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Interaction of Tillage and Soil Texture: Biologically Active Soil Organic Matter in Illinois

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ABSTRACT

Several long-term studies suggest that no-till (NT) practices do not increase soil organic matter (SOM) sequestration in all situations. We evaluated the interaction of tillage and soil texture effects on SOM in Illinois Mollisols and Alfisols by characterizing particulate organic matter (POM), potentially mineralizable N (PMN), and soil microbial biomass (SMB). Thirty-six fields were sampled during spring and summer of 1995 and 1996. Each field had been under either conventional tillage (CT) (disc, moldboard plow, and/or chisel plow) or NT management for at least 5 yr. No-till fields contained 15% (3.0 g C kg^{-1} soil) more soil organic C (SOC) than CT fields in the 0- to 5-cm depth; however, tillage did not affect SOC contents in the 5- to 15- or 15- to 30-cm depths, or in the overall sampling depth (0–30 cm). Fields under NT contained 33% more POM (1.4 g C kg^{-1} soil) and 54% more PMN in the 0- to 5-cm depth, but there was no tillage effect on POM (0–15 cm) or PMN (0–30 cm) contents overall. Average POM contents were 29% lower (0.73 g C kg^{-1} soil) in the 5- to 15-cm depth of the NT than of the CT soils. At sand contents below ≈50 g kg^{-1} soil, NT fields contained greater SOC, total N, and POM contents in the 0- to 5-cm depth and lower POM contents in the 5- to 15-cm depth than CT fields. In soils with sand contents higher than ≈50 g kg^{-1} soil, tillage practices did not affect the vertical distribution of SOC, total N, or POM.

Agronomic practices influence SOM dynamics and may improve or degrade SOM by altering above- and below-ground biomass production and the rates of topsoil erosion and organic matter decomposition. Conservation tillage, in particular NT, generally leads to greater retention of SOM than CT (Kern and Johnson, 1993; Paustian et al., 1997). The contents of SOM at the surface of soils under NT is greater than under CT (Doran, 1987; Havlin et al., 1990). Most simulations of tillage effects on SOM sequestration predict that NT will lead to greater sequestration of C than will CT (Lee et al., 1993; Parton et al., 1987). However, several studies that have considered the entire rooting zone and deeper soil depths have not found differences between the SOM contents of NT and CT soils (Angers et al., 1997; Franzluebbers and Arshad, 1996).

Few studies have investigated the influence of soil texture on the relationship between tillage and SOM dynamics. Campbell et al. (1996) reported that the positive relationship between clay and SOM contents was greater in NT than in CT soils at three sites in western Canada. Paustian et al. (1997) found no general relationship between texture and the effects of tillage on SOM contents in their analysis of data from twenty-seven long-term tillage trials. At two sites where NT did not increase SOM contents relative to CT, soils were fine-textured and poorly drained and crop biomass production was decreased by NT management (Dick et al., 1986; Havlin et al., 1990). Wander et al. (1998) found NT increased SOC and POM-C contents in the 0- to 5-cm depth at the expense of SOM stored at the 5- to 17.5-cm depth in three long-term studies in Illinois. The extent of this effect varied among soils with different textures and initial C contents. No-till practices increased SOC and POM-C contents in the top 5 cm of two silt loam soils, but had no effect on POM-C or SOC concentrations at the surface of a silty clay loam; however, NT reduced total and POM-C and -N contents in the 5- to 30-cm depth.

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Abbreviations: CR, central region; CT, conventional till; ECR, east-central region; NR, north region; NT, no-till; PMN, potentially mineralizable N; POM, particulate organic matter; SMB, soil microbial biomass; SOC, soil organic C; SOM, soil organic matter; SR, south region.

Changes in SOM occurring within a decade of practice alteration are difficult to document because SOM includes materials that vary in their chemical, physical, and biological lability. Models of SOM dynamics have used multiple pools, differentiated by turnover rates (Paul and van Veen, 1978; Parton et al., 1987). In such models, biologically active SOM has been represented by the active and slow (Parton et al., 1987) and the microbial biomass and decomposable (Paul and van Veen, 1978) pools. Measures of biologically active SOM can be used as early indicators of change in SOM status (Gregorich et al., 1994; Powlson et al., 1987). Three measures of biologically active SOM that have been proposed as indicators of soil quality are POM, PMN, and SMB (Turco et al., 1994). Particulate organic matter is composed of sand-sized, incompletely decomposed organic materials (Cambardella and Elliot, 1992), while PMN is a measure of readily degradable organic N (Drinkwater et al., 1996), and SMB is estimated as C in the living biomass (Gregorich et al., 1994).

The objective of this study was to quantify the effects of tillage practices on the quantity and vertical distribution of biologically active SOM and total SOM in Illinois soils. Most agricultural fields in Illinois have been con-

Table 1. Site characteristics and selected properties of 16.2-ha Illinois farm fields sampled during 1995 and 1996.

