Management Practice Effects on Surface Soil Total Carbon: Differences along a Textural Gradient

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ABSTRACT

Management practice and soil texture are known to affect soil C. Relatively little information exists, however, on interactions between textural and management effects. The objective of this study was to evaluate management effects on soil total C along a textural gradient in well-drained Typic Hapludalfs in southwest Michigan. Three management practices considered in this study were conventional tillage (CT) and no-till (NT) both with conventional chemical inputs, and conventional tillage with leguminous cover crops and no chemical inputs (CT-cover). Four replicate plots were sampled for each practice, with approximately 100 soil samples taken at the 0- to 5-cm depth in each plot. In all management practices, the relationships of total C and N with clay + silt varied depending on the range of clay + silt values, with regression slopes at clay + silt <570 g kg^{-1} being 1.5 to 6 times lower than those at clay + silt >570 g kg^{-1}. Total C in the CT-cover and NT treatments was higher than that in the CT treatment across the whole range of studied textures; however, a greater difference in total C between NT and CT occurred at greater clay + silt contents. Total C in the CT-cover and NT treatments were not different when clay + silt was <600 g kg^{-1}, while the NT treatment had higher total C than the CT-cover treatment when clay + silt was >600 g kg^{-1}. The results indicate that the potential for C accumulation in surface soils via NT treatment depends on soil texture.

Soil organic matter (SOM) contains approximately two-thirds of the total terrestrial C pool (Trumbore et al., 1996) and is considered to be one of the most important indicators of soil quality (Seybold et al., 1997; Six et al., 2002). Soils play a key role in the global C cycle; by acting as either a sink or a source of atmospheric CO_2, they have a great potential to influence global climate change (Paustian et al., 1998, 2000). Agricultural practices affect SOM dynamics by altering above- and belowground organic matter inputs and decomposition rates. The changes in SOM produced in different agricultural practices may vary, however, depending on soil characteristics. Understanding the relationships between soil C and other soil properties under different agricultural management practices is necessary for assessing the impact of soil management on C dynamics across landscapes with diverse soil characteristics.

Changes in SOM dynamics as a result of tillage have been shown to affect soil structural stability, soil erosion, nutrient availability, nutrient losses, and environmental pollution (Doran et al., 1996). Increasing the intensity of tillage is known to increase the SOM turnover rate and to reduce SOM concentrations. Adoption of conservation tillage, especially NT, is considered to be an important management alternative that has a potential to decrease C loss from agricultural soils (Kern and Johnson, 1993; Paustian et al., 1997). Studies have shown that NT tends to increase soil organic C (SOC) levels compared with CT, especially at the soil surface (e.g., Doran, 1987; Havlin et al., 1990; Lal et al., 1990; Six et al., 1999; Paustian et al., 2000; Puget and Lal, 2005). No-till leads to higher soil C levels partly by reducing disturbance. This favors the formation of soil aggregates and protects the SOC in these aggregates from rapid decomposition (Elliott, 1986; Six et al., 1999, 2000a, 2000b). No-till also tends to modify the soil environment so that it restricts SOM biodegradation (Mielke et al., 1986; Kay and VandenBygaart, 2002). Several studies have shown, however, that relative to CT, greater SOC in NT topsoil was compensated by lower SOC at greater depths, particularly in areas with low relief and poor drainage (Wander et al., 1998; Needelman et al., 1999).

Soil texture plays an important role in influencing the amounts and turnover rates of SOC. Mineralization of SOC is generally more rapid in coarse-textured soils than in fine-textured soils, and a positive correlation between clay content and SOC has been reported in numerous studies (e.g., Sørensen, 1981; Amato and Ladd, 1992; Hassink, 1997). Two main mechanisms have been proposed to explain the greater physical protection of SOM by fine particles. One is physical–chemical stabilization, which generally refers to SOM adsorption to fine particles and the formation of complexes; the other is physical stabilization, which refers to "aggregate formation and consequent physical encapsulation and shielding of SOM from microbial and enzymatic attacks" (Krull et al., 2003). Moreover, specific respiratory activity is lower in fine-textured soils than in coarse-textured soils, which also contributes to the enhanced SOC accumulation in fine-textured soils (Hassink, 1994; Franzluebbers et al., 1996).

Although the overall effects of tillage and texture on SOC have been extensively researched, only limited information exists on interactions between soil texture and tillage practice effects on SOM dynamics. The results from different studies are somewhat conflicting. Based on three experimental sites comparing NT and CT in western Canada, Campbell et al. (1996) found that 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. Change in SOC

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Abbreviations: ANCOVA, analysis of covariance; CT, conventional tillage treatment; CT-cover, conventional tillage with leguminous cover crop and no chemical inputs treatment; KBS, Kellogg Biological Station; LTER, Long-Term Ecological Research site; NT, no-till treatment; SOC, soil organic carbon; SOM, soil organic matter.

