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Soil organic carbon and nitrogen in a Minnesota soil as related to tillage, residue and nitrogen management

M.S. Dolan [a,*], C.E. Clapp [a], R.R. Allmaras [a], J.M Baker [a], J.A.E. Molina [b]

[a] USDA-Agricultural Research Service, Department of Soil, Water and Climate, University of Minnesota, 439 Borlaug Hall, St. Paul, MN 55108, USA

[b] Department of Soil, Water and Climate, University of Minnesota, St. Paul, MN 55108, USA

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Abstract

Soil organic carbon (SOC) and nitrogen (N) are directly influenced by tillage, residue return and N fertilization management practices. Soil samples for SOC and N analyses, obtained from a 23-year field experiment, provided an assessment of near-equilibrium SOC and N conditions. Crops included corn (*Zea mays* L.) and soybean [*Glycine max* L. (Merrill)]. Treatments of conventional and conservation tillage, residue stover (returned or harvested) and two N fertilization rates were imposed on a Waukegan silt loam (fine-silty over skeletal, mixed, superactive, mesic Typic Hapludoll) at Rosemount, MN. The surface (0–20 cm) soils with no-tillage (NT) had greater than 30% more SOC and N than moldboard plow (MB) and chisel plow (CH) tillage treatments. The trend was reversed at 20–25 cm soil depths, where significantly more SOC and N were found in MB treatments (26 and 1.5 Mg SOC and N ha^{-1}, respectively) than with NT (13 and 1.2 Mg SOC and N ha^{-1}, respectively), possibly due to residues buried by inversion. The summation of soil SOC over depth to 50 cm did not vary among tillage treatments; N by summation was higher in NT than MB treatments. Returned residue plots generally stored more SOC and N than in plots where residue was harvested. Nitrogen fertilization generally did not influence SOC or N at most soil depths. These results have significant implications on how specific management practices maximize SOC storage and minimize potential N losses. Our results further suggest different sampling protocols may lead to different and confusing conclusions regarding the impact of tillage systems on C sequestration.
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Keywords: Carbon sequestration; Nitrogen; Tillage; Residue management

1. Introduction

Global increases in mean air temperature have been observed by numerous researchers. Schlesinger (1997) outlined the suspicion of many scientists that at least part of these increases may be due to the documented increase in the concentration of so called

* Corresponding author. Tel.: +1 612 625 2747; fax: +1 651 649 5175.
E-mail address: mdolan@umn.edu (M.S. Dolan).

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''greenhouse gases'' in the atmosphere, which trap infrared radiation and increase the atmosphere's ability to absorb heat. The gases carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are the most important anthropogenetically-related greenhouse gases and are of special interest to agricultural scientists. Carbon dioxide is both a product of respiration and a byproduct of the combustion of fossil fuels, while N_2O losses are apparent in fertilizer and manure applications. An informed assessment of the role production agriculture plays in global climate change requires knowledge of C and N cycling.

The cultivation of prairie soils in the Cornbelt has reduced total soil N and C (Allmaras et al., 2000). Conventional plowing increases soil aeration and soil-residue contact and hastens the oxidation of soil organic carbon (SOC), leading to increased emissions of CO_2 (Lal et al., 1998; West and Post, 2002). Conservation tillage practices maintain residue near the surface of soils, reducing wind and water erosion, increasing soil water storage and often reducing agricultural production costs (Allmaras and Dowdy, 1985). Lamb et al. (1985) found N losses due to erosion and leaching minimized by switching from plowing to minimum or no-tillage winter wheat (*Triticum aestivum* L.) systems. Lal et al. (1998) states that widespread modification of agricultural practices could result in more C sequestered in soils than agriculture generates through combustion of fossil fuels and conventional land use practices.

Tillage and related crop residue management practices have a major influence on C sequestration (Havlin et al., 1990; Kern and Johnson, 1993; Reicosky and Lindstrom, 1993; Robinson et al., 1994; Dao, 1998; Wander et al., 1998; Duiker and Lal, 1999; Deen and Kataki, 2003). However, tillage practices influence only the upper portion of the soil profile, causing stratification of residues dependent on the depth of tillage and the type of tillage tool (Allmaras et al., 1996). Potter et al. (1997) found that no-tillage increased mean total C mass in surface soils (0–20 cm) under continuous sorghum (*Sorghum bicolor* L.) and wheat. Wander et al. (1998) and Deen and Kataki (2003) both found increased SOC in surface soils of no-tillage treatments, but generally less SOC stored at lower soil depths, when compared to conventional tillage. These recent studies suggest conservation tillage practices may not always lead to net accumulations of SOC and N in the soil profile as a whole, as earlier studies have implied (Kern and Johnson, 1993; Lal et al., 1998; Moldenhauer et al., 1995; Doran et al., 1998).

