIALS AND METHODS Site Description

The experiment was conducted on a 2.4-ha field on the Macdonald Research Farm of McGill University in Ste-Anne de Bellevue, QC (45°30′ N, 73°35′ W, elevation 35.7 m). The mean annual temperature is 6.2°C with 979 mm of precipitation, based on meteorological data collected from 1971 to 2000 at the Pierre Elliott Trudeau International Airport, Dorval, QC (Environment Canada, 2002), which is approximately 16 km from the site. The soil is a mixed, frigid Typic Endoaquent (Dystric Gleysol) of the St-Amable and Courval series. This sandy loam soil contained, on average, 815 g kg⁻¹ sand, 89 g kg⁻¹ silt, and 96 g kg⁻¹ clay in the top 20 cm with 19.9 g SOC kg⁻¹ when the study was initiated. Further details of the site characteristics and preparation were described by Burgess et al. (1996) and Dam et al. (2005).

Experimental Design

The experiment was a factorial with three types of tillage (NT, RT, and CT) and two levels of residue input (HI and LI), for a total of six factorial treatments. Treatments were assigned randomly within

each of the three blocks, for a total of 18 experimental plots. Plots were 80 by 18.5 m, with a 2-m buffer separating the plots and an 8-m buffer between blocks. Buffers were cultivated regularly during the growing season to control weeds.

The site was plowed in the spring of 1991, when the experiment began. Thereafter, no additional tillage operations were undertaken in the NT plots. The RT plots were harrowed with an offset disk harrow (about 15-cm depth) each fall after harvest and with a tandem disk harrow to about 10-cm depth each spring before planting. The CT plots were cultivated with a moldboard plow to a depth of 20 cm each fall after harvest and with a tandem disk harrow (about 10-cm depth) each spring before seeding. Since 1991, the plots have been under continuous corn production, directly seeded each year with a John Deere 7100 Max Emerge seeder (Deere & Co., Moline, IL) at a rate of 76,000 seeds ha⁻¹ using the same hybrid throughout the field. The plots were always planted on the same day, between 4 and 26 May. Hybrids selected for this trial were Funk 4120 (1991-1993), an unknown hybrid (no data for 1994-1995), Cargill 2827 (1996-1998), Cargill 2277 (1999), Cargill 2610 (2000-2001), Mycogen 2610 (2002-2003), and Mycogen 2K350 (2004–2007). Nutrients required for corn production were supplied with inorganic fertilizers. Generally, a blend of calcium ammonium nitrate and monoammonium phosphate (23-12-0) was banded at planting to supply 40 kg N ha $^{-1}$ and 20 kg $\rm P_2O_5$ ha $^{-1}$, with a sidedress application of 140 kg N ha⁻¹ and 76 kg K_2 O ha⁻¹ from a blend of calcium ammonium nitrate and muriate of potash (22-0-12) when the corn height was approximately 20 cm. Weeds were controlled with postemergence applications of 213 g ha⁻¹ a.i. atrazine [6-chloro-*N*-ethyl-*N'*-(1-methylethyl)-1,3,5-triazine-2,4-diamine], 11 mL ha⁻¹ a.i. topramezone ([3-(4,5-dihydro-3-isoxazolyl)-2-methyl-4-(methylsulfonyl)phenyl](5-hydroxy-1methyl-1H-pyrazol-4-yl)methanone) and 0.87 L ha⁻¹ a.i. dimethenamid [2-chloro-*N*-(2,4-dimethyl-3-thienyl)-*N*-(2-methoxy-1-methylethyl)acetamide]. The herbicides were applied with a foliar fertilizer (15-3–6 plus B, Mn, Zn, and Mo) at a rate of 2.68 L ha⁻¹ and a surfactant (0.40 L ha⁻¹ a.i. nonylphenoxy polyethyoxyethanol) to enhance herbicide activity. Herbicide, surfactant, and foliar fertilizer treatments were generally identical for each plot, although spot applications of other herbicides were sometimes made to solve a specific weed problem (e.g., bromoxynil octanoate [2,6-dibromo-4-cyanophenyl octanoate] and bromoxynil heptanoate [2,6-dibromo-4-cyanophenyl heptanoate] were applied to three plots to control a broadleaf weed outbreak in 2004).

