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Soil carbon and nitrogen accumulation with long-term no-till versus moldboard plowing overestimated with tilled-zone sampling depths

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Abstract

Numerous investigators of tillage system impacts on soil organic carbon (OC) or total nitrogen (N) have limited their soil sampling to depths either at or just below the deepest tillage treatment in their experiments. This has resulted in an over-emphasis on OC and N changes in the near-surface zones and limited knowledge of crop and tillage system impacts below the maximum depth of soil disturbance by tillage implements. The objective of this study was to assess impacts of long-term (28 years) tillage and crop rotation on OC and N content and depth distribution together with bulk density and pH on a dark-colored Chalmers silty clay loam in Indiana. Soil samples were taken to 1 m depth in six depth increments from moldboard plow and no-till treatments in continuous corn and soybean–corn rotation. Rotation systems had little impact on the measured soil properties; OC content under continuous corn was not superior to the soybean–corn rotation in either no-till or moldboard plow systems. The increase in OC (on a mass per unit area basis) with no-till relative to moldboard plow averaged 23 t ha^{-1} to a constant 30 cm sampling depth, but only 10 t ha^{-1} to a constant 1.0 m sampling depth. Similarly, the increase in N with no-till was 1.9 t ha^{-1} to a constant 30 cm sampling depth, but only 1.4 t ha^{-1} to a constant 1.0 m sampling depth. Tillage treatments also had significant effects on soil bulk density and pH. Distribution of OC and N with soil depth differed dramatically under the different tillage systems. While no-till clearly resulted in more OC and N accumulation in the surface 15 cm than moldboard plow, the relative no-till advantage declined sharply with depth. Indeed, moldboard plowing resulted in substantially more OC and N, relative to no-till, in the 30–50 cm depth interval despite moldboard plowing consistently to less than a 25 cm depth. Our results suggest that conclusions about OC or N gains under long-term no-till are highly dependent on sampling depth and, therefore, tillage comparisons should be based on samples taken well beyond the deepest tillage depth.

Keywords: Carbon sequestration; Nitrogen; Bulk density; No-till; Crop rotation; Sampling depth

1. Introduction

Soils can act as sinks (absorbers) or as sources (emitters) of greenhouse gases (Allmaras et al., 2000). Conventional tillage has frequently been associated with losses in soil organic carbon (OC), but less intensive tillage systems (such as no-till) have been effective in helping soils act as a carbon (C) sink. Minimizing soil disturbance reduces mineralization of organic matter (OM) and can result in larger storage of soil OC relative to conventional tillage (West and Post, 2002; Al-Kaisi and Yin, 2005).

Less intensive tillage with residue management practiced for extended periods of time has been shown

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to increase OC and N concentration and mass of the surface soil compared to the low steady state reached after many years of conventional tillage (Dick, 1983; Blevins, 1984; Eghball et al., 1994; Madari et al., 1998; Allmaras et al., 2000). Most previous studies (e.g. Balesdent et al., 1990; Karlen et al., 1994; Lal et al., 1994; Potter et al., 1998; West and Post, 2002) regarding tillage system effects on OC concentration and mass have focused on the ''plow layer'' (0–30 cm depth) and did not account for potential changes at deeper depths. According to Kern and Johnson (1993) the change from conventional tillage to no-till management sequesters the greatest amount of OC in the upper 15 cm of soil, and no significant amount below 15 cm. They concluded further – based on samples taken to a 30 cm depth – that no-till and conventional tillage had similar OC mass below 15 cm. In addition, guidelines developed for accounting of greenhouse gases in agricultural ecosystems generally provide estimates based on the upper 30 cm layer (Johnson et al., 1995; Eve et al., 2001). However, in studies of Angers et al. (1997) and Vandenbygaart et al. (2002, 2003) it has been shown that although most soils under reduced tillage had more soil OC mass in the top 10 cm than under conventional tillage, the same reduced tillage systems had less OC mass at deeper depths (20–40 cm) than moldboard plow systems. Studies that have involved deeper sampling generally show no C sequestration advantage for conservation tillage, and gas exchange measurements also offer little support to the notion of a consistent soil C benefit from reduced tillage (Baker et al., 2007). The possible enrichment of soil C below the typical ''plow layer'' must be thoroughly investigated.