was shown to be positively related to clay content after 15 yr since adoption of NT with a corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] and wheat (*Triticum aestivum* L.) rotation (VandenBygaart et al., 2002). Needelman et al. (1999) reported that NT increased total SOM in the top 5 cm of soils with sand content <50 g kg^{-1} but had little effect on SOM in sandier soils in a corn–soybean or corn–wheat–soybean rotation. The range of sand contents considered in their study was relatively narrow, varying from 10 to 204 g kg^{-1} soil. On the other hand, Paustian et al. (1997) found no general relationship between texture and tillage effects on SOC from analysis of 27 long-term tillage trials. After comparing SOC in NT and CT from 56 published paired experiments, Puget and Lal (2005) also concluded that texture had no apparent effect on the difference in SOC between NT and CT. Climate, soil type, crop rotation, and the duration of the tillage treatments of the published experiments cited in their study varied greatly, however, thus potentially confounding the conclusions on texture effects. All these studies were conducted using a relatively small number of samples with tillage practices often not replicated. Puget and Lal (2005) pointed out that the mechanisms and pathways of SOC turnover are complex and can be as much or even more dependent on site-specific pedoclimatic conditions as on tillage practice. The objective of this study was to evaluate management effects on soil total C and N at the 0- to 5-cm depth as a function of soil texture in a replicated, densely sampled, long-term experiment.

MATERIALS AND METHODS

Data Collection

This study was conducted at the Long Term Ecological Research site (LTER), Kellogg Biological Station (KBS) in southwest Michigan, USA (42°24′ N, 85°24′ W). The soils developed on glacial outwash and are classified as well-drained Typic Hapludalfs, either fine-loamy, mixed, mesic (Kalamazoo series) or coarse-loamy, mixed, mesic (Oshtemo series). The field has 0 to 6% slopes (Mokma and Doolittle, 1993). The clay mineralogy of KBS soils is dominated by chlorite and illite (Six et al., 2000b), and the clay mineralogy of the soils across the experimental site is believed to be relatively uniform. Climate is characterized by cool, moist winters and warm, humid summers. Precipitation averages 860 mm yearly and is evenly distributed throughout the year (Robertson et al., 1993). The experiment was established in 1988, and before that the site had been plowed and planted every spring since at least 1950. A 1992 study showed that soil C contents at the experimental site were 10.7, 2.6, and 1.3 g kg^{-1} at the 0- to 20-, 25- to 50-, and 50- to 100-cm depths, respectively (Collins et al., 2000).

The LTER experimental design is a randomized complete block with seven treatments and six blocks. The experimental plots are approximately 80 by 100 m. The three treatments considered in this study are a conventionally tilled (chisel plowed) corn–soybean–wheat rotation with conventional chemical inputs (CT), a no-till corn–soybean–wheat rotation with conventional chemical inputs (NT), and a conventionally tilled (chisel plowed) corn–soybean–wheat rotation with no chemical inputs and a legume winter cover crop (CT-cover). For the conventional chemical treatments, NH_4NO_3 was applied annually at a rate equivalent to 123 kg N ha^{-1}. The cover crops grown in the CT-cover treatment were hairy vetch (*Vicia villosa* Roth) or red clover (*Trifolium pratense* L.). In this study, for each treatment we randomly selected three plots from LTER Blocks 1 to 4. The fourth plot for each treatment came from Block 6. Block 6 was known to have somewhat higher sand content than the rest of the LTER site, thus including it ensured the presence of coarser textured soil samples in all three studied treatments. Complete site description, experimental design, and management protocols are reported at the KBS website (Kellogg Biological Station, 2005).

Before setting up the experimental plots, approximately 400 georeferenced soil samples were collected in 1988 from the area of LTER Blocks 1 to 5 at the 0- to 15-cm depth and soil properties including organic C and total N and soil texture were determined (Robertson et al., 1997). On average, about five data points from the 1988 sampling were available for each plot from Blocks 1 to 5 used in this study. While these data were not suitable for direct comparisons with our measurements, they were useful for verifying whether the treatment plots of our study were spread randomly across textural, C, and N gradients.

Soil sampling for the present study was conducted in May 2003, about 2 wk after plowing in CT and CT-cover. Approximately 100 georeferenced soil samples were collected from the 0- to 5-cm depth from the middle 60- by 60-m portion of each of the 12 studied plots. Detailed description of the sampling scheme and procedures is given in Kravchenko et al. (2006). Two subsamples were taken for measurements from each soil sample. Subsamples of 20 g were used to determine soil particle size distribution. For that, soil was dispersed in 5% Na hexametaphosphate solution and placed on a reciprocating shaker overnight (about 16 h). Sand content was then isolated by wet sieving the dispersed sample through a 53-μm sieve. The soil slurry passing through the sieve was transferred to a 1-L sedimentation cylinder and the silt and clay contents were determined using the hydrometer method (Gee and Bauder, 1986). Subsamples of 30 g were ground on a rolling grinder to pass a 250-μm sieve and total C and N were measured using a Carlo-Erba C-N analyzer (Carlo Erba Instruments, Milan, Italy). Since it was not expected to find carbonates in the studied soils at the studied depth, no effort was made to remove them. Some soil samples were lost or were not large enough for both total C and particle size measurements; hence the total number of soil samples included in our analysis for each treatment was about 380.