Jenny (1933) stated that total soil N in grassland soils would reach a steady state only after decades of cultivation. More recently, West and Post (2002) described changes in soil C sequestration rates due to tillage over decades before coming to equilibrium. Both long-term studies and observations of the soil profile as a whole would seem vital to a comprehensive evaluation of the role management practices have on SOC and N storage and potential greenhouse emissions to the atmosphere. As such, the objectives of this experiment were as follows:

1. Determine the effects of tillage and residue management on soil profile C and N storage.
2. Determine the effects of N fertilization rates on soil profile C and N storage.
3. Observe treatment effects on other soil properties, including bulk density and $\delta^{13}C$.

2. Materials and methods

Our study was conducted as part of long-term field experiments at the UMORE (University of Minnesota Outreach, Research and Education) Park in Rosemount, Minnesota (latitude 44°45′N, longitude 93°4′W). Nitrogen fertilization, tillage and residue management treatments were established in 1980 on the site's Waukegan silt loam (fine-silty over skeletal, mixed, superactive, mesic Typic Hapludoll). Treatment blocks were 18 m × 50 m in size and randomly selected over an area with less than 1% slope. In November of 2002, soil cores were taken by hand using the technique outlined in Allmaras et al. (1988). Soils were collected in 5 cm increments to a depth of 45 cm, which generally contained the entire plant rooting zone. Plant root growth studies in the plot area found few roots growing below 45 cm (Dowdy et al., 2001), likely due to dense sand and gravel stratum below the 45–60 cm portion of the profile. Corn (*Zea mays* L., Pioneer[1] 3780) was grown from 1980 to 1992

[1] Mention of a trade or company name is for information only and does not imply an endorsement by the USDA-ARS or the University of Minnesota.

(13 years), followed by soybean [*Glycine max* L. (Merrill), Pioneer 9172] from 1993 to 1998 (6 years) and corn from 1999 to 2002 (4 years).

The main treatment effects involved fall tillage with moldboard plow (MB), chisel plow (CH) or no-tillage (NT), as previously described (Clapp et al., 2000). There was no secondary tillage before planting, minimal disturbance during planting and no post-planting cultivation. Corn residue, about 10 cm above the soil surface, was harvested from plots (h) or returned to plots (r) before fall tillage. Ammonium sulfate-N fertilizer was broadcast applied after the planting operation at rates of 0 kg N ha^{-1} (0N) and 200 kg N ha^{-1} (200N). Soil samples were also taken from rotary tilled fallow areas that had not received N fertilizer and had not been cropped. Twelve soil cores (18 mm diameter) were taken randomly within subplots, composited by depth of 5 cm cores, air-dried and weighed for air dry soil water content and soil bulk density (BD). Time constraints in the field allowed for two or three subplots per treatment combination (i.e. replicates) sampled.

Soils were subsampled to remove plant residue and roots by hand and ball milled to pass a 300-mesh sieve. Prior to analyses, a composite of the three soil depths between 30 and 45 cm was combined from equal parts of each depth increment. Samples were weighed (approximately 18 mg) in duplicate and run on an elemental analyzer (Carlo Erba Model NA1500) connected to a continuous flow, stable isotope ratio mass spectrometer (Fisons Optima). Total N and SOC concentrations were determined as percentages and $\delta^{13}C$ was calculated as follows:

$$\delta^{13}C = [(R_{sam}/R_{std}) - 1] \times 10^3 \quad (1)$$

The $^{13}C/^{12}C$ ratio for the sample is R_{sam} while R_{std} is the $^{13}C/^{12}C$ ratio of a working standard; $\delta^{13}C$ values were calculated relative to a Pee Dee Belemnite original standard and a working soil standard with a value of −17.64‰. Total N and SOC were expressed in Mg ha^{-1}, from the product of the elemental percentages, soil depth and BD. Soil profile SOC and N values were the sum of individual depths. The significance of mean differences was tested using analysis of variance and Tukey's studentized range (HSD) test via PROC GLM and MEANS procedures in SAS (SAS Institute, 1996). Differences were accepted as significant if $p \leq 0.05$.