Although the purpose of many soil C studies is related to mitigating the impacts of global climate change, a better understanding of management-induced changes has benefits far beyond the current objectives of C sequestration projects. In sustainable agricultural production, the maintenance of soil OM quantity and quality is of key importance, and the replenishment of decreased levels of OM is slow and not easily achieved (Eswaran et al., 1993).

Tillage system influences on soil bulk density are variable, but important to quantify in evaluations of tillage influences on soil C content. Lal et al. (1994) found a decrease in bulk-density in no-till relative to conventional tillage, but some researchers have found no differences in soil bulk density near the soil surface (Hill and Cruse, 1985). Others, such as Gantzer and Blake (1978) for example, have found that bulk density in no-till is significantly higher near the surface when compared to plowing. Voorhees et al. (1978) hypothesized that the latter happens because when the soil remains untilled, it becomes denser over time due to the effect of consolidation. Even in temperate climates, the loosening effect of annual freezing and thawing cycles, wetting and drying, and soil organism activities are not enough to prevent this increase in soil bulk density. The relative soil bulk density changes also depend upon length of time in the no-till system and the traffic-induced compaction (Kladivko and Larney, 1989).

Bulk density is also directly influenced by the OM content of the soil. Its accurate measurement is critical for converting OC percentage on a weight basis to content per unit volume. Davidson et al. (1967) showed that bulk density is inversely related to soil OM. As the OM content increases, aggregation tends to increase thus increasing porosity and decreasing bulk density. No statement of tillage system influence on OC or N sequestration on a mass basis is accurate without a rigorous determination of bulk density.

The actual effect of different tillage practices on soil C storage is highly dependent on the crops produced in the field. Studdert and Echeverria (2000) concluded that the lowest soil OC content corresponded with soybean–soybean sequences and soil OC increased as soybean was not present or corn was present in the crop sequences they investigated. Differences in soil OC between crop rotations are more dependent on residue quantity than any other factor, although even that factor is conditioned by other factors (Batjes, 1996). Nitrogen fertilization, for instance, helps maintain soil OC with respect to the initial level, because it promotes plant growth and consequently results in more plant residue (Barber, 1979).

In the United States approximately 25% of the corn prior to 2002 followed corn in sequence (Power and Follett, 1987; NASS, 2006), and the vast majority of the remaining corn is grown in a 2-year rotation with soybean (Bullock, 1992; NASS, 2006). Relatively few studies have investigated soil OC and N differences between continuous corn and soybean–corn rotations after two decades or more.

The continuity of management practices is an important factor in C storage, since soil OC differences among treatments can take several years to develop. Soil response to different management practices varies depending in part upon the length of time the management practices have been in place (Potter et al., 1998; Omonode et al., 2006).

The objectives of the research were to (1) determine the long-term impact of conventional tillage (moldboard plowing) and conservation tillage (no-till) on soil

OC and N mass and depth distribution in continuous corn and soybean–corn rotation to a 1 m depth, and (2) investigate the impact of the different tillage and rotation systems on soil bulk density and pH at alternate depth intervals.

2. Materials and methods

2.1. Sampling site

The sampling site of this study was the long-term tillage experiment initiated in 1975 by Purdue University, and located at the Agronomy Center for Research and Education near West Lafayette, IN (40°28′N latitude) (Vyn et al., 2000). The initial goal of the experiment was to determine long-term crop yield potential of different tillage systems in various crop rotations, and to determine changes in soil characteristics and crop growth that could be associated with yield differences. Plow, chisel, ridge and no-till systems have been compared in continuous corn (*Zea mays* L.), corn following soybean (*Glycine max* (L.) Merr.), soybean following corn, and continuous soybean rotations since the beginning of the trial. The soil is a poorly drained Chalmers silty clay loam (fine-silty, mixed, mesic Typic Haplaquoll according to the U.S. taxonomy), dark-colored, with approximately 4.0% OM in the surface 30 cm, developed under prairie vegetation. The experimental area has less than 1% slope and is systematically tile drained at 20 m intervals (Vyn et al., 2000). The experiment is a randomized complete block in a split-plot design with all treatments replicated four times. Crop rotations are the main units, and tillage treatments are the subunits.