Statistical Analysis

Data analysis was conducted using SAS (SAS Institute, 2001). Methods of statistical data analysis used in the study included linear regression analysis conducted with PROC REG, quadratic and segmented regression conducted with PROC NLIN, and analysis of variance (ANOVA) and analysis of covariance (ANCOVA) performed in PROC MIXED (Milliken and Johnson, 2002). In both ANOVA and ANCOVA, the treatment and block effects were treated as class variables, with block as a random factor. Soil clay + silt content was the continuous covariate used in ANCOVA. Plots nested within treatments and blocks were used as an error term for testing the treatment effects. Degrees of freedom for error for the covariate were set to be equal to those used for treatments.

Segmented regression was conducted using procedures described in detail by Shuai et al. (2003). The two-segment linear regression model used in our study is expressed as

$$y = \beta_1 \text{ median}(A_L, x, \alpha_1) + \beta_2 \text{ median}(\alpha_1, x, A_R) + c$$

where y is the dependent variable, either total C or total N, x is the independent variable, e.g., clay + silt content, α_1 is the break point between the two segments of the regression line, β_1 and β_2 are the slopes of the two regression segments, and A_L and A_R are the lower and upper boundaries of the independent variable, respectively. The median function indicates that the median among the three numbers specified in the function is being used. Since the median function is not available in the current version of SAS, a combination of maximum and minimum functions was used to create an equivalent of the median function, as shown in the following example:

$$\text{median}(a, b, c) = \max[\min(a, b), \min(a, c), \min(b, c)]$$

where *max* and *min* represent the maximum and minimum functions available in SAS (Shuai et al., 2003). The regression parameters and break points were estimated by the standard Marquardt routine of PROC NLIN. Comparisons between treatments at different levels of the texture covariate when the relationship between the response variable and the covariate was represented by a segmented regression model were obtained by conducting ANCOVA separately for data from each segment.

Performances of the overall linear, quadratic, and segmented linear regressions were assessed using MSE (Terra et al., 2004):

$$\text{MSE} = 1/n \sum [z(x_i) - \hat{z}(x_i)]^2$$

where $z(x_i)$ are the observed total C or total N, $\hat{z}(x_i)$ are the predicted total C or total N, and n is the number of samples. Comparisons between regression model performances were conducted using the sum-of-squares reduction test (Schabenberger and Pierce, 2002, p.11).

The data were checked for presence of outliers. For that, first the outliers were identified in simple linear regression analysis as the data points with Studentized residuals >2.5 (Pedhazur, 1997). Then we checked whether the regression outliers also could be regarded as spatial outliers. For that, the locations and data values of these outliers were examined visually in respect to the other data points. The regression outliers that also were found to be spatial outliers, that is, those that had distinctly different values of the studied dependent or independent variables from the surrounding points, were excluded from further analysis. Otherwise, the regression outliers were kept in the analysis since it was believed that these points represented the actual spatial distribution of soil texture and total C or N. Overall, only two points from the CT data and one from the CT-cover data were classified as outliers and excluded from further analysis.

Unless specified otherwise, an α level of 0.05 was used to identify statistically significant effects and comparisons.

RESULTS AND DISCUSSION

Relationship of Clay + Silt Content with Total Carbon

Table 1 shows minimum, mean, and maximum values and coefficients of variation for clay, silt, and sand contents and total C and N contents in the three treatments based on the data from all four plots for each treatment. For the whole-site data set, clay, silt, and sand contents ranged from 21 to 334, 178 to 730, and 62 to 735 g kg^{-1} soil, respectively. The range of clay + silt values in CT was somewhat lower than that of CT-cover and NT, with clay + silt values above 800 g kg^{-1} absent in CT data, while present in CT-cover and NT (Fig. 1 and 2). However, overall clay, silt, and sand contents were not significantly different among the three treatments (Table 1), for example, the P value for clay + silt content was 0.11. Texture, total C, and total N data collected in 1988 also were not significantly different among the treatments, with ANOVA producing P values for clay + silt, total C, and total N of 0.13, 0.41, and 0.35, respectively.

As expected, soil total C was significantly related to clay, silt, and sand contents in all three studied treatments. Table 2 shows regression equations, r^2, and MSEs for linear relationships of total C with soil clay, silt, and sand content for the combined data from all four plots per treatment. In all treatments, total C increased with increasing clay or silt content and decreased with increasing sand content. These results were consistent with the findings of many previous studies (e.g., Hassink, 1997; Needelman et al., 1999; Galantini et al., 2004). Regression results indicated that in all treatments, variations in silt or sand content explained >40% of the variations in total C. The linear regressions with sand content produced similar or higher r^2 than those with either clay or silt content, suggesting sand content as the primary textural covariate to be used in this study. The relationships of total C with sand or silt appeared to be stronger in NT and CT-cover than in CT. In this study, clay contents were generally low, which might be responsible in part for the somewhat lower importance of clay in explaining total C and N variability compared with that of sand and silt.