3. Results

3.1. SOC and N

Soil organic carbon (SOC) and soil nitrogen (N) responses to tillage, stover residue management and N fertilization treatments were essentially the same. In the top three soil depths (0–5, 5–10 and 10–15 cm), conservation tillage practices stored significantly more SOC and N than conventional tillage ($p < 0.01$, Table 1). Error bars shown in all figures indicate variation around the mean ± 1 S.D. Specifically, the order of stored SOC and N was NT > CH > MB for each depth to 15 cm (Figs. 1 and 2). Soil N was significantly less in the MB (1.4 Mg ha^{-1}) than fallow soil (1.6 Mg ha^{-1}) in 10–15 cm depth (Table 1 and Fig. 2).

The 15–20 cm soil depth was a transition zone for both SOC and N values. This soil depth is near the deepest point in the profile where tillage implements have penetrated. In this soil depth, no differences in SOC were observed among the three primary tillage treatments, although SOC content in NT was significantly higher than in the fallow treatment (Table 1 and Fig. 1). Soil N also did not vary among the three primary tillage treatments, but all three treatments had higher soil N than the fallow treatment (Table 1 and Fig. 2).

An abrupt change was observed beginning at the 20–25 cm soil depth. The MB treatment had as much as 2× the SOC and 30% more soil N in both the 20–25 and 25–30 cm depths over all other treatments (Table 1 and Figs. 1 and 2). In the 30–45 cm soil depth, the MB treatment still contained significantly more ($p < 0.01$) SOC and soil N (8.0 and 1.1 Mg ha^{-1}, respectively) than the NT treatment (6.5 and 0.85 Mg ha^{-1}, respectively); SOC and soil N in CH soils fell in between MB and NT treatments and were not significantly different from either treatment. Fallow soils tended to contain significantly lower ($p < 0.05$) SOC and soil N than the other treatments at these lower depths.

Stover residue management influenced SOC and soil N intermittently throughout the soil profile. Within each depth, the r treatment stored more SOC and N in soils than the h treatment (Figs. 1 and 2). Tillage and residue interactions were also observed intermittently throughout the profile. Notably absent was any significant effect of N fertilization on SOC

Table 1
Tillage, corn residue management and fertilizer nitrogen effects on SOC and N

Source	Depth (cm)							Sum (cm)
	0–5	5–10	10–15	15–20	20–25	25–30	30–45	0–45
SOC								
Tillage (T)	**	**	**	**	**	**	**	*
Residue (R)	*	NS	**	**	NS	*	NS	*
Nitrogen (N)	NS	NS	NS	NS	NS	NS	NS	NS
T × R	*	NS	**	**	NS	NS	**	NS
T × N	*	NS	NS	NS	NS	NS	NS	NS
R × N	NS	NS	NS	NS	NS	NS	NS	NS
N								
Tillage (T)	**	**	**	**	**	**	**	**
Residue (R)	**	**	NS	**	NS	*	NS	*
Nitrogen (N)	NS	NS	NS	NS	NS	NS	NS	NS
T × R	**	NS	NS	NS	NS	NS	**	NS
T × N	NS	NS	NS	NS	NS	NS	NS	NS
R × N	NS	NS	NS	NS	NS	NS	NS	NS

* Significant at $p = 0.05$.
** Significant at $p = 0.01$.

and soil N. In only the surface 0–5 cm depth did N fertilization come close to significantly influencing soil N ($p = 0.1$) and no significant interactions between tillage and residue management each with N fertilization were found (Table 1).

When the sum of SOC in all soil depths above 45 cm was calculated, SOC did not vary among the three primary tillage treatments, but all three were significantly higher ($p < 0.05$) than in the fallow soils (79 Mg ha^{-1}, Tables 1 and 2). Soil N in the profile as a whole was significantly higher ($p < 0.01$) in NT (9.1 Mg ha^{-1}) versus MB and CH (8.7 and 8.8 Mg ha^{-1}, respectively); the tilled treatments in turn had higher soil N than fallow soils (7.3 Mg ha^{-1}, Tables 1 and 2). It should be noted, however, that while significant, the difference in soil N among the three primary tillage treatments was less than 1 Mg ha^{-1} (Table 2). Returned residue resulted in significantly higher SOC and soil N in the profile as a whole ($p < 0.05$) than when removed. As with individual depths, N fertilization did not significantly influence SOC or soil N.