Corn Yield and Residue Management

Corn was harvested each year after the crop had reached physiological maturity and contained <20% moisture content. Yields were estimated by harvesting corn plants along a 5-m transect at six locations within each plot by hand. Corn plants were cut with a machete just above the soil surface. Cobs were removed from the husk, placed in a paper bag for drying (to a constant mass at 60°C), then shelled to remove kernels and determine the grain yield. Corn stover included stems, leaves, and husks, which were weighed (wet weight) in the field and chopped with a mechanical chopper to generate a subsample that was dried (60°C) to a constant mass. Grain yield and stover mass were expressed on a megagram dry matter per hectare basis. Following yield assessment, the LI-residue plots were harvested with a silage harvester, which removed the stalks and leaves, leaving <15 cm of stalk and the roots in the field. The HI-residue plots were harvested with a combine harvester to remove the grain, leaving stems, leaves, husks, and cobs in the field. The mass of stover (Mg ha⁻¹ of dry matter) left in the HI plots was estimated from the handharvested subsamples (Table 1).

Soil Sampling and Analysis

Soil samples were taken after corn harvest and before fall tillage operations in October 2007. Samples were collected with a hand trowel and carefully separated into two depths, 0 to 5 and 5 to 20 cm. A composite sample for each depth was made by mixing subsamples (about 300 g each) from five randomly selected loca-

tions within the plot. Soils were sieved through a 6-mm-mesh screen in the field to remove rocks and residues, placed in sealed polyethylene bags, and stored at 4°C until analysis.

Microbial biomass C and N concentrations in field-moist soil samples (20–25% gravimetric moisture content) from each plot and sampling depth (36 samples) were determined using the chloroform fumigationdirect extraction method described by Voroney et al. (2008). Paired subsamples were either directly extracted with 0.5 mol L^{-1} K₂SO₄ (1:4 soil/ extractant) or kept at 20°C and fumigated with chloroform for 5 d before extraction. Analytical blanks (empty beakers without soil) were used to correct the baseline C and N concentrations. The dissolved organic C (DOC) concentration in unfumigated and fumigated soil extracts was determined using a Shimadzu TOC-V analyzer (Shimadzu Corp., Kyoto, Japan) and compared with a standard curve of 0 to 100 μ g C mL⁻¹. Microbial biomass C (MBC) was the difference in DOC concentration of fumigated and unfumigated extracts divided by an efficiency factor $k_{\rm FC}$ = 0.45 (Joergensen, 1996). For microbial biomass N (MBN), the fumigated and unfumigated extracts underwent persulfate digestion (Cabrera and Beare, 1993) and colorimetric analysis for NH₄-N and NO3-N using a Lachat Quik Chem AE flow injection autoanalyzer (Lachat Instruments, Milwaukee, WI) with a standard curve of 0 to $10\,\mu g\,N\,mL^{-1}.$ Microbial biomass N was the difference in mineral N concentration between fumigated and unfumigated extracts, divided by the efficiency factor $k_{\rm EN}$ = 0.54 (Joergensen and Mueller, 1996).

A subsample of soil from each plot and sampling depth was dried (60°C) and finely ground to pass through a 1-mm-mesh sieve before analysis for total C and N with a ThermoFinnigan Flash EA 1112 CN analyzer (Carlo Erba, Milan, Italy). No carbonates were detected by treatment with dilute acid (1 mol L⁻¹ HCl), so it was assumed that total C was equivalent to organic C at this site. The SOC pool (Mg SOC ha⁻¹) in the 0- to 20-cm depth was the sum of the SOC in the 0- to 5- and 5- to 20-cm layers, adjusted for bulk density and calculated for a constant soil mass (2000 Mg ha⁻¹) based on the equivalent soil mass concept of Ellert and Bettany (1995). The soil bulk density was measured in April 2008 and values ranged from 0.98 to 1.28 Mg m⁻³ in the 0- to 5-cm depth and from 1.03 to 1.37 Mg m⁻³ in the 5- to 20-cm depth, which is lower than the initial bulk density at the site (1.36–1.44 Mg m⁻³ in the 0–25-cm depth in 1991 [Dam et al., 2005]). Soil bulk density values from April 2008 were

Table 1. Grain yield (2003–2007) in plots under continuous corn production, as affected by tillage and residue inputs. Tillage treatments included no-till (NT), reduced tillage (RT), and conventional tillage (CT). Plots where corn roots and stover were retained had a high input (HI) of residues, in contrast to the low-input (LI) treatment in which only corn roots were left after harvest. Values are the mean \pm standard error (n = 3).