Each of the four blocks consists of 16 tillage plots. Individual plots are 9 m wide, 45 m long (0.04 ha), and consist of 12 rows. Row width is 76 cm for corn, was also 76 cm in soybean from 1975 to 1995, and has been 19 cm for soybean since 1996. Cultural practices have been relatively consistent since the study began. Fall moldboard plowing occurred annually to a depth of 20–25 cm, and secondary tillage operations of disking plus field cultivation to 10 cm prior to planting each spring. No-till planting from 1975 to 1996 was accomplished with a single coulter to cut through the residues and loosen the soil ahead of standard planter units. Since 1997, tined row cleaners have been used in place of no-till coulters in front of the standard seed disk openers. Lime was applied periodically to maintain soil pH in a favorable range, and the last lime application (2.0 t ha^{-1}) before soil sampling in this experiment occurred before primary tillage in November of 2001. Starter fertilizer was routinely applied when corn was planted (37 kg N ha^{-1} in the form of ammonium nitrate). Since 2001, N fertilizer has been side-dress applied in June (222 kg N ha^{-1} as 28% urea-ammonium nitrate). Blended phosphorus and potassium fertilizers were broadcast applied before fall primary tillage when required; the last application before the present soil sampling occurred in November of 2002 (in that application phosphorus fertilizer (0-46-0) was applied at a rate of 224 kg ha^{-1} and potassium fertilizer (0-0-60) was applied at a rate of 336 kg ha^{-1}). There was no nitrogen fertilizer applied for soybean, but blended phosphorus and potassium fertilizers were routinely broadcasted at the same rate as for corn (Vyn et al., 2000).

2.2. Soil sampling

We limited our intensive soil sampling to the conventionally tilled (annual moldboard plow (P)) and no-till (NT) plots with corn monoculture (CC) and soybean–corn (BC) rotations.

Samples were obtained mainly in the spring of 2003 before secondary tillage, but after primary tillage in the fall of 2002, from plots, which had been in corn production in 2002. A few deep soil cores were taken in the fall of 2003 after harvest because of excessively wet soil conditions at those sampling points in the spring. Six samples per plot were taken from both sides of the fourth row from the west edge of each plot approximately 20 cm from the prior corn row (quarter row position). The samples were taken in six depth increments to a depth of 1 m (0–5, 5–15, 15–30, 30–50, 50–75 and 75–100 cm) with a hydraulically driven core sampler (core 6.7 cm in diameter). When sampling the moldboard plowed plots some compression of the soil occurred in the shallow depths. Therefore, the upper segments of the core (0–5 and 5–15 cm) were not kept and shallow samples were collected by hand using a shovel. All deeper cores (i.e. 15–100 cm) were taken via the hydraulically driven probe. The samples were air-dried, the easily identified organic matter (roots, stems, leaves) was removed, and the soil was ground with a soil hammer mill and sieved through a 2 mm diameter sieve.

The bulk density samples from the depths of 0–5, 5–15 and 15–30 cm (four samples per plot taken from both sides of the row) were collected by the core method using double-cylinder, hammer-driven core samplers (Blake and Hartge, 1986) in the spring of 2003 before secondary tillage, but after the primary tillage operation in the fall of 2002. The fall period was not appropriate for taking the bulk density samples on this soil type, because it is high in swelling clays. The precipitation in the fall is generally insufficient to rehydrate the clay minerals after a summer period on this type of soil; the latter results in inaccurate bulk density determination, since the volume of the bulk density samples depends on the water content at the time of sampling. For the deeper depths (30–50, 50–75 and 75–100 cm), bulk density was determined directly from the cores taken with the hydraulically driven probe. The 1 m long cores were sliced into proper lengths; all soil from each depth increment was collected into a paper bag and air-dried.