Table 2
Tillage and residue management effects on SOC and N in the summation of soil depths sampled

Sum of depths to 45 cm		
Tillage (residue)[a]	Mean SOC [Mg ha^{-1}]	Mean N [Mg ha^{-1}]
No-tillage (r)	106(a)[b,c]	9.1 (a)
No-tillage (h)	108 (a)	9.0 (a)
Chisel plow (r)	117 (a)	8.8 (b)
Chisel plow (h)	97 (a)	8.0 (b)
Moldboard plow (r)	117 (a)	8.7 (b)
Moldboard plow (h)	108 (a)	8.5 (b)
Fallow	79 (b)	7.3 (c)

[a] r is stover residue returned; h is stover residue harvested.
[b] Mean values were averaged over two N fertilization treatments (0 and 200 kg N ha^{-1}).
[c] Values followed by the same letter are not significantly different as indicated in Table 1.

3.2. Soil bulk density

Soil bulk density did not vary among tillage treatments (Table 3) in the surface 0–5, 20–25 and 30–45 cm soil depths. In individual soil depths from 5 to 20 cm, fallow and NT soils consistently had 5–12% higher BD than soils in MB treatments. Soil bulk density in the CH treatments ranged from 1.11 to 1.38 Mg m^{-3}, less than or equal to fallow and NT treated soils in these same depths (Fig. 3). These BD profiles among tillage treatments were generally similar to those sampled earlier in the same experiment (Clapp et al., 2000 and Layese et al., 2002). Residue harvested treatments had 6% higher BD in the 0–5 and 5–10 cm soil depths than the r treatments in the same soil depths. The trend was reversed in the 30–45 cm soil depths, where the r