Region	Farm	Tillage	Taxonomic subgroups	Rotation†	Sand	Silt	Clay	Soil organic C
					g kg^{-1} soil			
Central	1	No-till	Typic Arguidoll, Aquic Argiudoll, Typic Haplaquoll	C/S	57	525	418	19.7
	2	Conventional	Typic Arguidoll, Aquic Argiudoll, Typic Haplaquoll	C/S	53	520	427	19.4
	3	Conventional	Typic Argiaquoll	C/S	48	508	444	19.1
	4	No-till	Typic Argiaquoll	C/S	56	492	452	19.6
	5	No-till	Typic Argiaquoll	C/S	56	505	439	19.9
	6	Conventional	Typic Argiaquoll, Aquic Argiaquoll	C/S/H	53	543	404	15.8
	7	Conventional	Typic Haplaquoll	C/S	10	447	543	27.0
East-central	8	No-till	Aquic Argiudoll, Typic Haplaquoll, Typic Argiudoll	C/S	91	478	431	22.9
	9	No-till	Aquic Argiudoll, Typic Haplaquoll	C/S	100	491	409	26.6
	10	No-till	Aquic Argiudoll, Typic Haplaquoll, Typic Argiudoll	C/S	139	507	354	17.9
	11	No-till	Aquic Argiudoll, Typic Haplaquoll, Typic Argiudoll	C/S	154	460	386	17.8
	12	Conventional	Typic Haplaquoll, Aquic Argiudoll, Typic Argiudoll	C/S	212	339	449	21.7
	13	Conventional	Typic Haplaquoll, Typic Argiudoll	C/S	204	359	437	21.7
	14	No-till	Typic Hapludalf, Aquic Hapludalf, Aeric Ochraqualf	C/S	104	513	383	8.2
	15	No-till	Typic Argiaquoll, Aquic Argiudoll	C/S	107	256	637	23.0
	16	No-till	Aquic Argiudoll, Typic Haplaquoll	C/S	66	432	512	25.2
	17	Conventional	Aquic Argiudoll, Typic Haplaquoll	C/S	105	418	477	22.6
	18	No-till	Aquic Argiudoll, Typic Haplaquoll	C/S	55	467	478	19.6
	19	Conventional	Aquic Argiudoll, Typic Haplaquoll	C/S	106	471	423	18.1
	20	Conventional	Aquic Argiudoll, Typic Haplaquoll	C/S	108	462	430	20.7
	21	Conventional	Aquic Argiudoll, Typic Argiudoll, Aeric Ochraqualf	C/S	81	520	399	16.6
	22	Conventional	Aquic Argiudoll, Typic Haplaquoll	C/S	72	478	450	19.0
North	23	Conventional	Typic Argiudoll, Aquic Argiudoll	C/C	22	561	417	21.5
	24	No-till	Typic Argiudoll, Typic Hapludalf, Fluvaquentic Hapludoll	C/S	16	605	379	14.9
	25	No-till	Typic Argiudoll, Mollic Hapludalf	C/S	19	586	395	16.5
	26	Conventional	Typic Argiudoll, Aquic Argiudoll	C/S	17	546	437	17.7
	27	Conventional	Typic Haplaquoll, Typic Argiudoll, Aquic Argiudoll	C/S	80	497	423	20.4
	28	Conventional	Mollic Hapludalf, Aquic Argiudoll	C/S	38	529	433	19.4
	29	No-till	Typic Argiudoll, Typic Haplaquoll	C/S	181	383	436	17.4
South	30	No-till	Typic Hapludalf, Aeric Albaqualf	C/S	48	638	314	8.6
	31	No-till	Typic Hapludalf, Aeric Albaqualf	C/S	66	622	312	7.1
	32	Conventional	Typic Hapludalf	C/W/S	67	627	306	8.7
	33	No-till	Typic Hapludalf	C/S	96	567	337	11.5
	34	No-till	Aeric Fluvaquent	C/W/S	143	561	297	9.7
	35	No-till	Aquollic Hapludalf	C/W/S	67	620	313	7.7
	36	Conventional	Udollic Ochraqualf, Aeric Albaqualf, Typic Hapludalf	C/W/S	58	663	279	7.0

† C/S: Corn/soybean; C/C: Continuous corn; C/W/S: Corn/wheat/soybean; C/S/H: Corn/soybean/hay.

ventionally tilled for a half century or more. The use of conservation tillage practices such as NT within the region became common within the last decade. Accordingly, there are few long-term tillage trials in Illinois. We hypothesized that in these soils, tillage practices affect the vertical distribution but not the total quantity of biologically active SOM and that the impacts of tillage are not constant across soil textures.

MATERIALS AND METHODS

Thirty-six 16.2-ha fields located in four regions (central [CR], east-central [ECR], north [NR], and south [SR]) of Illinois were sampled during the spring and summer of 1995 and 1996 (Table 1). All surface soils were developed from loess. The southern region was not glaciated as recently as the other regions and soils are lower in organic matter. Each field had been under either CT (disc, moldboard plow, and/or chisel plow) or NT management for at least 5 yr. Fields were sampled in the corn (*Zea mays* L.) or soybean [*Glycine max* (L.) Merr.] phase of their rotation (Table 1). A variety of agronomic practices were used on the fields. Three of the CT fields were under organic management.

Nine 30-cm cores were taken on a 100 by 100 m grid from each field. Cores were divided into 0- to 5-, 5- to 15-, and 15- to 30-cm depth increments. Soils were transported with ice, stored at 4°C for up to 1 wk, and then air dried. Air-dried soils were ground to pass a 2-mm sieve.