	Grain yield					
Year	NT-HI	RT-HI	CT-HI	NT-LI	RT-LI	CT-LI
	Mg dry matter ha ⁻¹					
2003	$8.1 \pm 0.3 \pm$	7.7 ± 0.3	9.1 ± 0.2	8.1 ± 0.3	8.4 ± 0.4	8.3 ± 0.4
2004	11.4 ± 0.4	12.1 ± 0.4	12.4 ± 0.4	12.1 ± 0.5	12.2 ± 0.3	12.4 ± 0.4
2005	8.4 ± 0.3	7.5 ± 0.3	8.2 ± 0.3	7.9 ± 0.2	8.6 ± 0.5	7.6 ± 0.5
2006	$10.2 \pm 0.3 \text{ ab}$	10.5 ± 0.4 ab	9.7 ± 0.4 b	11.4 ± 0.3 a	10.8 ± 0.4 at	10.6 ± 0.3 ab
2007	11.3 ± 0.5	11.4 ± 0.2	11.6 ± 0.3	11.4 ± 0.3	11.8 ± 0.2	11.6 ± 0.2
5-yr avg.	9.9	9.8	10.2	10.2	10.4	10.1

 \pm Within a given year, treatments with the same letter or no letter did not differ significantly at P < 0.05 (Tukey test).

also lower than those reported in an earlier study at this site, which demonstrated greater bulk density in NT plots than RT and CT plots, with no consistent increase or decrease in the bulk density in the 0- to 10-cm depth during an 11-yr period from 1992 to 2003 (Dam et al., 2005). Hence, we used the average bulk density for the 0- to 10- and 10- to 20-cm depths of each tillage treatment from 1992 to 2003 to represent the bulk density in the 0- to 5- and 5- to 20-cm depths, respectively. The same approach was used to calculate the total N pool (Mg total N ha⁻¹) in 2007. The historical SOC pool was based on total C and bulk density in soil samples collected in 1991. The change in the SOC pool during the 16-yr study period (SOC pool in 2007 minus SOC pool in 1991) was then calculated.

Soil Mineralization Assay

Soil C and N mineralization were determined under laboratory conditions. About 40 g (dry-weight basis) of field-moist soil was weighed into an uncovered plastic vial (90 cm³, 4.25-cm diameter) and moistened to 40% water-filled pore space. The vial was placed in a 500-mL jar and incubated in the dark at $25 \pm 1^{\circ}$ C for up to 20 wk. About 3 mL of water was added to the bottom of the jar to maintain soil humidity. For the N mineralization assay, 252 jars were prepared with soil from both depths (0-5 and 5-20 cm) sampled in each experimental plot (18 plots in total), replicated seven times to permit destructive sampling of soil samples after incubation for 1, 2, 4, 8, 12, 16, and 20 wks. The jars were capped with an air-tight lid; the jars prepared for the 20-wk incubation had lids equipped with an air-tight rubber septum for the measurement of soil respiration every 7 d. After gas was sampled from the headspace, the lids were removed from all jars for 10 to 15 min to prevent the soil from becoming anaerobic and dissipating the accumulated CO2 from the previous week. Gas samples (20 mL) were taken with a gas-tight syringe and stored in pre-evacuated 12-mL Exetainers (Labco, Wycombe, UK) with an extra 60-mL Teflon-silicone septa (National Scientific, Rockwood, TN) until analysis for CO₂ on a gas chromatograph (Hewlett-Packard 5890 Series II, Hewlett-Packard Co., Avondale, PA) equipped with a Porapak Q column (ethylvinylbenzene and divinylbenzene copolymer beads; 80-100 mesh; length, 25 m; internal diameter, 0.20 mm; Supelco 20331). The carrier gas was He (50 mL min⁻¹). Oven and detector temperatures were 120 and 250°C, respectively. Detection of CO₂ was achieved with a thermal conductivity detector.