Several previous studies have used clay + silt content as a variable representing soil texture when discussing soil texture effects on SOC (Hassink, 1997; Galantini et al., 2004). Soil clay + silt content is also the functional variable that accounts for soil textural effects on the decomposition rate of soil C pools in the CENTURY model, which is one of the most widely used models in predicting tillage effects on C sequestration (Parton et al., 1987). Consequently, we decided to use clay + silt content, which is the equivalent of (1000 − sand) content, as a soil textural covariate in

Table 1. Minimum, mean ($\bar{x}$), maximum, coefficients of variation, and number of samples (n) for soil clay, silt, and sand contents along with total C and N contents at the 0- to 5-cm depth based on combined data from four plots of each treatment.

		Clay				Silt				Sand				Total C				Total N			
Treatment†	n	min.	$\bar{x}$	max.	CV	min.	$\bar{x}$	max.	CV	min.	$\bar{x}$	max.	CV	min.	$\bar{x}$	max.	CV	min.	$\bar{x}$	max.	CV
		g kg^{-1}			%	g kg^{-1}			%	g kg^{-1}			%	g kg^{-1}			%	g kg^{-1}			%
CT	383	21	117a‡	196	28	182	407a	611	25	209	477a	735	26	3.9	7.1a	13.7	20	0.3	0.7a	1.3	22
CT-cover	379	29	138a	334	36	178	420a	694	28	62	442a	680	32	5.2	10.1b	18.2	23	0.4	0.9b	1.8	27
NT	388	60	144a	290	25	241	473a	730	21	99	383a	662	31	5.6	11.9c	22.3	24	0.3	1.1b	2.1	29

† CT, conventional tillage; CT-cover, conventional tillage with legume cover crops; NT, no-till.
‡ Means within each column followed by the same letter are not significantly different from each other ($P < 0.05$).

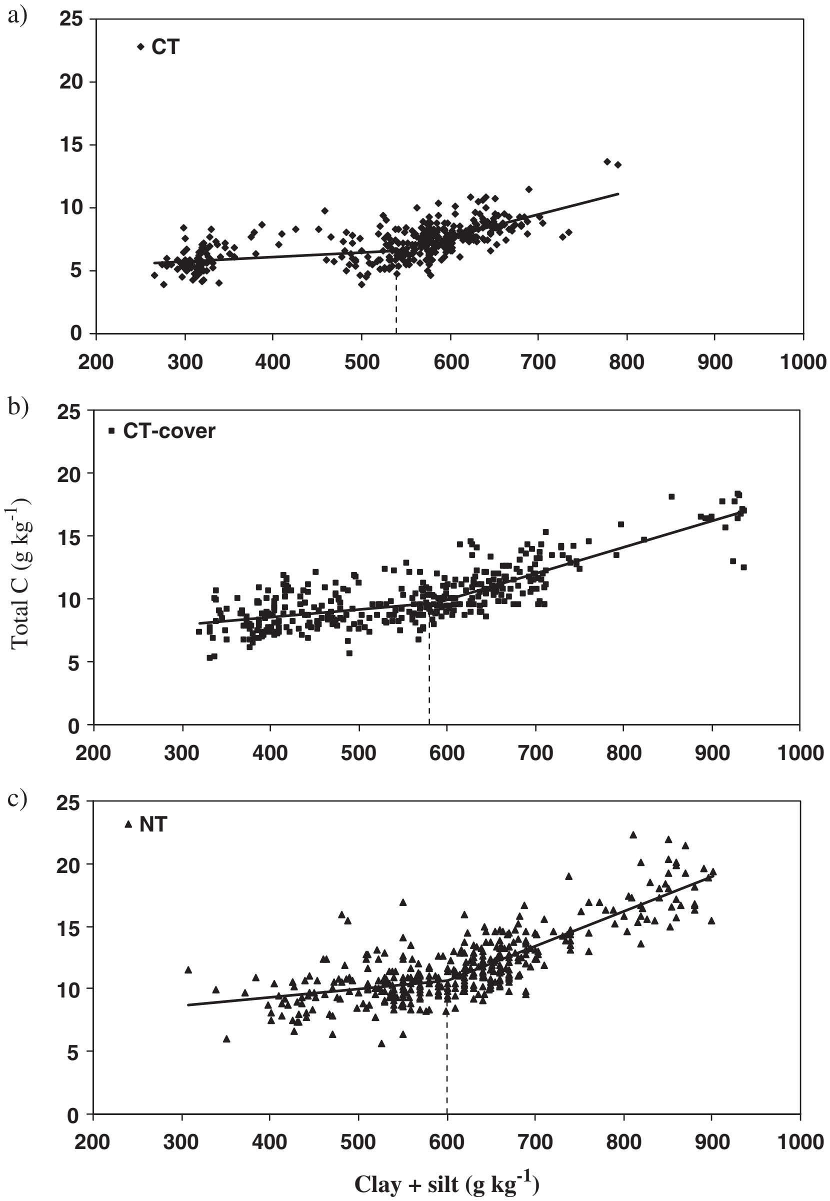

Fig. 1. Relationships between soil total C and clay + silt content at the 0- to 5-cm depth based on combined data from four plots for each treatment fitted with two-segment linear regressions in (a) conventional tillage with conventional chemical inputs (CT), (b) conventional tillage with leguminous cover crops and no chemical inputs (CT-cover), and (c) no-till with conventional chemical inputs (NT) treatments. The dash lines indicate locations of optimal break points from two-segment regressions.

the subsequent regression analyses and ANCOVA of this study.