2.3. Laboratory methods

Organic C and N concentrations were determined by dry combustion of duplicate subsamples using a LECO® 2000 CHN Analyzer (Leco Corporation, St. Joseph, MI) at the USDA Soil Erosion Laboratory (West Lafayette, IN). Since the parent material is calcareous, all samples from the 50–75 and 75–100 cm depth were treated to remove any inorganic C (LECO Corporation, 1987). The latter samples were pre-treated with 1 M hydrochloric acid (HCl) until fizzing stopped, washed with deionized water, air-dried and ground again. The no-till samples from the 0 to 5 cm layer were also treated with HCl based on a preliminary carbonate determination. This preliminary carbonate determination was done by measuring the C concentration on a set of samples representing all the tillage and rotation treatments in depth intervals between 0 and 50 cm before and after removing calcium-carbonate with the above mentioned pre-treatment. The requirement for such treatment in no-till, but not in plow, may have been associated with the recent liming history and the lack of lime incorporation in no-till. Atomic C/N ratios were also calculated based on the respective OC and N concentrations.

Soil pH determination was done by the A&L Great Lakes Laboratories Inc. (Fort Wayne, IN) in soil/water slurry (Watson and Brown, 1998).

Amounts of soil OC and N were expressed as concentration (g kg^{-1}) and mass per unit area in depth increments (t ha^{-1}), mass per unit area to a fixed depth of 1 m, and mass per unit area in an equivalent soil mass. The element mass and soil mass per unit area (t ha^{-1}) for each depth increment was calculated using the equation from Ellert and Bettany (1995). Tillage practices might alter the mass of soil in the surface or deeper soil horizons due to physical and biological processes. To account for different soil masses, we also calculated the amount of OC and total N in an equivalent soil mass. The tillage system with the lightest soil mass was considered to be the standard, and the heavier soil mass was adjusted by calculating with less thickness in the 75–100 cm layer (Ellert and Bettany, 1995). Masses of OC and total N per unit area to a depth of 1 m and in an equivalent soil mass were calculated by summing the element masses in individual depth increments.

Bulk density samples (the hand-sampled cores from the 0 to 30 cm depth) were oven-dried for 48 h at 105 °C (drying to constant weight), weighed and bulk density was determined as the mass of dry soil per volume of field-moist soil (Blake and Hartge, 1986). Bulk density of the deeper soil samples (30–100 cm) was determined by weighing the air-dried core sample and calculating the moisture content from a sub-sample (oven-dried at 105 °C for 48 h) so that the remainder of the soil could be used for chemical analysis. Bulk density was calculated using the soil weight of the sample (corrected by subtracting the water content) and dividing with core volume in that certain depth increment.

2.4. Statistical analysis

The statistical analysis was performed with SAS (SAS Institute Inc., 2002). Analysis of variance (ANOVA) was performed within each depth increment and differences among treatment means were tested using the least significant difference test (LSD) at α-level of 0.05. Rotation and tillage were the experimental factors and the interactions between these factors were examined as well.

3. Results and discussion

In general, tillage treatments had more impact on OC, total N storage, bulk density and pH of the soil than crop rotation treatments. Interactions of rotation × tillage were consistently insignificant for these soil chemical and physical parameters.

In the 0–5 cm depth interval, differences due to tillage in OC and total N concentrations between the no-till and plow treatment were highly significant; indeed, no-till resulted in 33% higher OC and 32% higher total N concentration than plow (Table 1). No-till also resulted in significantly higher OC and total N concentration in the 5–15 cm depth (9% higher OC and total N). Because of the close relationship between soil OC and N concentrations it is logical that N concentration trends with depth are similar to those for OC concentration.

Table 1
Tillage treatment effects (averaged for two crop rotations) on organic carbon, total nitrogen concentrations, C/N ratio, bulk density and pH at multiple depth increments to a 1 m sampling depth