The CO₂–C concentration in the headspace was calculated according to Holland et al. (1999) after converting gas concentrations from micromoles per mole to a mass per volume concentration (mgCO₂–CL⁻¹) with the ideal gas equation, considering the molecular mass of the gas (e.g., CO₂ = 12 g C mol⁻¹ CO₂). Cumulative C mineralization was the sum of weekly soil respiration (g CO₂–C produced kg⁻¹ soil) during the 20-wk incubation. The mineral N (NH₄–N and NO₃–N) concentrations in incubated soils and in unincubated, field-moist soil (representing the initial mineral N concentration at Week 0) were determined by extracting with 2 mol L⁻¹ KCl (1:5 soil/extractant) according to the procedure of Maynard et al. (2008), followed by colorimetric analysis using a Lachat Quik Chem AE flow injection autoanalyzer (Lachat Instruments, Milwaukee, WI). The size of the potentially mineralizable C and N pools (X_{max} , in mg kg⁻¹ soil) was estimated from the first-order kinetic model

$$X_t = X_{\max} \left[1 - \exp(-kt) \right]$$
[1]

where X_t is the amount of C or N mineralization (in mg kg⁻¹ soil) during a given time period, k is the rate constant (wk⁻¹), and t is time (wk) since the beginning of the incubation.

Statistical Analysis

Before undertaking ANOVA, the data were first checked for normality with a Shapiro–Wilks test and for equal variance among populations with Levene's test, but it was not necessary to transform the data before ANOVA. Differences in corn yields, microbial biomass C and N, and the SOC and total N pools due to tillage, residue input, and the interaction term (tillage × residue input) were evaluated by ANOVA using PROC GLM in SAS (SAS for Windows, version 9.1, SAS Institute, Cary, NC) or Minitab (version 14, Minitab Inc., State College, PA). When treatment effects had a significant (P < 0.05) effect on corn yields and microbial biomass, mean values were compared with a post-hoc Tukey test at the 95% confidence level. Because the GLM model was not significant for the SOC pool (P = 0.172) or the total N pool (P = 0.074), the tillage and residue effects were evaluated with orthogonal contrasts at the P < 0.1 significance level. Data presented in the tables and figures are the untransformed means (\pm standard errors). Estimates of C_{max} and N_{max} were made from a non-

Table 2. Mean residue input from corn stover (stems, leaves, husks, and cobs) in the high-input (HI) treatment of three tillage treatments from 1991 to 2007. Tillage treatments included no-till (NT), reduced tillage (RT), and conventional tillage (CT). The cumulative C input from plant residues was estimated, based on the assumption that corn stover contained 450 kg C Mg⁻¹.

Voar	Stover yield+			
Tear	NT-HI	RT-HI	CT-HI	
	—— Mg dry matter ha ⁻¹ ——			
1991–2002‡	98.4	98.1	105.7	
2003	8.6	7.2	9.4	
2004	8.1	7.9	8.1	
2005	8.7	7.8	8.5	
2006	8.2	8.7	9.8	
2007	11.9	11.3	12.2	
Cumulative C input, Mg C ha ⁻¹	64.8	63.5	69.2	

+ Mass of stems, leaves, and husks was measured. Cob weight was estimated to be 15% of total stover yield (Shinners and Binversie, 2007).
+ Annual grain and stover yield was reported by Dam et al. (2005).

linear regression model with the Marquardt method, while correlations between the labile fractions (MBC, MBN, C_{max} , and N_{max}) and the total SOC pool were evaluated using the PROC CORR function of SAS.