Two-Segment Linear Regression between Total Carbon and Clay + Silt Content

Visual examination of the regression plots revealed that, across the whole range of the studied clay + silt values, the relationship between total C and clay + silt did not seem to be adequately characterized by a single regression line (Fig. 1). The increase in soil total C with increasing clay + silt content was relatively minor in the lower range of clay + silt contents while it became substantially greater at higher clay + silt contents. To account for the observed different portions of the total C vs. clay + silt relationship, we conducted both quadratic and two-segment linear regression analyses for the three treatments. Since the two-segment linear regressions produced a better fit of the observed data than the quadratic regression models ($P < 0.01$), and since their parameters were easier to interpret than the parameters of the quadratic models, we considered further only the two-segment regressions.

Fitting two-segment regression equations to the data allowed obtaining parameter estimates of the two regression lines as well as estimates of the break points. The optimal break points were 540, 580, and 600 g kg^{-1} of clay + silt content for CT, CT-cover, and NT, respectively. To make comparisons between the treatments consistent, we decided to use a single break point at 570 g kg^{-1} clay + silt content, obtained by averaging the three optimal

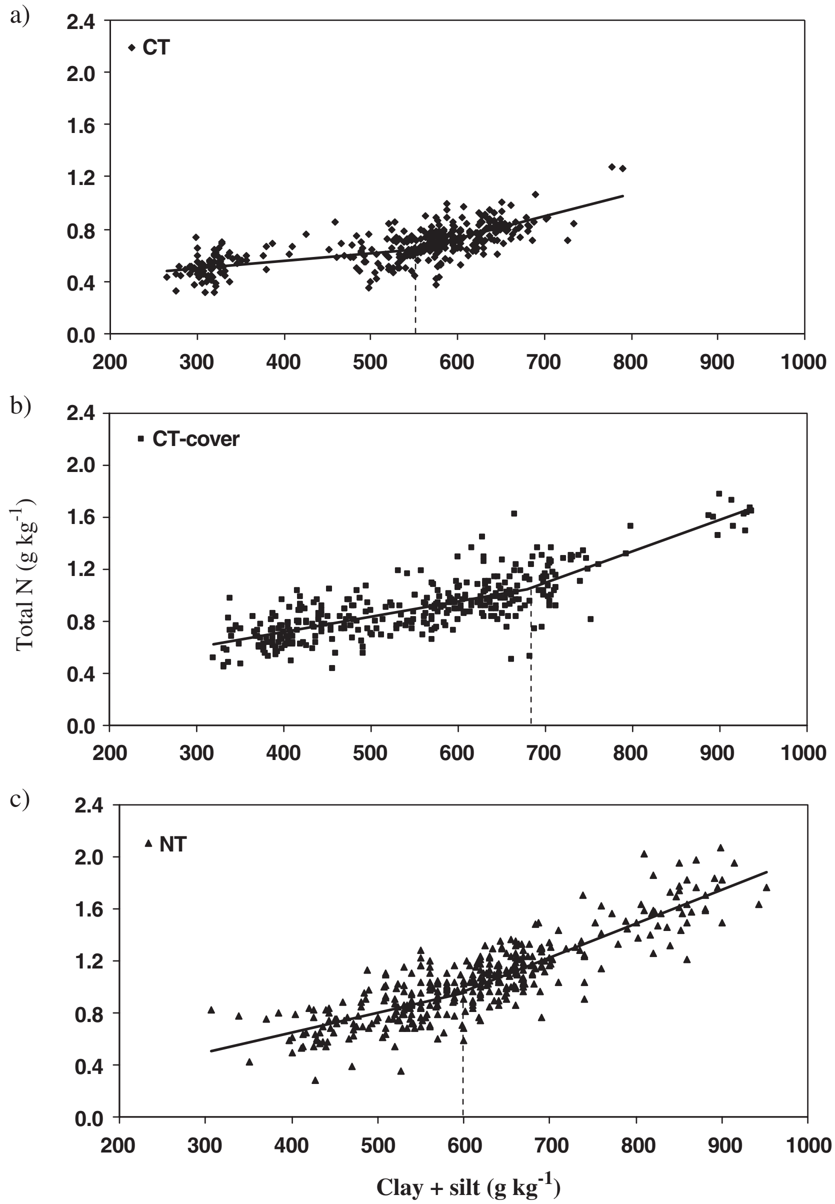

Fig. 2. Relationships between soil total N and clay + silt content at the 0- to 5-cm depth based on combined data from four plots for each treatment fitted with two-segment linear regressions in (a) conventional tillage with conventional chemical inputs (CT), (b) conventional tillage with leguminous cover crops and no chemical inputs (CT-cover), and (c) no-till with conventional chemical inputs (NT) treatments. The dashed lines indicate locations of optimal break points from two-segment regressions.

break points of the three treatments. The effect on the precision of regression results from using a single common break point instead of optimal treatment break points was minimal. The r^2 for the regressions with the common break point at 570 g kg^{-1} clay + silt content were 0.48, 0.67, and 0.70 for CT, CT-cover, and NT, respectively. These were only marginally different from the r^2 obtained from the regressions with the optimal

Table 2. Linear regression equations, r^2, and MSE for regression of total C (g kg^{-1}) with clay, silt, and sand contents (g kg^{-1}) based on combined data from four plots of each treatment. All regressions were statistically significant with $P < 0.01$.