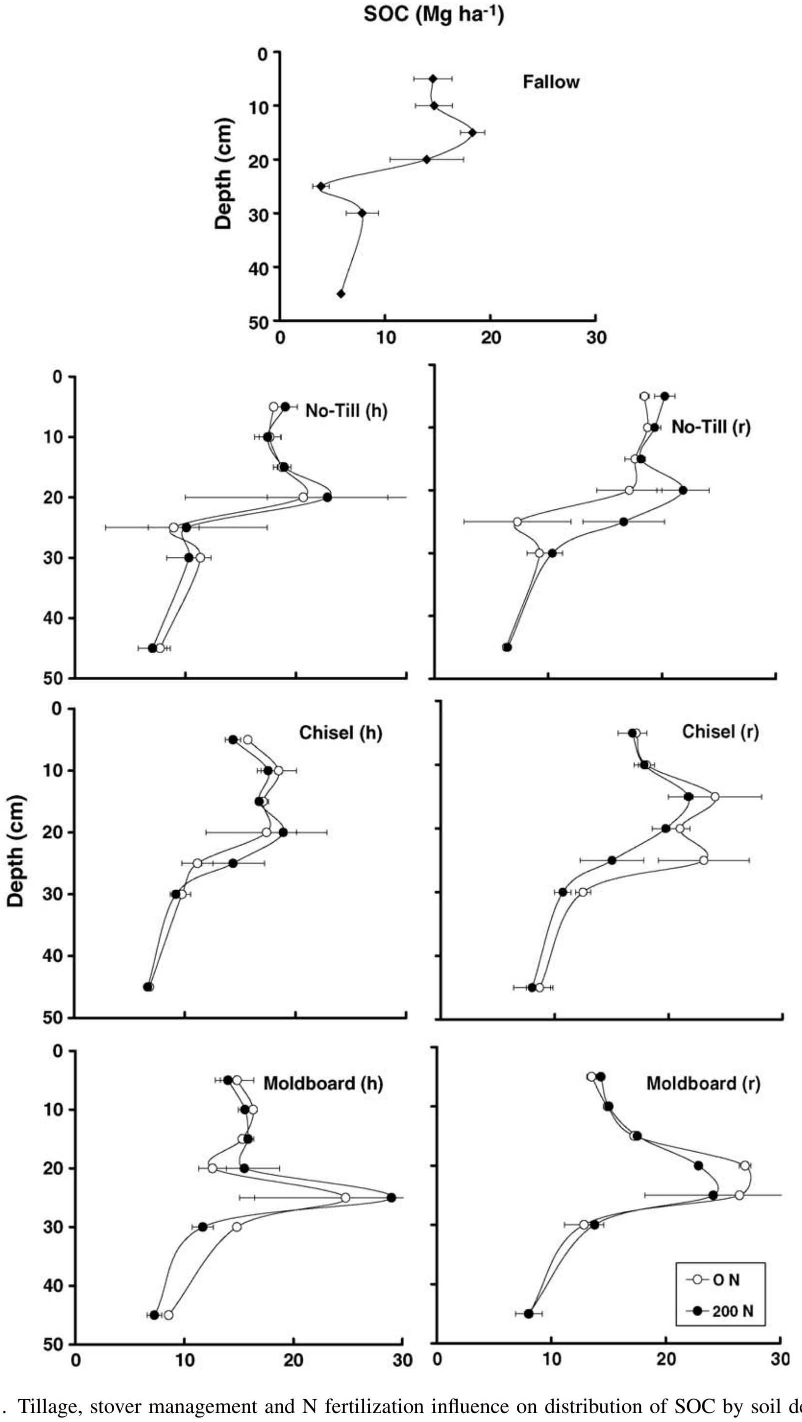

Fig. 1. Tillage, stover management and N fertilization influence on distribution of SOC by soil depth.

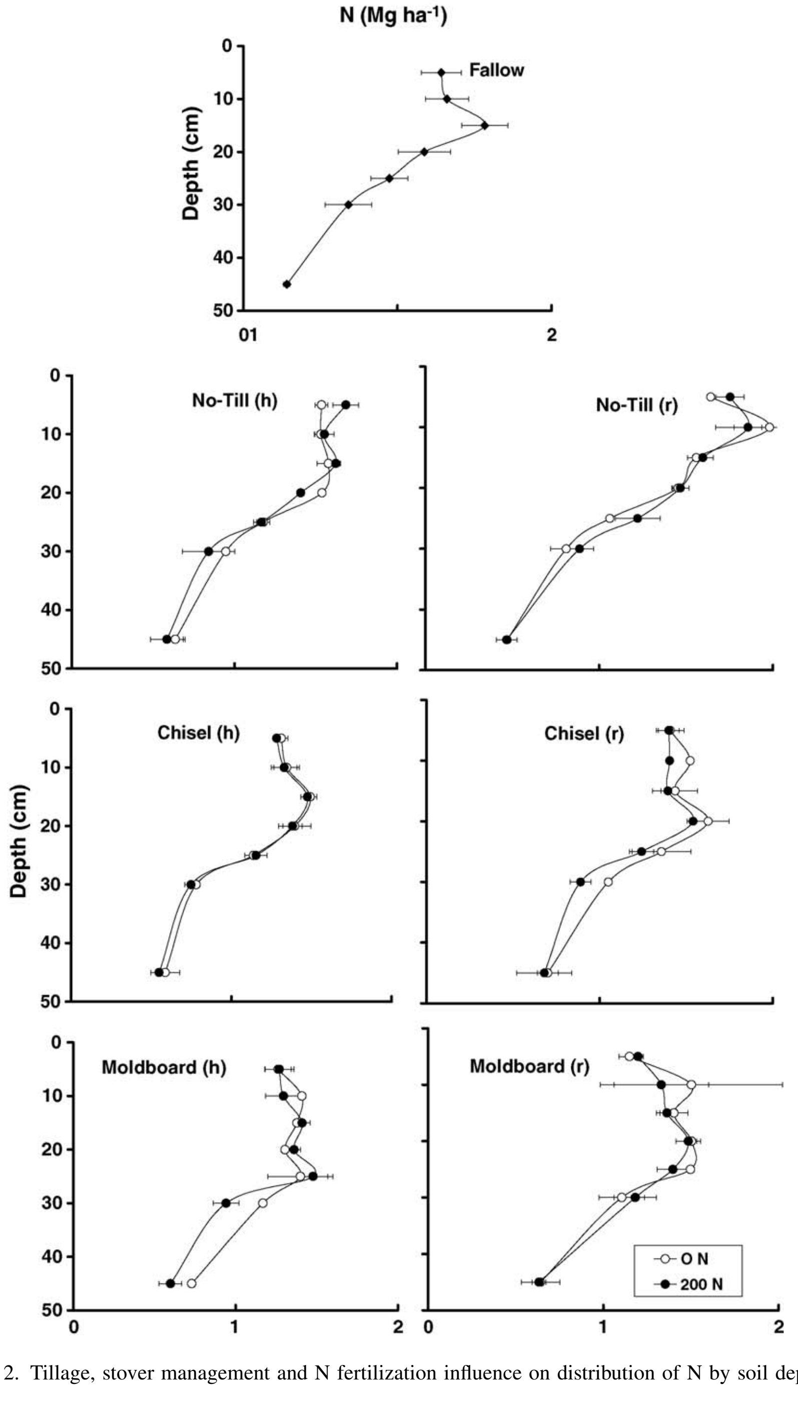

Fig. 2. Tillage, stover management and N fertilization influence on distribution of N by soil depth.