RESULTS AND DISCUSSION Grain and Stover Yield

Dam et al. (2005) reported that grain yield in the experimental plots averaged 7.3 Mg dry matter ha⁻¹, with values ranging from 0.8 to 12.6 Mg ha^{-1} during the period 1991 to 2002. Since then, the annual corn yield has ranged from 7.5 to $12.4 \text{ Mg} \text{ ha}^{-1}$ (Table 1), which gives average grain yields of 9.8 to 10.4 Mg ha^{-1} from 2003 to 2007. Seasonal variation in grain yield was related to climatic conditions, with lower values reported in years with drought or cool, wet growing conditions, and to crop damage by raccoons (Procyon lotor) in 2001. The experimental treatments (tillage and residue inputs) did not affect grain yield, except in 1992 and 1994 when there was significantly lower grain yield in the NT-HI treatment than the CT-HI treatment and all LI plots (Dam et al., 2005). Dam et al. (2005) attributed the lower yield in 1992 and 1994 to a delay in seedling emergence in the NT-HI treatment, surmising that crop residues left at the surface created cool, wet soil conditions that impeded corn germination. No delay in seed germination was observed after 1994. New coulters installed on the NT seeder were better able to cut through the surface residue and loosen the soil ahead of the opener, but it could also be that soil conditions in the NT plots had changed in the 5 yr since the experiment began. The NT plots contained more earthworms, on average 422 individuals m⁻², compared with fewer than 100 individuals m⁻² in the CT and RT treatments (Eriksen-Hamel et al., 2009). Earthworms create macropores that can facilitate soil drainage in NT agroecosystems (Chan 2001). We do not have an explanation for the difference in grain yield observed in 2006, namely the lower yield in the CT-HI than the NT-LI treatment (Table 1).

The residue input to the LI treatment consisted of corn roots and a small amount of corn stem, whereas the HI residue treatment received corn roots, stems, leaves, and cobs. In the HI plots, the cumulative input of corn stems, leaves, and cobs provided about 63.5 to 69.2 Mg C ha⁻¹ more than the residues returned to the LI plots during the 16-yr study period (Table 2).

Total Soil Organic Carbon and Nitrogen Pools

The SOC pool in the 0- to 20-cm depth was 57 to 81 Mg C ha⁻¹, and the total N pool was 5.2 to 7.6 Mg N ha⁻¹ (Table 3). These values are slightly higher than the average of 46 to 52 Mg C ha⁻¹ and 4.1 to 4.3 Mg N ha⁻¹ reported for seven sites with CT and NT treatments in eastern Canada (Angers et al., 1997). There was considerable variation in SOC and total N pools at the study site and the ANOVA produced nonsignificant models. This is attributed to inherent soil heterogeneity: when the study was initiated in 1991, the mean SOC concentration at the site was 22.4 ± 6.5 g C kg⁻¹ (minimum = 17.7 g C kg⁻¹, maximum = 27.0 g C kg⁻¹) and the SOC pool size ranged from 59.8 to 69.0 Mg C ha⁻¹ (Table 3). Contrast analysis revealed that the SOC

Table 3. Initial soil organic C (SOC) in 1991 and the SOC and total N pools (0–20 cm) as affected by 16 yr of tillage and residue inputs in plots under continuous corn production. Tillage treatments included no-till (NT), reduced tillage (RT), and conventional tillage (CT). Plots where corn roots and stover were retained had a high input (HI) of residues, in contrast to the low-input (LI) treatment in which only corn roots were left after harvest. Values are the mean \pm standard error (n = 3).

	SO	Total NL 2007				
Treatment	1991	2007	- Iotai N, 2007			
	Mg C ha ⁻¹		Mg N ha⁻¹			
NT-HI	67.4 ± 4.8	79.4 ± 12.0	7.6 ± 1.0			
RT-HI	62.3 ± 1.4	80.8 ± 1.9	7.7 ± 0.1			
CT-HI	69.0 ± 5.1	59.1 ± 5.2	5.4 ± 0.4			
NT-LI	66.2 ± 2.7	64.5 ± 4.2	6.4 ± 0.6			
RT-LI	62.1 ± 3.7	65.2 ± 11.2	6.1 ± 0.9			
CT-LI	59.8 ± 3.4	57.0 ± 3.4	5.2 ± 0.3			
Contrast (significance probability)†						
CT vs. NT	_	P = 0.085	P = 0.024			
CT vs. RT	-	P = 0.066	P = 0.028			
CT vs. NT and RT	-	P = 0.044	P = 0.013			
RT vs. NT	-	NS	NS			
HI vs. LI		P = 0.097	P = 0.085			

+ Significant (P < 0.1) and nonsignificant (NS) treatment effects.