	Linear regression equations, r^2, and MSE		
Treatment†	Clay	Silt	Sand
CT	0.019clay + 4.90 r^2 = 0.18, MSE = 6.12	0.0092silt + 3.39 r^2 = 0.41, MSE = 1.26	−0.0077sand + 10.8 r^2 = 0.41, MSE = 1.25
CT-cover	0.022clay + 7.04 r^2 = 0.21, MSE = 4.30	0.014silt + 4.19 r^2 = 0.51, MSE = 2.68	−0.013sand + 15.9 r^2 = 0.60, MSE = 2.19
NT	0.046clay + 5.34 r^2 = 0.31, MSE = 5.77	0.023silt + 1.14 r^2 = 0.58, MSE = 3.51	−0.019sand + 19.3 r^2 = 0.63, MSE = 3.12

† CT, conventional tillage; CT-cover, conventional tillage with legume cover crops; NT, no tillage.

break points: 0.50, 0.69, and 0.69 for CT, CT-cover, and NT, respectively. In all three treatments, the two-segment regression model fitted the observed data significantly better than the single-line regression model ($P < 0.01$). Compared with the single-line regression, the two-segment regression improved r^2 and reduced MSE by 13, 16, and 18% for CT, CT-cover, and NT, respectively. The equations from the two-segment regression analysis are shown in Table 3. The regression slopes at clay + silt <570 g kg^{-1} were 4.1, 3.8, and 6 times lower than those at clay + silt >570 g kg^{-1} for CT, CT-cover, and NT treatments, respectively. These results indicated that, in the studied soils, the relationship between total C and texture may not be adequately described by a single linear equation across the entire observed range of soil textures.

Treatment Effects on Total Carbon at Different Levels of Clay + Silt Content

Based on the two-segment regression, we conducted the ANCOVA analysis separately for the two clay + silt ranges. The results showed that there was no significant interaction between treatments and clay + silt content for the first regression segment that extended from 300 to 570 g kg^{-1} clay + silt content ($P = 0.30$). Lack of significant interaction between treatments and clay + silt content indicated that differences in total C among the three treatments were relatively constant across this range of clay + silt (Table 4). Across this range, NT and CT-cover had significantly higher C content than the CT treatment, while there was no significant difference in total C between NT and CT-cover. The relatively small regression slopes suggested that, in soils with low clay + silt and somewhat low SOC such as those used in this study, a modest increase in fine-particle content did not contribute substantially to soil C accumulation.

There was a statistically significant interaction between treatments and clay + silt at clay + silt contents ranging from 570 to 900 g kg^{-1} ($P < 0.01$). In this range of clay + silt contents, the regression slope for NT was greater than the slopes for CT and CT-cover. The regression slopes for CT and CT-cover were not significantly different from each other. The similar regression slopes of CT and CT-cover indicated that the increase in total C associated with increasing clay + silt was similar for CT and CT-cover across this range of clay + silt contents.

As a result of the significant difference between the slopes, comparisons with NT at this range of clay + silt varied depending on the clay + silt value (Table 4). Similar to the 300 to 570 g kg^{-1} range, across the whole 570 to 900 g kg^{-1} range, the total C of NT and CT-cover was significantly greater than that of CT, which was consistent with the findings of most previous studies (e.g., Mielke et al., 1986; Campbell et al., 1996; Lal et al., 1994; Hendrix et al., 1998; Peterson et al., 1998). The differences between CT and CT-cover can be partially attributed to potential differences in quantity and quality of biomass inputs from primary crops and cover crops of these treatments. The differences between NT and CT treatments probably resulted from increases in the number and stability of macroaggregates as well as improved formation of stable microaggregates in soil under NT (Six et al., 2000a). Moreover, because of mixing due to tillage, SOC inputs were most likely diluted with depth in CT, while being concentrated on the surface in NT. The differences in total C between the NT and CT-cover treatments were not significant at clay + silt content <600 g kg^{-1}, while becoming significant at higher clay + silt values (Table 4).

The observed outcome appears to be consistent with the theory of protection mechanisms of SOC by fine particles. Previous studies have shown that SOM is one of the important binding agents that link individual microaggregates into stable macroaggregates (Tisdall and Oades, 1982; Elliott, 1986). Thus, a larger number of soil macroaggregates might be expected in CT-cover than in CT because CT-cover had a higher soil C content. The protection due to aggregates can be greatly limited in conventional tillage, however, regardless of the number of newly formed macroaggregates, due to mechanical disruption of soil structure by plowing (Dexter, 1988; Puget et al., 1995; Paustian et al., 1997). Consequently, any greater SOC protection ability in soils with higher clay + silt content in CT and CT-cover could be attributable to the physical–chemical stabilization rather than to physical stabilization alone (Krull et al., 2003). The physical–chemical stabilization process depends mainly on the amount of fine particles in the soil. This may explain why the differences in SOC between CT and CT-cover were similar across the studied range of clay + silt content.