Total organic C and N and PMN were determined in all depths, and POM and SMB were determined in the 0- to 5- and 5- to 15-cm depths. The POM fraction was determined according to the method described by Gregorich and Bettany (1995). Using a Carlo Erba NA 1500 C/N analyzer (Carlo Erba, Milan, Italy), total N and organic C contents of the whole soil and POM were determined by dry combustion according to Nelson and Sommers (1982). Free carbonates were removed with sulfurous acid prior to analysis.

The PMN fraction was determined by anaerobic incubation after Waring and Bremner (1964). A field-moist soil sample (6 g) was placed in a 50-mL centrifuge tube, saturated with 10 mL of deionized water, and incubated at 40°C for 7 d. Then, 40 mL of 0.625 *M* K_2SO_4 was added to give a final concentration of 0.5 *M*. The tube was shaken for 1 h on a reciprocating shaker. The supernatant was filtered through Whatman no. 42 filter paper. The same procedure was used on nonincubated samples. Ammonium was determined colorimetrically (Sims et al., 1995). The PMN was determined as the NH_4 recovered from the incubated soil minus NH_4 recovered from the nonincubated soil.

Carbon in the SMB was estimated using the chloroform fumigation extraction method (Vance et al., 1987). A 10-g sample of field-moist soil was placed in a 30-mL centrifuge tube, transferred to a desiccator, and fumigated with chloroform for 24 h in the dark. After chloroform removal, 30 mL of 0.5 *M* K_2SO_4 was added, the tube was shaken for 1 h on a reciprocating shaker, and the supernatant was filtered through Whatman no. 42 filter paper. Extracted C was determined with a Dohrmann Xertex DC-80 C analyzer (Dohrmann, Santa Clara, CA). The same procedure was used on a nonfumigated soil sample. Chloroform-labile C was calculated as the amount of dissolved organic C recovered from the fumigated soil minus that recovered from the nonfumigated soil. The SMB was expressed in units of chloroform-labile C.

Additional soil parameters measured were bulk density by the core method; gravimetric water content; pH at a 1:1 soil/water ratio; and texture, determined using the hydrometer method adapted from Gee and Bauder (1986). The particle size classes considered were clay (<2 μm), fine silt (2–20 μm), coarse silt (20–53 μm), and sand (53–2000 μm).

The experimental design was a split-plot in a randomized complete block. The inference space for the study is the state of Illinois. Thirty-six 16.2-ha fields were assigned to the CR, ECR, NR, or SR according to their geographic locale (Table 1). The four regions were used as blocks. Fields were treated as main plots within the blocks. Each year–field combination was considered an environment (Carmer et al., 1989), and environments were considered random within blocks. Analysis of variance was performed using PROC GLM (SAS Institute, 1994, p. 229.). Tillage, crop, region, and depth were the class variables. Each SOM fraction was measured in one of the two sampling years; accordingly, year was not a factor in the analysis. Uniformly minimum variance unbiased estimators were used to estimate field means for the PMN data, which were lognormally distributed within fields. For a lognormally distributed population, uniformly minimum variance unbiased estimators are preferable to the arithmetic mean (Parkin and Robinson, 1994). Results were considered statistically significant at $P = 0.05$, except where noted.

Further investigations of tillage, crop, and depth were carried out using texture as a covariate. Region was not used as a class variable in these models because texture was expected to vary with loess origin and locale (Fehrenbacher et al., 1986). Analysis of covariance was performed to assess the interaction of textural covariates (sand, coarse silt, fine silt, total silt, and clay) and tillage effects on SOM and SOM fractions. Main effects were only significant for models using sand and clay as covariates. Texture variables not found significant are not discussed further. Statistical contrasts of means were used to test three-way interactions (tillage, depth, and sand contents) (Littell et al., 1991).

RESULTS

Soil Organic Carbon and Total Nitrogen

The effect of tillage on SOC is shown in Fig. 1a and 1b; statistical analyses are in Tables 2 and 3. The contents of SOM fractions were calculated on gravimetric, volumetric, and equivalent-mass bases (Ellert and Bettany, 1995). Statistical analyses gave similar results with all three means of expression. Only gravimetric units are reported here. No-till increased SOC contents in the 0- to 5-cm depth 15% in comparison with CT soils. At the 5- to 15- and 15- to 30-cm depths, CT soils SOC contents were 5.8 and 2.3% greater than in NT soils. The SOC contents of the three organic CT fields did not differ from the other CT fields (data not shown). Region and soil depth had the greatest effects on SOC contents, the most apparent difference being the lower SOC contents of the SR soils. This region contained five NT fields and two CT fields (Table 1). To ensure that treatment numbers did not bias the overall analysis of SOC against NT, the analysis was performed with and without the southern region (Table 3). Tillage did not effect overall SOC contents (0–30 cm), but there was a significant depth × tillage interaction (Table 3, Fig. 1a). Regardless of tillage, SOC contents were greater in the 0- to 5-cm than in the 5- to 15-cm depth (NT, $P < 0.0001$; CT, $P < 0.05$; *P* values represent significance level of statistical contrasts). Stratification of SOC was greater in NT than in CT fields.