Depth (cm)	OC (g kg^{-1})		N (g kg^{-1})		C/N ratio		BD (g cm^{-3})		pH	
	NT	P	NT	P	NT	P	NT	P	NT	P
0–5	35.7**	23.9	2.8**	1.9	12.8	12.6	1.26**	1.13	7.05**	6.65
5–15	26.6*	24.1	2.1*	1.9	12.7	12.7	1.37**	1.16	5.94**	6.74
15–30	22.9	24.5	1.8	1.9	12.7	12.9	1.40**	1.16	5.39**	6.78
30–50	11.6*	15.2	1.0*	1.3	11.6	11.7	1.44	1.45	6.38	6.61
50–75	4.7	5.1	0.6	0.6	7.8	8.5	1.42	1.44	6.99	7.02
75–100	3.1*	3.5	0.4	0.3	7.8	11.7	1.55	1.50	7.51	7.48

NT, no-till; P, moldboard plow.
* Significant differences between two tillage systems at $\alpha = 0.05$.
** Significant differences between two tillage systems at $\alpha = 0.01$.

In the 15–30 cm depth the trend for higher OC and N concentrations with no-till reversed and plow resulted in somewhat, although not significantly ($P = 0.05$) higher concentrations (7% higher OC and 5% higher total N). The slight increase in OC with the plow treatment at this depth interval might be the consequence of turning down crop residue to a depth between 20 and 25 cm annually during moldboard plowing, while with continuous no-till plant residues remain on the surface. However, in the 30–50 cm depth interval the plow treatment had a remarkable 23% higher OC and total N concentration than no-till. Our results corresponds with results of Wanniarachchi et al. (1999), who found that no tillage had no significant impact on the soil C compared with conventional tillage in the 0–50 cm soil depth.

Crop root-derived C may be very important for C storage in soil (Flessa et al., 2000; Gregorich et al., 2001; Tresder et al., 2005). Some studies have found that no-till practices produced greater horizontal distribution of roots and greater root density near the surface (Frye and Blevins, 1997; Ballcoelho et al., 1998), or that rhizodeposition increased when there was tillage in the system (Allmaras et al., 2004). Holanda et al. (1998) measured root characteristics in the same experiment as our current study; these former authors also found that the no-till system resulted in a higher root density compared to moldboard plow in the upper soil layers (0–25 cm). Differences in rooting depth under these contrasting tillage systems were also reported by Dwyer et al. (1996) who found that despite the fact that total root mass was not significantly different among tillage treatments, rooting was generally shallower in no-till than in conventional tillage. Gregorich et al. (2001) also observed that 10% of root residue C was retained in the plow layer versus 45% below the plow layer for both corn monoculture and corn in a legume-based rotation. These studies suggest that the increase in the OC and N pool at the 30–50 cm depth may have resulted in part from the higher contribution of roots and root excretions in the moldboard plow treatment at this soil depth interval.

Factors other than root distribution may also have played a role in our results. Microbial cycling and possibly leaching of OM constituents from the residue-enriched layer just above the bottom of the plow zone might have also increased OC and total N concentration and mass at this depth under moldboard plow compared with no-till (Szabó, 1986). It is also possible that soil pH was a contributing factor to this unexpected increase in OC with moldboard plowing. Tillage effects on pH were highly significant in the upper 30 cm (Table 1). In the 0–5 cm depth plow had lower pH than no-till, while in the 5–15 and 15–30 cm depths no-till resulted in lower pH values. The lowest individual plot values were pH 4.7 in the 15–30 cm and pH 5.2 in the 30–50 cm depth in no-till; according to Hoeft et al. (2000), these low pH environments may reduce root exploration of deeper soil layers. The stratification in pH distribution is due to the incorporation of the broadcast lime in plow, the lack of soil mixing in no-till, and the injection of N fertilizers. Rotation effects on pH were significant only in the 0–5 cm depth; soybean–corn rotation resulted in higher values (pH 6.98) than continuous corn (pH 6.72). Lower pH with continuous corn may be due to the doubling of N fertilizer amounts, since N fertilizer was only applied every other year in the soybean–corn rotation.

Tillage differences in OC concentration were also significant in the 75–100 cm depth, but overall concentrations were very low (Table 1). It appears that differences between the two tillage systems in OC and total N storage were generally small at depths below 50 cm, and of little consequence to the total profile C and N storage to a 1 m depth.

There were no significant differences between tillage systems in C/N ratio (Table 1), but an overall decrease could be observed below 30 cm.