The greater regression slope in NT vs. CT and CT-cover indicated that the difference in total C between NT and the conventional tillage treatments was greater in soils with higher clay + silt content than in coarser textured soils, which could probably be explained by a hierarchical aggregate theory that is widely applied

Table 3. Linear regression slopes, intercepts, r^2, and MSE resulting from a two-segment regression of total C (g kg^{-1}) with clay + silt content. All regressions were statistically significant with $P < 0.05$.

Treatment†	n	Clay + silt	Slope (SE)	Intercept (SE)	r^2	MSE
CT	198	<570 g kg^{-1}	0.0049 (0.0006)	4.25 (0.90)	0.48	1.10
	181	>570 g kg^{-1}	0.020 (0.0017)a‡	−4.13 (0.90)		
CT-cover	183	<570 g kg^{-1}	0.0053 (0.0010)	6.40 (0.57)	0.67	1.84
	192	>570 g kg^{-1}	0.020 (0.0010)a	−2.15 (0.57)		
NT	133	<570 g kg^{-1}	0.0043 (0.0019)	7.68 (0.96)	0.70	2.64
	251	>570 g kg^{-1}	0.026 (0.0010)b	−4.52 (0.96)		

† CT, conventional tillage; CT-cover, conventional tillage with legume cover crops; NT, no tillage.
‡ The regression slopes at clay + silt >570 g kg^{-1} followed by the same letter are not significantly different ($\alpha = 0.05$). The regression slopes at clay + silt <570 g kg^{-1} among the studied treatments were not significantly different ($\alpha = 0.05$).

Table 4. Analysis of covariance estimates of total C based on two-segment regression model at selected levels of clay + silt content.

Treatment†	Total C (g kg^{-1}) at clay + silt content of			
	450 g kg^{-1} (average‡ of the <570 g kg^{-1} segment)	570 g kg^{-1} (the break point)	660 g kg^{-1} (average of the >570 g kg^{-1} segment)	700 g kg^{-1} (upper quartile‡ of the >570 g kg^{-1} segment)
CT	6.5a§	7.0a	8.8a	9.6a
CT-cover	8.8b	9.4b	11.2b	12.1b
NT	9.6b	10.1b	12.4c	13.5c

† CT, conventional tillage; CT-cover, conventional tillage with legume cover crops; NT, no tillage.
‡ Averages and the upper quartile of clay + silt content obtained based on all measured clay + silt contents of respective segments.
§ ANCOVA estimates within the same column followed by the same letter are not significantly different (α = 0.05).

to characterize the mechanisms of greater C sequestration in NT (Six et al., 2000a, 2000b; Denef et al., 2004). The theory assumes the presence of three different classes of SOM associated with three different soil physical units: silt and clay particles, microaggregates <250 μm, and macroaggregates >250 μm. The higher C content in NT vs. CT has been found in part to be related to greater number and stability of macroaggregates (Tisdall and Oades, 1982), and enhanced formation of stable microaggregates (Six et al., 2000a; Denef et al., 2004). Presumably, in NT, larger amounts of fine particles and higher C content would greatly enhance the formation and stability of macroaggregates. Moreover, higher clay + silt content could further reduce the macroaggregate turnover rate, hence increasing both the number and stability of microaggregates in NT. Denef et al. (2004) found that soils with the highest clay + silt content had the greatest difference in SOC between NT and CT, and also had the greatest microaggregate-associated C levels, compared with the other two soils used in their study. Our results are consistent with their findings, suggesting that soil clay + silt content might have contributed to improved microaggregates stability and helped sequester more C in the surface 0- to 5-cm soil in NT than in the conventional tillage treatments.

Relationship of Clay + Silt with Total Nitrogen and Treatment Effects on Total Nitrogen at Different Levels of Clay + Silt Content

Similar analyses were conducted for the relationship of total N with clay + silt content for CT, CT-cover, and NT. In all three treatments, total N increased with increasing clay + silt content ($P < 0.01$). Figure 2 shows the relationships of total N with clay + silt content for the three treatments along with the two-segment regression lines. Similar to total C, two-segment regressions performed better than the single-line regressions, producing higher r^2 and lower MSE (Table 5). The optimal break points were 550, 680, and 600 g kg^{-1} of clay + silt for CT, CT-cover, and NT, respectively. In CT and NT, the break points for total N were close to those for total C. The break point for total N in CT-cover, however, was higher than that of total C. As mentioned above, the CT-cover treatment has not received any direct N fertilizer inputs and most soil N inputs came from cover crops. This could be a reason for the observed difference in the relationship between total N and clay + silt content in CT-cover compared with the other two treatments that received direct N fertilizer inputs.