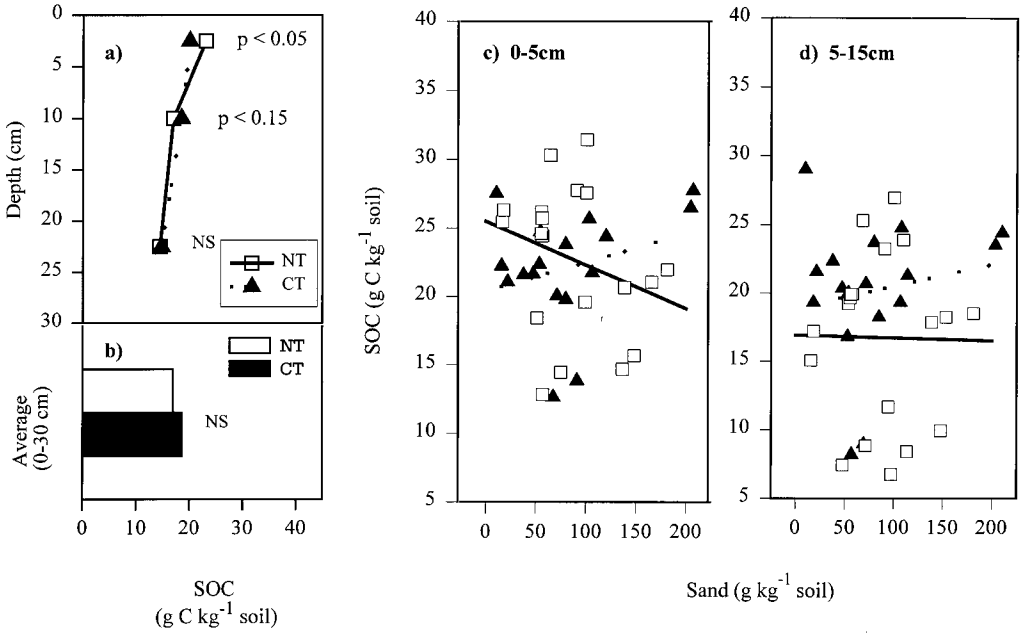

Fig. 1. Soil organic C (SOC) as affected by (a) the interaction of tillage × depth, (b) the main effect of tillage, and the interaction of tillage × depth × sand content in the (c) surface (0–5 cm) and (d) subsurface (5–15 cm) depths. The lines in (c) and (d) represent the linear response of tillage × depth to sand content used as a covariate.

While sand content did not influence the effect of tillage on overall (0–30 cm) SOC contents (Table 4), sand content did influence the effect of tillage on the vertical distribution of SOC (Table 5). In the 0- to 5-cm depth, NT fields contained greater SOC contents than CT fields for soils with sand contents less than ≈50 kg g^{-1} soil, but not in sandier soils (Fig. 1c). Note that even the sandiest soils in this study were relatively fine-textured (Table 1). This sand-content effect on tillage impacts was not observed in the 5- to 15-cm (Fig. 1d) or 15- to 30-cm (data not shown) depths. The SOC contents increased linearly with clay content ($R^2 = 0.65$). However, tillage × clay (Table 4) and tillage × clay × depth interactions were not significant (Table 5). Based on values reported for mapped units, estimated clay values were consistently greater than expected for these soils.

Trends in total N contents ($P < 0.10$; Table 4) were generally similar to those observed in SOC contents (Tables 2 and 3), as were the tillage × depth, clay × depth, and tillage × clay × depth interactions (Table 5).

Soil C/total N ratios were influenced by region and depth but not by tillage or crop (Tables 2 and 3). The C/N ratios were smaller in the SR than in the other regions and decreased with depth (data not shown). Soil C/N ratios were positively correlated with clay content ($R^2 = 0.65$) (Table 4). When clay was included in the

Table 2. The influence of tillage, crop, and region variables on the total quantities of soil organic matter fractions. This table provides *P* values for main effect and interaction terms derived through analysis of variance (ANOVA). Dependent variables have been averaged across depth.

Dependent variable†	Tillage	Crop	Region‡	Tillage × Crop
	P value			
POM C	0.80	0.004	0.09	0.12
POM N	D§	0.07	0.005	D
POM C/N	D	D	0.03	D
PMN	D	0.03	D	D
SMB	D	D	D	D
SOC¶	D	D	0.0001	D
Total N¶	D	D	0.0001	D
SOC/Total N	D	D	0.0001	D

† POM = particulate organic matter; PMN = potentially mineralizable N; SMB = soil microbial biomass; SOC = soil organic C.
‡ Interactions between region and tillage and between region and crop were not included in this table because they were not statistically significant.
§ D = terms that were dropped from the model due to lack of statistical significance at α = 0.25.
¶ One outlier was removed from this model.

Table 3. The influence of tillage and crop variables on the vertical distribution of soil organic matter fractions. This table provides *P* values for main effect and interaction terms which were derived through analysis of variance (ANOVA). Terms which do not include depth have been excluded from this table, but were present in the statistical models. See Table 2 for *P* values associated with terms that do not include depth. Main effect and interaction terms which included region are not included in this chart, although they are included in the models.