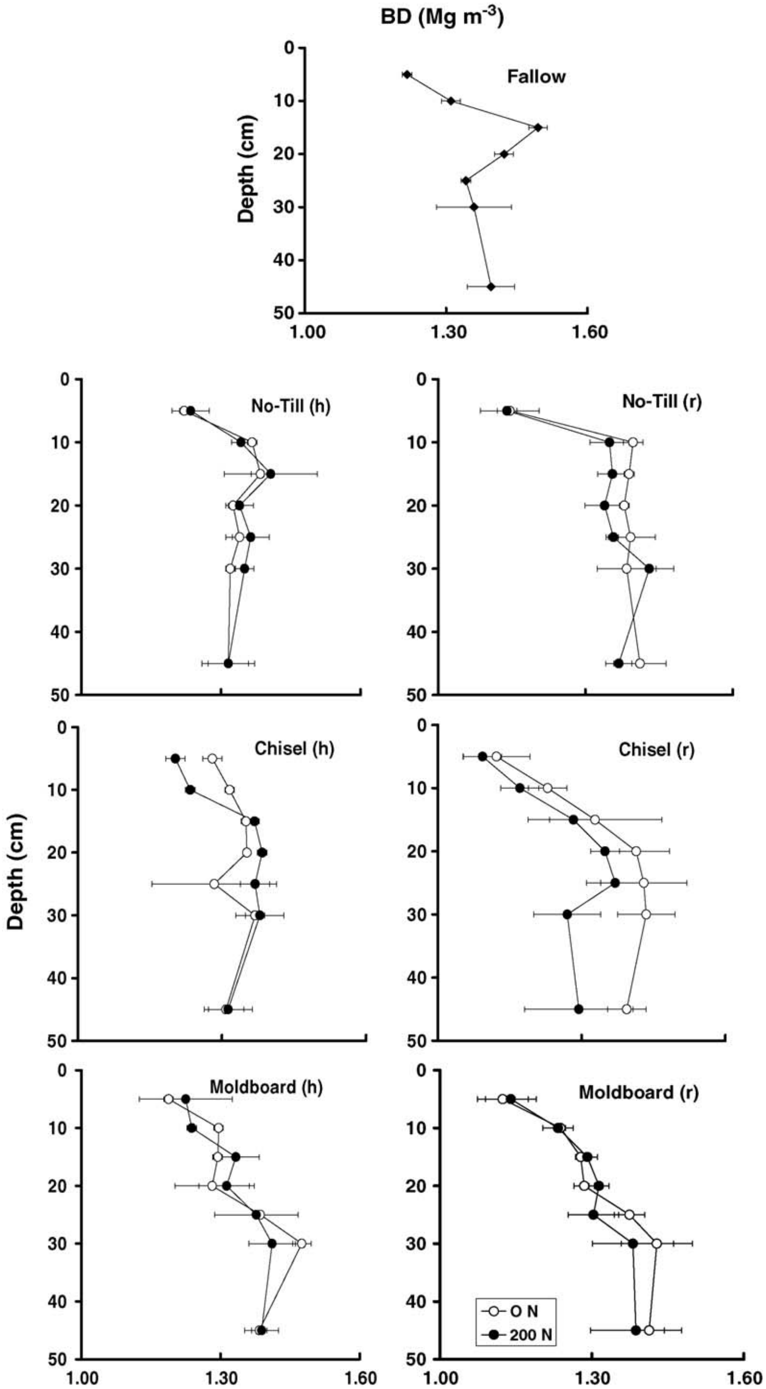

Fig. 3. Tillage, stover management and N fertilization influence on distribution of soil bulk density (BD) by soil depth.