Bulk density was influenced by tillage in the upper 30 cm, with significantly higher values occurring for no-till than for plow (10% higher in the 0–5 cm, 15% higher in the 5–15 cm and 17% higher in the 15–30 cm depth increment) (Table 1). At depths between 30 and 100 cm, there were no tillage treatment differences in bulk density. Total mass of OC and total N in the upper layers (0–5, 5–15 and 15–30 cm) was higher for no-till than plow, but in the 30–50 cm layer plow stored a higher amount of both OC and total N (Table 2). On a mass per unit area basis, about 65% higher OC and 64% higher total N accumulated in no-till in the 0–5 cm depth compared to plow: the latter differences were highly significant (Table 2). Tillage effects were highly significant in the 5–15 cm depth increment on a mass basis for both OC (30% higher in no-till) and total N (32% higher in no-till). In the 15–30 cm depth, although tillage effects were not significant on a concentration basis, there were significant tillage effects on mass per unit area basis (13% higher in no-till for OC and 15% higher in no-till for total N) due to the higher bulk densities in no-till. However, in the 30–50 cm depth, plow had 32% higher OC and 23% higher total N than no-till.

The importance of calculating C and N storage on a mass basis (Table 2) for different tillage systems is illustrated by our results. Because OC and total N mass is calculated by combining the concentration of these elements and the bulk density of the soil, differences between no-till and plow were even greater when calculated on mass per unit area basis (Table 2) than on a concentration basis (Table 1). In the 5–15 cm depth interval tillage treatment differences became highly significant ($P = 0.01$) on a mass basis compared to a concentration basis (differences were significant at $P = 0.05$; Table 1). In the 15–30 cm depth there were no significant differences between concentrations, but since differences in densities of the different tillage systems were highly significant, differences in OC and total N masses between no-till and moldboard plow became significant as well. Conclusions about the relative no-till system effects compared to moldboard plowing on soil OC sequestration based simply on concentration values are misleading in the absence of simultaneous measurements of soil bulk density.

In terms of relative soil mass, the weight of the no-till soil to a 1 m depth (14,405 t ha^{-1}) was higher than for plow (13,715 t ha^{-1}), so plowed soil was considered as the standard when calculating OC and total N on an equivalent soil mass basis. No-till stored 10.1 t ha^{-1} (6%) more OC than plow to the depth of 1 m, and 8.02 t ha^{-1} (5%) more OC on an equivalent soil mass basis (Table 2). As for total N, no-till stored 1.4 t ha^{-1} (11%) more N than plow to a 1 m depth, and 1.25 t ha^{-1} (10%) more N based on an equivalent soil mass basis (Table 2).

A limitation of numerous studies examining tillage effects on C sequestration is that they were carried out only to the depth of plowing; that approach results in very little information about the C status of the deeper soil profile. Our calculations show that tillage changes the vertical distribution of OC and total N to a depth of at least 50 cm, and the C and N mass stored in the 30–50 cm depth increment leads to a different conclusion about the extent of C sequestration with no-till than discussions limited to either 20 or 30 cm sampling depths. Although the increase in OC and total N content in the upper 30 cm in no-till resulted in an overall gain in OC to a depth of 1 m on this soil, we might have overestimated the amount of C stored in no-till soils, compared to plow, if we had not taken into consideration changes resulting from tillage effects below the plowing depth.

Estimates of C and N stored in the surfaces of no-till and plowed soils also are influenced by the method used to calculate the element status. Bulk densities of no-till soils often are greater than those of conventionally tilled soils in the upper 30 cm depth increment. Consequently, estimates of OC accumulation in no-till soils are smaller for calculations based on an equivalent soil mass basis than for calculations based on a fixed sampling depth. Variability among masses to a 1 m depth originates from compaction of surface layers and from lateral

Table 2
Tillage treatment effects (averaged for two rotation systems) on mass of organic carbon and total nitrogen in soil at multiple depth increments, summed to a 1 m sampling depth and on an equivalent soil mass basis

Depth (cm)	OC (t ha^{-1})		N (t ha^{-1})	
	NT	P	NT	P
0–5	22.5**	13.6	1.8**	1.1
5–15	36.4**	27.9	2.9**	2.2
15–30	48.2*	42.8	3.8*	3.3
30–50	33.3*	43.9	3.0*	3.7
50–75	16.7	18.2	1.9	2.0
75–100	12.2	12.8	1.6	1.3
To 1 m depth	169.3*	159.2	15.0*	13.6
Equivalent soil mass	167.1*	159.1	14.7*	13.4

NT, no-till; P, moldboard plow.
* Significant differences between two tillage systems at $\alpha = 0.05$.
** Significant differences between two tillage systems at $\alpha = 0.01$.