pool was smaller in the CT than the RT and NT treatments (P < 0.1), with a similar trend in the total N pool (P < 0.05) (Table 3). The change in the SOC pool from 1991 to 2007 revealed a significant (P = 0.018) effect of tillage, with a net loss of $-6.3 \text{ Mg C} \text{ ha}^{-1}$ from the CT treatment and net gains of 5.1 Mg C ha⁻¹ in the NT and 10.8 Mg C ha⁻¹ in the RT treatment (Fig. 1). Changes in SOC pools were calculated on an equivalent soil mass basis, so the values reflect an actual gain or loss of C from the site in the past 16 yr, independent of changes in soil density resulting from tillage operations. In agroecosystems under continuous corn production, VandenBygaart et al. (2003) reported a net gain of $2.6 \pm$ 3.4 Mg C ha⁻¹ in NT compared with CT. The SOC pool was 13 to 34% greater in the NT than the CT treatment in 2007 (Table 3) and the change in the SOC pool during the 16-yr study showed a net difference of 11.4 Mg C ha⁻¹ between NT and CT treatments (Fig. 1). The net gain in the SOC pool during the 16-yr study period was not different in the RT and NT treatments (Fig. 1).

Retention of crop residues is expected to contribute to the SOC pool. Gregorich et al. (1996) concluded that 10 to 20% of corn residues were converted to SOC, while Blanco-Canqui and Lal (2007) showed that approximately 33% of all C from wheat residues returned to a silty loam soil during a 10-yr experiment was sequestered in the SOC pool. In our study, there was a marginal (P < 0.1) effect of residue management on the SOC and total N pools in 2007 (Table 3) and no change in the SOC pool from 1991 to 2007 due to residue inputs (P = 0.109). This was surprising, given the considerable input of corn residues to the HI treatment during the past 16 yr (Table 2). Numerically, the net gain in the SOC pools of the RT and NT plots represented 17 and 8%, respectively, of the estimated, cumulative C input from corn residues (Table 2). While these values are within the range suggested by Gregorich et al. (1996), it appears that a relatively small proportion of the additional C input in the HI treatment was transformed into stable SOC, perhaps because sandy



Fig. 1. Change in soil organic C (SOC) pools (difference between 2007 and 1991 values) following 16 yr of no-till (NT), reduced tillage (RT), and conventional tillage (CT) treatments in plots under continuous corn production. Values are the mean \pm standard error (n = 3). Tillage treatments with the same letter were not significantly different (P < 0.05, contrast analysis).

soils (<33% clay content) have a limited capacity to accumulate SOC compared with clay-rich soils (Laganière et al., 2009).

Labile Carbon and Nitrogen Fractions

The MBC and MBN concentrations reported in this study are of the same magnitude but more variable than values of 135 to 200 mg MBC kg⁻¹ and 17 to 27 mg MBN kg⁻¹ reported in the 0- to 15-cm depth of soil from the same experimental site determined by Spedding et al. (2004). The MBC and MBN concentrations in soil from the 0- to 5-cm depth were greater in the NT treatment than the CT treatment (P < 0.05, Tukey test), with intermediate values in the RT treatment (Table 4). Litter and nutrients are concentrated at the surface of NT systems, and more microbial biomass was often

Table 4. Microbial biomass C (MBC) and N (MBN) concentrations in the 0- to 5- and 5- to 20-cm depths of plots under continuous corn production after 16 yr of tillage and residue input treatments. Tillage treatments included no-till (NT), reduced tillage (RT) and conventional tillage (CT). Plots where corn roots and stover were retained had a high input (HI) of residues, in contrast to the low input (LI) treatment in which only corn roots were left after harvest. Values are the mean \pm standard error (n = 3).

	0–5 cm		5–20	cm
Treatment	MBC	MBN	MBC	MBN
	mg C kg ⁻¹	mg N kg ⁻¹	mg C kg ⁻¹	mg N kg ⁻¹
NT-HI	417 ± 36 a†	95 ± 39 a	263 ± 36	31 ± 3.0 B
RT-HI	361 ± 30 a	65 ± 1.5 a	332 ± 32	53 ± 3.9 A
CT-HI	211 ± 33 b	21 ± 5.7 b	245 ± 18	25 ± 1.6 B
NT-LI	286 ± 33 a	32 ± 5.5 a	268 ± 32	21 ± 2.9 B
RT-LI	219 ± 72 a	21 ± 5.0 a	276 ± 33	25 ± 1.5 B
CT-LI	190 ± 13 b	20 ± 2.4 b	277 ± 54	23 ± 1.0 B
Treatment effects				
Tillage	$P = 0.008^{*}$	$P = 0.036^{*}$	P = 0.857 NS	$P = 0.022^{*}$
Residue	$P = 0.010^{*}$	$P=0.060^*$	P = 0.527 NS	$P = 0.003^{*}$
Tillage × residue	<i>P</i> = 0.251 NS	P = 0.122 NS	<i>P</i> = 0.536 NS	$P = 0.031^*$