Table 3
Tillage, corn residue management and fertilizer nitrogen effects on BD and $\delta^{13}C$

Source	Depth (cm)						
	0–5	5–10	10–15	15–20	20–25	25–30	30–45
BD							
Tillage (T)	NS	**	**	**	NS	NS	NS
Residue (R)	**	**	NS	NS	NS	NS	*
Nitrogen (N)	NS	**	NS	NS	NS	NS	NS
T × R	NS	*	NS	NS	NS	NS	NS
T × N	NS	NS	NS	NS	NS	NS	NS
R × N	NS	NS	NS	NS	NS	NS	NS
$\delta^{13}C$							
Tillage (T)	**	*	*	**	NS	**	NS
Residue (R)	**	NS	**	**	NS	**	NS
Nitrogen (N)	NS	NS	NS	NS	NS	NS	NS
T × R	NS	*	NS	**	NS	NS	NS
T × N	NS	NS	NS	NS	NS	NS	NS
R × N	NS	NS	NS	NS	NS	NS	NS

* Significant at $p = 0.05$.
** Significant at $p = 0.01$.

treatments had 5% higher BD ($p < 0.05$) than the h treatments (Table 3). A significant BD response to N fertilization was generally not evident; only in the 5–10 cm soil depth were there any significant differences (0N > 200N, $p < 0.01$).

3.3. $\delta^{13}C$ distribution

Significant differences in $\delta^{13}C$ were found in most soil depths to 30 cm (Table 3 and Fig. 4). Surface soil (0–5 cm) $\delta^{13}C$ in the MB treatments was significantly higher, that is less negative ($p < 0.05$), than all other treatments. The same trend followed in the 10–15 cm layer, while in the 5–10 cm soil depth, soil $\delta^{13}C$ values in the MB treatment were significantly higher than only the NT treated soils ($p < 0.05$). Values of $\delta^{13}C$ in NT continued to be significantly less negative ($p < 0.01$) than among other treatments in the 15–20 cm depth. However, as with SOC and soil N data, an abrupt reversal was evident below surface soil depths. The MB treatment had significantly lower (more negative) $\delta^{13}C$ values than all other treatments ($p < 0.01$) in 25–30 cm soils. In a similar fashion, the r treatments had significantly higher $\delta^{13}C$ values (less negative) than in h treatments in three out of four soil depths to 20 cm. The trend was reversed in the 25–30 cm soil depth, where the r treatments had significantly lower (more negative) $\delta^{13}C$ values than in the h treatments. Nitrogen fertilization had no significant ($p > 0.05$) effect on $\delta^{13}C$ values at any soil depth measured.

4. Discussion and conclusions

Long-term (20+ years) use of conservation tillage practices influenced the distribution of SOC and N in the soil profile. Soils near the surface had more SOC and N stored in NT and CH systems as compared to the MB system. However, below 20 cm, the MB treatment retained more stored SOC and N than in conservation tillage practices. The net result of these differences in the distribution of SOC and N was that when observing the soil profile as a whole, or at least in the upper 45 cm, no differences in SOC and N were observed between conservation and conventional tillage practices. Allmaras et al. (2004) describe a generally overlooked but important source of SOC in soils: the deposit and decomposition of below ground rhizodeposits. Tillage in this plot area both buries unharvested plant residues below the soil surface and can enhance root growth in subsurface soils over that in NT (Dowdy et al., 2001). Allmaras et al. (2004) demonstrated that as buried unharvested plant materials and roots decompose, more SOC may remain in subsurface soils of tilled plots than in NT,