Dependent variable†	Depth	Tillage × depth	Crop × depth	Tillage × crop × depth
	P value			
POM C	0.0001	0.0001	D‡	D
POM N	0.0001	0.002	D	D
POM C/N	D	D	D	D
PMN	0.0001	0.012	0.04	D
SMB	0.0001	D	D	D
SOC (all regions)¶	0.0001	0.02	D	D
SOC (without) Southern region	0.0001	0.07	D	D
Total N§	0.0001	0.02	D	D
SOC/Total N	0.0003	D	D	D

† POM = particulate organic matter; PMN = potentially mineralizable N; SMB = soil microbial biomass; SOC = soil organic C.
‡ D = terms that were dropped from the model due to lack of statistical significance at α = 0.25.
§ One outlier was removed from this model.
¶ The southern region was excluded from this model.

Table 4. The influence of tillage, crop, sand, and clay variables on the total quantities of soil organic matter fractions. This table provides *P* values for main effect and interaction terms which were derived through analysis of covariance. Dependent variables have been averaged across depth.

Dependent variable†	Tillage	Crop	Tillage × crop	Sand	Tillage × sand	Crop × sand	Tillage × crop × sand	Clay	Tillage × clay	Crop × clay	Tillage × crop × clay
	P value										
POM C	0.48	0.27	0.09	D‡	D	D	D	0.72	0.45	0.46	0.13
POM N	D	0.16	D	D	D	D	D	0.005	D	D	D
POM C/N	D	D	D	0.14	D	D	D	0.0001	D	D	D
PMN	0.81	0.61	0.06	0.009	0.098	D	D	0.17	0.42	0.39	0.05
SMB	0.21	0.03	0.24	0.34	0.13	0.04	0.13	D	D	D	D
SOC	0.43	0.18	0.21	D	D	D	D	0.0001	0.16	0.40	0.15
Total N	D	0.09	D	0.19	D	D	D	0.0001	D	0.09	D
SOC/Total N	0.26	0.45	0.03	D	D	D	D	0.0001	0.20	0.39	0.02

† POM = particulate organic matter; PMN = potentially mineralizable N; SMB = soil microbial biomass; SOC = soil organic C.
‡ D = terms that were dropped from the model due to lack of statistical significance at $\alpha = 0.25$.

model, a crop × tillage interaction was observed. For corn fields, soil C/N ratios were greater in CT than in NT fields (statistical contrast $P < 0.10$). No differences in soybean field C/N ratios were found. The R^2 between C/N ratios and clay contents decreased in the following order: CT corn > NT soybean > CT soybean > NT corn.

Particulate Organic Matter

Tillage effected the vertical distribution of POM C (Fig. 2a) but had no effect on POM-C contents in the 0- to 15-cm depth (Tables 2 and 3). The NT contained on average 33% more POM C in the 0- to 5-cm soil depth and 29% less POM C in the 5- to 15-cm depth than CT fields. The POM contents in the 15- to 30-cm depth were not evaluated. For each tillage system, POM-C contents were greater in the 0- to 5-cm layer than in the 5- to 15-cm layer (statistical contrast $P < 0.001$). Crop type affected POM-C contents (Table 2). Fields in soybean and corn contained on average 3.4 and 2.9 g POM-C kg^{-1} soil. When texture was included in the analyses, interactions between tillage and crop were noted (statistical contrast $P < 0.009$; Table 4). The POM-C contents decreased in the following order: CT soybean > NT soybean > NT corn > CT corn. Accordingly, the effect of crop on POM-C contents was greater in CT fields than in NT fields. The significant crop × depth interaction was due to the slightly greater stratification of POM C in soybean than in corn fields (Table 5).

Soil texture did not influence tillage effects on POM-C contents in the 0- to 15-cm depth (Table 4), and POM C was not affected by sand content. However, a notable tillage × sand × depth interaction (Table 5) mirrored effects found for SOC (Fig. 3). In soils with low sand content, NT fields had greater POM-C contents than CT fields in the 0- to 5-cm depth, whereas, in sandier soils, there was little or no tillage effect (Fig. 3a). In the 5- to 15-cm depth, NT contained less POM C than CT fields in low sand content soils, and again tillage had no effect on POM C in sandier soils (Fig. 3b).

Trends in the POM-N data were similar to POM-C trends (Tables 2 and 3). Clay was negatively correlated with overall POM-N contents. These trends were associated with a positive correlation between the POM C/N ratio and clay contents. Region was the only factor that effected POM C/N ratios (Tables 2 and 3); POM C/N ratios decreased in the following order: CR > NR > ECR > SR.

Potentially Mineralizable Nitrogen

No-till soils contained 54% more PMN in the 0- to 5-cm depth than CT soils. In both tillage systems, the concentration of PMN was highly stratified, with most labile N located in the 0- to 5-cm depth. Tillage did not affect PMN contents in the 5- to 15- or 15- to 30-cm depths, or on PMN contents overall (0–30 cm) (Table 2, Fig. 2b). The PMN contents were greater (statistical contrast $P < 0.03$) in fields planted to corn than in fields planted to soybean. Overall (0–30 cm), PMN concentrations averaged 10.7 mg NH_4–N kg^{-1} soil in corn fields and 6.6 mg NH_4–N kg^{-1} soil in soybean fields.

At all depths, PMN had a negative linear response ($R^2 = 0.18$) to sand content and there was a tillage × sand interaction (at $P < 0.10$) (Table 4). No-till soils had greater PMN contents than CT soils in soils with low sand content; however, tillage had no effect on PMN contents in sandier soils. While the tillage × sand × depth interaction was not statistically significant (Table 5), the effect of texture and tillage on PMN was most expressed in the 0- to 5 cm depth (data not shown).