* Treatment effects significant at P < 0.05; NS, treatment effects not significant. + Within a column, values with the same letter did not differ significantly at P < 0.05 (Tukey test). Differences due to tillage are indicated with lowercase letters and the tillage × residue interaction is indicated with uppercase letters. found in the0- to 5-cm depth of the NT than the CT soils (Carter, 1986; Angers et al., 1993). The microbial biomass C/N ratio ranged from 6 to 13, but was not affected by tillage. Long-term NT is often assumed to favor the development of a dominant fungal population, which could increase the C/N ratio of the microbial biomass due to the higher C/N ratio of fungal than bacterial biomass (Paul and Clark, 1996). Previous work at this site by Spedding et al. (2004) found that the microbial biomass was greater under NT than CT, but tillage did not affect the fungal/bacterial biomass C/N ratios were not affected by tillage in the present study. Similarly, Helgason et al. (2009) reported no difference in the fungal/bacterial biomass ratio in soils from the Northern Great Plains.

There was a greater MBC concentration in the 0- to 5-cm depth of the HI than the LI residue treatment (Table 4), probably due to an abundance of labile C from corn residues near the soil surface. The MBN concentration in the 5- to 20-cm depth was affected significantly (P < 0.05) by the tillage × residue interaction, with the greatest MBN concentration in the RT-HI treatment (Table 4). Crop residues are partially fragmented and mixed to a depth of 10 to 15 cm when the RT plot is harrowed, which could slow decomposition and preserve N-rich substrates for incorporation into the microbial biomass by the end of the growing season. Eriksen-Hamel et al. (2009) demonstrated that earthworm growth rates in intact soil cores (0-30 cm) were 1.7 to 3.0 times greater in the RT-HI treatment than the other tillage-residue combinations. This was attributed to greater availability of N-rich residues in the RT treatment than the NT and CT treatments, as earthworm growth is strongly related to the N content of the available substrates (Shipitalo et al., 1988).

In contrast to the total SOC pool, labile C compounds are more transient and therefore more measurably affected by tillage and residue management (Haynes, 2005). The tendency for greater C_{max} values in the RT and NT treatments relative to the CT treatment, and in the HI than the LI treatment (Table 5), suggests that this labile C pool is protected from decomposition in situ but susceptible to breakdown when soils are collected, sieved, and incubated under optimal conditions for microbial growth in the laboratory. Our results are consistent with Tracy et al. (1990), who

Table 5. Size of the potentially mineralizable C and N pools (C_{max} and N_{max}) in the 0- to 5- and 5- to 20-cm depths of plots under continuous corn production, as affected by 16 yr of tillage and residue input treatments. Tillage treatments included no-till (NT), reduced tillage (RT) and conventional tillage (CT). Plots where corn roots and stover were retained had a high input (HI) of residues, in contrast to the low input (LI) treatment in which only corn roots were left after harvest. Values are the estimated C_{max} or $N_{max} \pm$ approximate standard error (n = 3).

	0–5 cm		5-20) cm
Treatment	C _{max}	N _{max}	C _{max}	N _{max}
	mg C kg ⁻¹	mg N kg ⁻¹	mg C kg ⁻¹	mg N kg ⁻¹
NT-HI	2765 ± 129	115 ± 18	2416 ± 697	151 ± 69
RT-HI	1310 ± 273	102 ± 12	2008 ± 309	131 ± 19
CT-HI	949 ± 126	67 ± 7.3	1374 ± 124	65 ± 11
NT-LI	2239 ± 409	123 ± 33	2020 ± 617	72 ± 14
RT-LI	1324 ± 153	87 ± 19	1494 ± 442	91 ± 19
CT-LI	1141 ± 336	59 ± 5.4	1145 ± 169	77 ± 28

reported nearly twice as much labile C in incubated soils from NT than CT treatments 16 yr after establishing a tillage experiment on a loamy soil. Our C_{max} values ranged from 949 to 2765 mg C kg⁻¹ soil, representing 4 to 11% of the total SOC content. Haynes (2005) reported that between 0.5 and 12% of the total SOC is labile and readily mineralized during short-term laboratory incubations.