Table 3
Rotation effects (averaged for two tillage treatments) on organic carbon, total nitrogen concentrations, C/N ratio, bulk density and pH at multiple depth increments to a 1 m sampling depth

Depth (cm)	OC (g kg^{-1})		N (g kg^{-1})		C/N ratio		BD (g cm^{-3})		pH	
	CC	BC	CC	BC	CC	BC	CC	BC	CC	BC
0–5	30.7	29.0	2.3	2.3	13.3	12.6	1.18	1.21	6.72**	6.98
5–15	25.7	24.9	1.9	2.0	13.5	12.5	1.24	1.28	6.25	6.43
15–30	24.4	23.1	1.8	1.9	13.6	12.2	1.30	1.27	5.99	6.18
30–50	13.8	13.0	1.1	1.2	12.5	10.8	1.44	1.45	6.38	6.62
50–75	5.0	4.8	0.5	0.6	10.0	8.0	1.43	1.43	6.97	7.04
75–100	2.9*	3.8	0.3	0.4	9.7	9.5	1.53	1.52	7.39	7.60

CC, continuous corn; BC, soybean–corn rotation.
* Significant differences between two rotations at $\alpha = 0.05$.
** Significant differences between two tillage systems at $\alpha = 0.01$.

redistribution by soil erosion or deposition. However, when the variability by unequal soil masses is eliminated, the remaining variability among element masses originates from different management impacts (Ellert and Bettany, 1995). The latter authors concluded that observed differences between C and N stored in no-till and plow soils were smaller when an equivalent soil mass was considered. Comparisons between no-till and plowed soils in England also indicated no significant differences in soil C and N when differences in soil mass were considered (Powlson and Jenkinson, 1981).

Overall, OC of no-till soil increased significantly compared to soils under moldboard plowing. However, the overall increases were much smaller than that reported in other literature from similar environments (Dick, 1983; Lal et al., 1994), in part because of the unexpected increase in OC with plow at 30–50 cm depth. Our results are similar to those of Angers et al. (1997), who found no significant differences between tillage treatments in the total OC and N storage to a 60 cm depth in cool, humid soils of eastern Canada. Although no-till resulted in more OC and N in the surface 10 cm, the plow treatment in their study had higher OC and N than no-till at deeper depths (20–40 cm).

In our research, rotation effects were less pronounced than tillage effects. Differences in OC and total N concentrations between the corn monoculture and soybean–corn rotation were not significant (Table 3). The resulting trends indicate that the corn monoculture had somewhat higher OC concentrations, but lower total N concentration than the soybean–corn rotation. Lower soil N in continuous corn resulted from the higher amount of residue left on the field and the subsequent N immobilization in residue decomposition, from N fixation of soybean in the soybean–corn rotation in alternate years, and the fact that identical rates of N fertilizer for both rotations might have exceeded optimum N levels more often in the soybean–corn rotation. Corn monoculture had a consistently higher C/N ratio at each depth interval, but differences between rotations were not significant in individual depth increments. Bulk density was not influenced by rotation at any depth increment.