As was the case for POM, the PMN crop × sand × depth interaction was significant (Table 5). The negative relationship between PMN and sand contents was strongest in soybean fields in the 0- to 5- and 5- to 15-cm depths (corn 0–5 cm: $R^2 = 0.00$; corn 5–15 cm, $R^2 = 0.14$; soybean 0–5 cm: $R^2 = 0.33$; soybean 5–15 cm, $R^2 = 0.34$). Corn fields contained greater PMN contents than soybean fields (data not shown). The tillage × crop and tillage × crop × clay interactions were significant at $P < 0.10$ (Table 4), with the effect of crop slightly greater in NT than in CT fields.

Soil Microbial Biomass

Tillage did not affect SMB contents at either depth (Fig. 2d, Table 2). The SMB was greater in the 0- to 5-cm depth than in the 5- to 15-cm depth. Soybean fields contained 72.5 mg chloroform-labile C kg^{-1} soil, while corn fields contained 66.1 mg chloroform-labile C kg^{-1} soil in the 0- to 15-cm depth. The crop × sand interaction

was significant at $P = 0.05$ (Table 4). This was due to a small positive influence of sand on SMB contents in fields planted to corn and a small negative influence of sand in fields planted to soybean. The SMB was greater in soybean fields than in corn fields, most likely because of differences in residue input from the previous year's crop. A clay × depth interaction (at $P = 0.10$) was due to a slight positive linear response of SMB to clay content in the 5- to 15-cm depth that was not present at the 0- to 5-cm depth (0–5 cm: $R^2 = 0.03$, $P < 0.30$; 5–15 cm: $R^2 = 0.098$, $P < 0.08$).

DISCUSSION

It is difficult to predict what the long-term effects of NT on SOM will be in Illinois. Conservation tillage came into wide use in central and northern Illinois during the last decade (Conservation Technology Information Center, 1995). In southern Illinois, where such practices have been in use for a decade or more, reduced erosion has been a principal factor increasing SOM contents of NT in comparison with CT soils (Hussain, 1997). Simulations by Lee et al. (1993), which include data from 100 sites selected from the USDA-National Resource Inventory, identify erosion prevention as the principal mechanism, and losses within the profile as a secondary mechanism, by which NT increases SOM contents relative to CT. Alvarez et al. (1998) asserted that use of NT does not notably influence SOM pools in situations with low erosion. We argue that in much of Illinois, where slopes are <2%, it is the impact of tillage on C dynamics within the profile, not erosion, which controls the relationship between tillage practices and SOM dynamics.

Our results reflect the relatively recent adoption of conservation practices. Although changes in soil characteristics continue to occur for decades after conversion to NT (Dick et al., 1991), the most dramatic changes occur within the first decade of practice adoption (Dick, 1983).

Our findings generally indicate that NT affected the vertical distribution but not the overall quantity of SOC, total N, POM, or PMN. Also, NT increased the concentration of SOC and biologically active organic matter (POM and PMN) in the upper 5 cm of soil and decreased SOC and POM in the 5- to 15-cm layer. Trends in total N, PMN, and SMB ($P < 0.10$) also suggest that biologically active and total SOM fractions were relatively depleted below the surface in NT soils. These results agree with the general findings of Wander et al. (1998) from a decade-old trial at three Illinois sites where NT increased POM in surface soils (0–5 cm) at the expense of POM stored at depth (5–17.5 cm). These on-farm findings indicate that continuous NT for several years (≈5) will redistribute C within the profile without necessarily increasing SOC storage (Dick et al., 1991; Karlen and Cambardella, 1996).

In this study, trends in POM were more sensitive indicators of tillage-based depth effects than trends in SMB or PMN. Our failure to find significant main factor effects on the SMB might be due to the large spatial

Table 5. The influence of tillage, crop, sand, and clay variables on the vertical distribution of soil organic matter fractions. This table provides *P* values for main effect and interaction terms which were derived through analysis of covariance. Terms which do not include depth have been excluded from this table, but are present in the statistical models. See Table 4 for *P* values associated with terms that do not include depth.

Dependent variable	*P* value											
	Depth	Tillage × depth	Crop × depth	Tillage × crop × depth	Sand × depth	Tillage × sand × depth	Crop × sand × depth	Tillage × crop × sand × depth	Clay × depth	Tillage × clay × depth	Crop × clay × depth	Tillage × crop × clay × depth
POM C	0.0001	0.0001	0.009	0.01	0.97	0.0001	0.05	D†	0.004	D	0.03	D
POM N	0.0001	0.0002	0.02	0.048	0.32	0.003	0.04	D	0.002	D	0.049	D
POM C/N	0.17	0.11	D	D	0.06	0.18	D	D	D	D	D	D
PMN	0.0001	0.003	D	D	0.32	D	0.045	D	D	D	D	D
SMB	0.009	0.15	D	D	0.36	0.19	D	D	0.09	D	D	D
SOC	0.006	0.25	0.15	D	0.84	0.04	D	D	0.29	0.13	D	D
Total N	0.004	0.095	D	D	0.58	0.03	D	D	0.09	0.06	D	D
SOC/Total N	0.03	D	0.17	D	D	D	D	D	0.16	D	D	D

† POM = particulate organic matter; PMN = potentially mineralizable N; SMB = soil microbial biomass; SOC = soil organic C.
‡ D = terms that were dropped from the model due to lack of statistical significance at $\alpha = 0.25$.