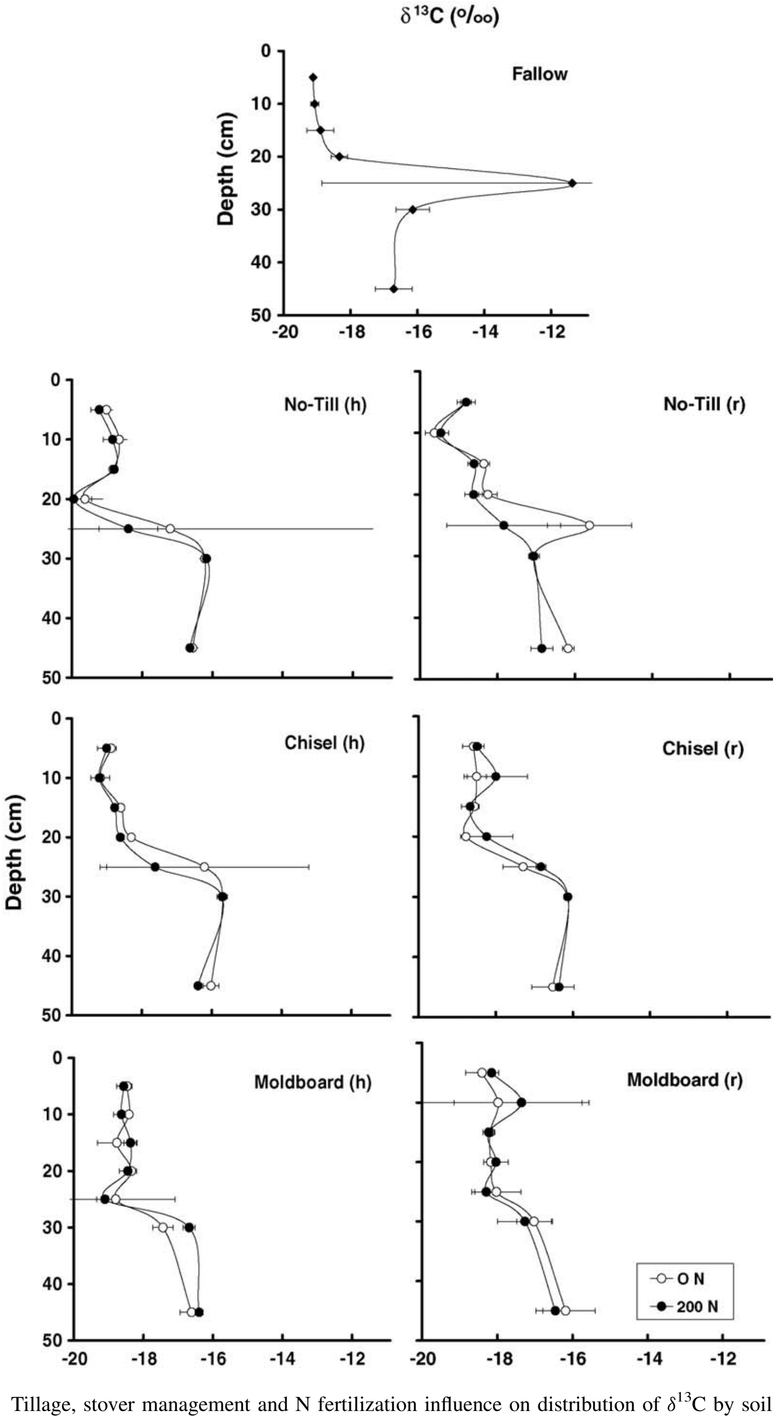

Fig. 4. Tillage, stover management and N fertilization influence on distribution of $\delta^{13}C$ by soil depth.

thus compensating for SOC losses near the surface. Plant residue returned to soils tended to increase SOC and N in all three tillage systems. Wilhelm et al. (2004) also found the removal of corn stover, in this case for biofuel production, can have detrimental effects on SOC. Unlike residue removal, nitrogen fertilization had no appreciable effect on SOC and N storage.

Soil bulk densities were higher in the surface soils of NT treatments than conventional tillage, but lower below 30 cm, reflecting the rupture action of tillage near the surface and the compacting and shearing action of tillage implements below tillage depths. As with SOC and N, N fertilization had no consistent effect on BD. Clapp et al. (2000), in an earlier paper based on the same field experiment, also observed no BD response to N fertilization as well as lower BD in subsurface soils versus surface soils in all three tillage systems. The fact that both our study and that in Clapp et al. (2000) produced the same trends tends to confirm a near-equilibrium between SOC production and losses in this experimental area. The lack of residue in stover harvested treatments tended to increase BD over treatments where stover residue was returned; not as much less dense residue was incorporated into harvested treatments. Buried corn and soybean residues may also have influenced the abundance of ^{13}C. Residues from corn, as a C_4 plant, produce a larger $\delta^{13}C$ abundance label than from soybean residues (C_3). Furthermore, previous studies in these soils suggest a higher percentage of SOC is derived from corn residue than soybean residue (Layese et al., 2002).

Our conclusion that SOC and N storage was not enhanced in the soil profile after years of conservation tillage practices is also supported by observations made in a similar study in eastern Canada (Angers et al., 1997). Both studies point to the importance of not only the soil's inherent physical properties but also cool, humid northern climates in evaluating soil organic matter storage potential. Further, Vanden Bygaart et al. (2002) report results similar to our study as well as that of Angers et al. (1997). They outlined not only climatic conditions but also landscape position as an important factor in evaluating C sequestration potential. As in our study, these authors emphasized the importance of obtaining SOC values in the entire soil profile. There is a strong implication in our study, and both studies in Canada, that differing sampling protocols may lead to different conclusions regarding the impact of tillage on C sequestration. Our study would clearly have had other conclusions had we not sampled below 30 cm. Sampling in the entire soil profile is necessary for a more accurate view of C sequestration potential among tillage systems.

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