The potential N mineralization (N_{max}) tended to be greater in soils from the NT and RT treatments than the CT treatment, particularly in the 0- to 5-cm depth, and $\mathrm{N}_{\mathrm{max}}$ also tended to be greater in the HI than the LI treatment (Table 5). These results are consistent with other laboratory-based soil mineralization studies that reported greater N mineralization in NT soils than CT soils collected from the field after 16 yr of tillage treatments on a loamy soil (Tracy et al., 1990) and in soils from other field sites with contrasting tillage management (Martens and Dick, 2003; Liebig et al., 2004; Sharifi et al., 2008). The larger pool of potentially mineralizable N in the NT and RT soils (0-5 cm) as well as the HI treatment, implies that there is less N mineralization from these treatments in the field, leading to a buildup of labile N, which is susceptible to mineralization when the soil is disturbed for incubation in the laboratory (Haynes, 2005). This is consistent with the physical protection of labile C and N in aggregates under NT (Six et al., 2002).

In the 0- to 5-cm depth, the labile C and N fractions measured in this study (microbial biomass and potentially mineralizable C and N) were correlated with the total SOC pool, with significant (P < 0.05) correlations between the total SOC pool, MBN and N_{max} in the 5- to 20-cm depth (Table 6). Management-induced effects on the total SOC and the labile fractions of the SOC are therefore stronger in the 0- to 5- than the 5- to 20-cm depth. These relationships support the use of labile fractions as indicators of management-induced change in the total SOC pool, as suggested by Haynes (2005). Changes in the microbial biomass and potentially mineralizable C and N pools may therefore be used to infer changes in SOC, which is particularly useful in field sites with high inherent heterogeneity in SOC content like the site evaluated in this study.

CONCLUSIONS

We hypothesized that reducing the tillage intensity and retaining more residues in agroecosystems under continuous corn

Table 6. Pearson correlation coefficients (*r*) between the total soil organic C (SOC) pool and labile fractions of SOC (microbial biomass C [MBC], microbial biomass N [MBN], and the size of the potentially mineralizable C [C_{max}] and N [N_{max}] pools) in the 0- to 5- and 5- to 20-cm depths (*n* = 18 for each depth) of plots under continuous corn production subject to 16 yr of tillage and residue input treatments.

Labile fraction	Total SOC pool		
of SOC	0–5 cm	5–20 cm	
мвс	0.816***	0.348 NS	
MBN	0.434†	0.483*	
max	0.466†	0.068 NS	
N _{max}	0.708***	0.679**	

* Significant at P < 0.05.

** Significant at P < 0.01.

*** Significant at *P* < 0.001.

+ Significant at P < 0.1; NS, not significant.

production would increase the SOC pool. After 16 yr of implementing these management practices, there was a net gain in the SOC pool of 5.1 Mg C ha⁻¹ in the NT treatment and 10.8 Mg C ha⁻¹ in the RT treatment, which was not statistically different, and a net loss of $-6.3 \text{ Mg C} \text{ ha}^{-1}$ in the CT treatment, which was statistically (P < 0.05) different from the NT and RT treatments. Residue management had a marginal (P < 0.1) effect on SOC and total N pools, but did not result in a net gain or loss of SOC between 1991 and 2007. The labile fractions of SOC in the microbial biomass and potentially mineralizable C and N pools were greater at the soil surface (0-5 cm) of plots where conservation tillage (RT and NT) was practiced, and also increased with higher crop residue inputs. In the 5- to 20-cm layer, the RT treatment had a larger labile C and N pool than the NT and CT treatments, ostensibly because the crop residues were mostly retained at the surface of the NT plots or rapidly decomposed in the CT plots. These labile fractions were correlated to the total SOC pool, particularly in the 0- to 5-cm layer. We conclude that the microbial biomass and potentially mineralizable C and N are indicators of management-induced changes in agroecosystems that are not always clearly reflected in the SOC pool.

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