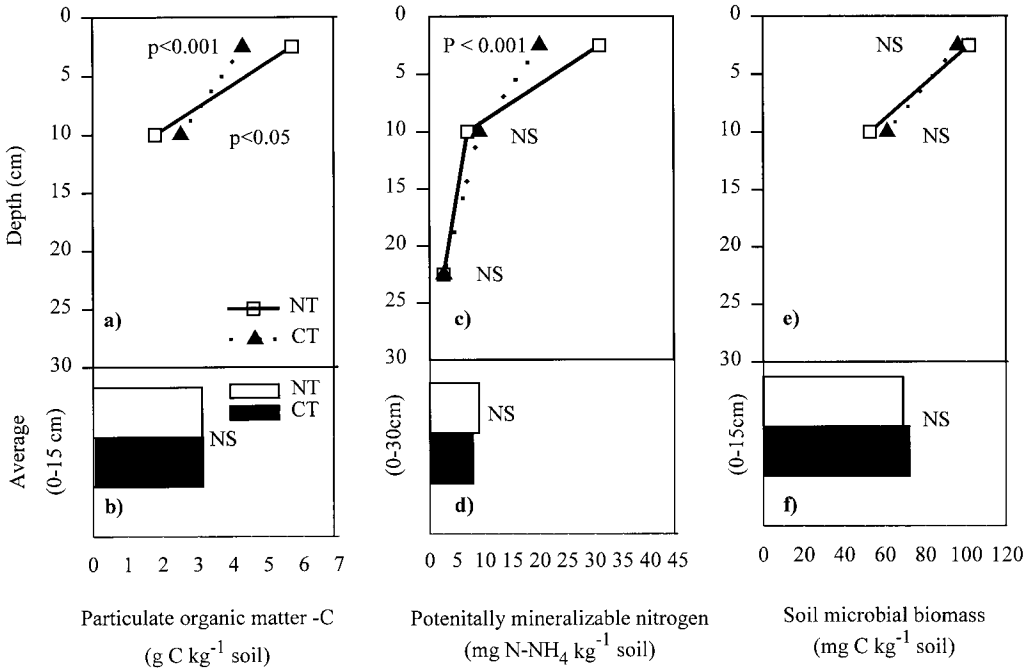

Fig. 2. Tillage effects on biologically active soil organic matter within soil depths (0–5, 5–15, and 15–30 cm) and in the overall sampling depth (0–30 cm): (a) and (b) particulate organic matter C, (c) and (d) potentially mineralizable N, and (e) and (f) microbial biomass C.

(Winter and Beese, 1995), temporal (Kaiser and Heinemeyer, 1993), and methodological (Jenkinson, 1976) variability associated with the SMB measure. The PMN was most responsive to crop type and probably the associated fertility practices. Shifts in POM were the most sensitive indicators of tillage effects on the vertical distribution of SOM.

The effects of NT on SOM storage may be associated with biomass production, which is usually correlated with crop yield. Yield may be reduced by conservation tillage in fine-textured soils in humid regions where soils are cold in spring (Griffith et al., 1988; Karlen, 1990). Models describing the effects of tillage on SOM storage have assumed that yield is reduced under NT (Donigan et al., 1995; Kern and Johnson, 1993). In our study, anecdotal information about crop yields provided by farmers cooperating in the project suggest there was no substantial yield difference between CT and NT. Based on eight replicated trials, Angers et al. (1997) reported that in eastern Canada, crop production and residue inputs were equal in CT and NT and that NT generally did not contain more SOC or N than CT. They also reported that SOM concentrations were greater in the surface (10 cm) of NT than CT and that the reverse was true in the lower plow depth (20–40 cm). Residue placement and a cool climate that would slow decay rates and minimize the effects of fall tillage were thought to minimize tillage practice effects on total SOM contents. Residue burial can increase the SOC contents of the lower plow layer in CT compared with NT (Ishmail

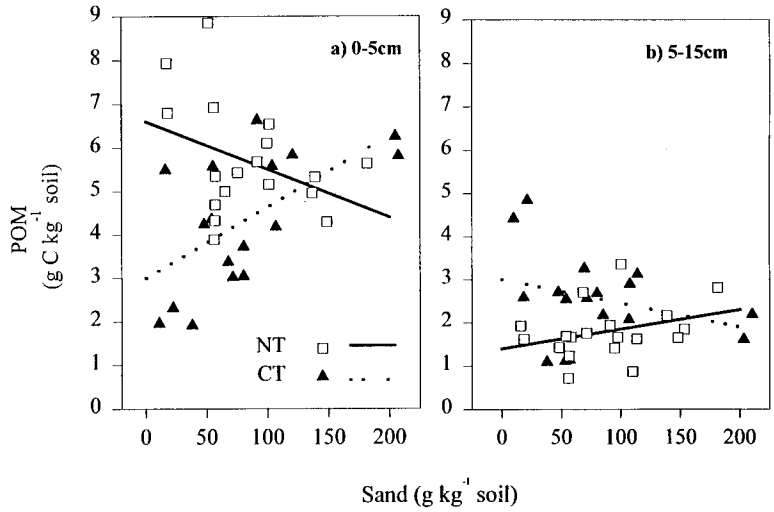

Fig. 3. Particulate organic matter (POM) C as affected by the interaction of tillage × depth × sand content in the (a) surface (0–5 cm) and (b) subsurface (5–15 cm) depths. The lines in (a) and (b) represent the linear response of tillage × depth to sand content used as a covariable.