The mass of OC was somewhat higher for continuous corn than for soybean–corn rotation at depths to 75 cm, while soybean–corn rotation stored slightly more total N than continuous corn (Table 4). However, rotation system differences in both OC and total N were not significant at any depth interval except from 75 to 100 cm. Grain corn yields averaged over 11 t ha^{-1} while soybean seed yields averaged over 3.4 t ha^{-1} in the corn–soybean rotation during the 28-year period. Continuous corn resulted in 5% less grain yield than rotation corn in the plow treatment, but 15% less grain yield than rotation corn in the no-till system (Omonode et al., 2007). In spite of these large differences in yield in continuous corn and the

Table 4
Rotation treatment effects (averaged for two tillage systems) on mass of organic carbon and total nitrogen in soil at multiple depth increments and summed to a 1 m sampling depth

Depth (cm)	OC (t ha^{-1})		N (t ha^{-1})	
	CC	BC	CC	BC
0–5	18.2	17.9	1.4	1.4
5–15	32.4	32.0	2.4	2.6
15–30	47.2	43.7	3.5	3.6
30–50	39.7	37.5	3.2	3.4
50–75	17.9	17.0	1.8	2.2
75–100	11.0*	14.0	1.2	1.6
To 1 m depth	166.4	162.1	13.5	14.8

CC, continuous corn; BC, soybean–corn rotation.
* Significant differences between two rotations at $\alpha = 0.05$.

soybean–corn rotation, there were no statistically significant differences between these systems in cumulative OC and total N storage to a depth of 1 m; however, continuous corn had 4.3 t ha^{-1} (3%) more soil OC than the soybean–corn rotation and soybean–corn rotation had 1.3 t ha^{-1} (9%) more total N than continuous corn. This shows that despite the fact that the total surface residue returned in continuous corn was about 30% higher (estimated), properly managed soybean–corn cropping systems may store similar soil OC and total N as continuous corn. Since rotation systems did not affect the soil bulk density or mass of soil to 1 m depth, calculations based on an equivalent soil mass were not necessary for the rotation treatment comparison.

4. Conclusions

Most prior experiments to quantify effects of tillage and crop rotation on C sequestration generally limited soil sampling to the depth of the deepest tillage treatment (e.g. moldboard plowing). The latter approach has resulted in substantially less information being available about tillage consequences on the OC status of the deeper soil profile. Because tillage systems may change the mass and distribution of soil properties under the tilled layers, scientists who ignore these deeper layers might overestimate the positive effects of particular conservation tillage practices on soil OC sequestration.

Our results from a 28-year experiment involving continuous (annual) moldboard plowing versus continuous no-till on a Chalmers silty clay loam confirmed that no-till resulted in a substantial gain of OC and total N at the 0–5 and 5–15 cm depth intervals, a generally equal OC and total N status at the intermediate depth of 15–30 cm, but a substantial reduction, relative to the plow system, in the 30–50 cm depth interval. These two tillage systems also had approximately similar soil OC concentrations at 50–100 cm depth. Calculations based on soil OC content increases solely from the upper 30 cm in no-till would have suggested that no-till resulted in 23 t ha^{-1} more OC than plow. However, calculations based on soil OC to the full 1 m depth suggested that no-till resulted in an overall gain of just 10 t ha^{-1}. Clearly, C sequestration assumptions about tillage systems based on shallow sampling depths would have been highly inaccurate for this soil.

We speculate that plow gained OC at the 30–50 cm depth due to the effects of turning down crop residues to 20–25 cm depths (whether continuous corn, or soybean–corn rotation), due to root distribution differences between tillage systems in the soil profile, and to soil depth-, moisture-, or temperature-dependent differences in soil C cycling into more stable C pools. However, those possible explanations require further research before any definitive conclusions can be made. Primarily, our research confirmed the value of soil sampling to a 1 m depth for tillage system comparisons of these soil chemical attributes.

Another common limitation in tillage system research on soil properties is reporting soil OC and total N storage as concentrations, without considering the effect of potentially different bulk densities under different tillage systems. Therefore, our calculation based on equivalent soil mass (t ha^{-1}) gave perhaps the best estimation of OC storage under different tillage systems.

Continuous corn stored slightly more OC relative to soybean–corn rotation, but no substantial gain in OC was observed with continuous corn. The latter suggests that crop residue mass may not be the most important factor in OC retention by agricultural soil. The mechanism of capturing C in stable and long-term forms might also be different for these crop species. Soil N storage was higher with soybean–corn rotation than for continuous corn.

Finally, the most important contribution of our study was to confirm the necessity of deep sampling for improved accuracy in the assessment of C or N sequestration with no-till versus conventional tillage systems.

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