Similar to total C, we used a common break point of 570 g kg^{-1} clay + silt content to conduct two-segment regression analysis for CT and NT; however, we decided to use the optimal break point of 680 g kg^{-1} of clay + silt content for the CT-cover treatment. The regression slopes at the lower range of clay + silt contents, i.e., clay + silt <570 g kg^{-1} for CT and NT and clay + silt <680 g kg^{-1} for CT-cover, were 2.8, 2.1, and 1.6 times lower than those at respective higher ranges of clay + silt contents in CT, CT-cover, and NT treatments, respectively. The ANCOVA results for total N were similar to those for total C. When clay + silt was in the range from 300 to 570 g kg^{-1} soil, there was no significant interaction between treatments and clay + silt content ($P = 0.43$). Interaction between treatments and clay + silt content was significant when clay + silt ranged from 570 to 900 g kg^{-1} soil, with the regression slope in NT being significantly greater than that in CT. The regression slope in CT-cover at clay + silt content ranging from 680 to 900 g kg^{-1} soil was not significantly different from NT; however, it was significantly greater than in CT. Total N was significantly higher in NT and CT-cover than in CT across all studied clay + silt levels, while

Table 5. Linear regression equations, r^2, and MSE resulting from single-line and two-segment linear regressions of total N (g kg^{-1}) with clay + silt content. All regressions were statistically significant with $P < 0.05$.

Treatment†	Two segment					Single line			
	Clay + silt	Slope (SE)	Intercept (SE)	r^2	MSE	Slope (SE)	Intercept (SE)	r^2	MSE
CT	<570 g kg^{-1}	0.0006 (0.00007)	0.31 (0.03)	0.55	0.009	0.0009 (0.00004)	0.22 (0.03)	0.50	0.011
	>570 g kg^{-1}	0.0017 (0.0002)a‡	−0.31 (0.14)						
CT-cover	<680 g kg^{-1}	0.0012 (0.0003)	6.29 (0.13)	0.71	0.022	0.0014 (0.0002)	0.13 (0.10)	0.63	0.023
	>680 g kg^{-1}	0.0025 (0.0008)b	−2.43 (0.67)						
NT	<570 g kg^{-1}	0.0016 (0.0003)	−0.0004 (0.14)	0.82	0.023	0.0022 (0.0001)	−0.32 (0.07)	0.75	0.024
	>570 g kg^{-1}	0.0026 (0.0002)b	−0.57 (0.14)						

† CT, conventional tillage; CT-cover, conventional tillage with legume cover crops; NT, no tillage.
‡ The regression slopes at clay + silt >570 g kg^{-1} for CT and NT and >680 g kg^{-1} for CT-cover followed by the same letter are not significantly different (α = 0.05). The regression slopes at clay + silt <570 g kg^{-1} for CT and NT and <680 g kg^{-1} for CT-cover were not significantly different (α = 0.05).

Table 6. Analysis of covariance estimates of total N based on two-segment regression model at selected levels of clay + silt content.

	Total N (g kg^{-1}) at clay + silt of		
Treatment†	450 g kg^{-1} (average‡ of the <570 g kg^{-1} segment)	570 g kg^{-1} (break point for CT and NT)	700 g kg^{-1} (upper quartile‡ of the >570 g kg^{-1} segment)
CT	0.55a§	0.64a	0.90a
CT-cover	0.79b	0.89b	1.22b
NT	0.72b	0.84b	1.25b

† CT, conventional tillage; CT-cover, conventional tillage with legume cover crops; NT, no tillage.
‡ Averages and the upper quartile of clay + silt content obtained based on all measured clay + silt contents of respective segments.
§ ANCOVA estimates within the same column followed by the same letter are not significantly different ($\alpha = 0.05$).

there was no significant difference in total N between CT-cover and NT (Table 6).

CONCLUSIONS

We found clay + silt content (the equivalent of 1000 g kg^{-1}soil minus sand content) to be more effective as a textural covariate for studying the effects of treatments on total C and N in the studied Alfisol than either clay or silt content alone. The relationships of total C and total N with clay + silt differed depending on the range of clay + silt contents and were more precisely described by a two-segment regression than by a single-line regression.

When clay + silt content ranged from 300 to 570 g kg^{-1}, the interaction of treatments and clay + silt content was not significant, and the differences in total C among the three treatments were constant across this range. Within this range, total C and total N in CT-cover and NT treatments were not significantly different from each other, while they were both significantly higher than those of CT. When soil clay + silt content ranged from 570 to 900 g kg^{-1}, the effect of management treatments on total C appeared to be more strongly influenced by soil clay + silt content than at the lower range of clay + silt content, and the increase in total C associated with increasing clay + silt content was greater in NT than in CT and CT-cover. This suggests that total C accumulation associated with higher fine particle content was more pronounced in NT than in CT and CT-cover. Within this range of clay + silt values, NT and CT-cover also had significantly higher total C and N than CT. Unlike soils with clay + silt ranging from 300 to 570 g kg^{-1}, however, in soils with clay +silt >600 g kg^{-1}, total C of NT was significantly higher than that of CT-cover. The results indicate that the potential for C accumulation in surface soils via no-till treatment probably depends on soil texture and thus may vary across landscapes with diverse soil textures.

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