et al., 1994; Haynes and Beare, 1996). Other authors have noted the influence of climate on the relationship between tillage practices and SOM contents. Decomposition rates, which are generally increased by disruption of soil aggregates and increased aeration, may not always be greater in CT. Franzluebbers and Arshad (1996) did not observe greater total SOM, SMB, and PMN contents in NT than in CT treatments at three sites in a semiarid climate in western Canada. They supposed that greater soil water conservation under NT may have resulted in greater decomposition of SOM and that the cold climate minimized the effects of CT on decomposition rates.

Few studies have investigated the effects of texture on tillage impacts on SOM. Campbell et al. (1996) investigated the effects of texture in an 11-yr comparison of NT and CT at three sites in Western Canada. They found soil C storage in the 0- to 15-cm depth of NT exceeded that in CT by 0, 1.6, and 3.9 Mg ha^{-1} in a sandy loam, a silt loam, and a clay soil, respectively. In our study, the textural range of samples was comparatively narrow and the soils, classified mostly as silty clay loams, contained almost no coarse fragments. We explored the relationship between soil size separates (sand, fine silt, coarse silt, and clay), and tillage effects on SOC and found that tillage effects on SOM were influenced by soil texture. Sand content was the most statistically effective textural covariate. There was no correlation between sand and clay contents. Although clay contents were positively correlated with SOC contents at all soil depths, clay did not influence the effects of tillage on SOC sequestration or stratification. Sand content [1 − (silt + clay)] is the functional equivalent of the silt plus clay variable used in the CENTURY model (Parton et al., 1987). Their finding that decay of labile SOM decreases as silt plus clay contents increase is consistent with our observations. We found that the use of NT in soils with low sand content increased total and biologically active SOM, in particular POM, in the top 5 cm. However, in soils with $< \approx 50$ g sand kg^{-1} soil, use of NT decreased POM C in the 5- to 15-cm depth. Tillage had little effect on SOM in sandier soils. Similar but less pronounced effects were found for PMN contents.

The influence of sand content on SOM stratification by depth in CT and NT may be indirect and is probably physical in nature. Hassink (1996) asserted that the stabilization of applied residues in soils is a function of the unsaturated protective capacity of the soil rather than the quantity of fine particles per se. Soils with low sand content may have a larger unsaturated protective capacity. If so, then in our study, POM increased where residues and/or root biomass were concentrated and soil C saturation capacity was unfilled. Storage porosity [1 − (bulk density/2.65) − (% macropores)] and SOC were positively related ($P < 0.0001$). Tillage may have had little effect on biologically active SOM in soils with high sand content because of limited unsaturated protective capacity. Hassink and Whitmore (1997) asserted that the rate at which SOM becomes stabilized by physical protection is proportional to the concentration of free organic matter and the fraction of pore space that could contain SOM. The greater capacity of low sand content soils to sequester C added as residues may have been a function of porosity rather than clay content (Wander et al., 1998). The influence of sand content within the narrow range of soil textures considered in this work is not well understood.

The influence of tillage on soil porosity and O_2 supply has been explored by Topp et al. (1997), who hypothesized that rapid biological activity in the surface of NT may exhaust and limit O_2 diffusion to subsurface soils, especially in fine-textured soils where SOM is highly stratified. They determined that the upper rooting zone of fall-tilled soils contained more O_2 during spring than soils that were under NT. This may explain why in the soils with low sand content under NT, POM was concentrated in the 0- to 5-cm depth and depleted in the 5- to 15-cm depth. The distribution of POM may reveal a texturally dependent distribution of root-derived material.

Alternatively, SOM decomposition rates may increase with sand content. Comparatively slow decay rates in the soils with low sand content may have allowed accumulation of biologically active SOM to occur where residue placement, and possibly root growth, was concentrated in the surface of NT and subsurface of CT soils.

CONCLUSION

Results from this study suggest that the adoption of conservation tillage has not increased SOM storage in the upper 30 cm of Illinois farm fields. Because of the low relief and poor drainage of the region, adoption of NT probably has less impact on soil erosion than it has in many other regions. The effects of tillage on SOM dynamics in Illinois are dependent on factors that influence internal C-cycling patterns. Both residue placement and constraints on its decay may explain why in this study the use of NT increased accumulation of SOM in the surface 5 cm of the soil at the expense of SOM retained at depth.

No-tillage of poorly drained, fine-textured soils that are not erosion prone may lead to SOM stratification without increasing SOM sequestration. Tillage effects were expressed in the finest-textured soils, where NT had more POM in the surface 5 cm and less in the next 10 cm than CT fields. In sandier soils, the use of NT did not increase stratification or SOM or POM contents. The rapid shifts in POM distribution that were the result of NT adoption identified changes in the quantity, allocation, and conservation of young, biologically active SOM.

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