Topography Influences Management System Effects on Total Soil Carbon and Nitrogen

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Topography is one of the major factors affecting soil C and N contents at the field/landscape level. However, topographical effects are likely to differ in magnitude in different agricultural systems. The objective of this study was to examine the interactions between topography and management systems on soil C and N. The study was conducted at the Kellogg Biological Station Long-Term Ecological Research (LTER) site in southwest Michigan. The studied treatments were chisel-plow (CT) and no-till (NT) with conventional chemical inputs and a chisel-plow organic management system with winter leguminous cover crops (CT-cover). At the 0- to 5-cm depth in both upperslope and valley positions total C and N contents of NT management were the highest followed by CT-cover and then CT. At 0- to 15-, 20- to 30-, and 30- to 40-cm depths, treatment effects varied depending on the landscape position. There were no differences among the treatments in upperslopes, while in the valleys total C and N tended to be the highest in NT and CT-cover followed by CT. The results indicated the importance of accounting for interaction between topography and management practices when assessing C sequestration across landscapes with varying topography. Total C stocks at the 0- to 30-cm depths were around 35, 32, and 27 Mg C ha^{-1} soil (± 2 Mg C ha^{-1}standard error) in CT-cover, NT, and CT, respectively, across upperslopes and valleys. Overall, CT-cover was found to be as efficient in maintaining C and N content as no-till with conventional chemical inputs. Power analysis for C and N stocks at the 0- to 40-cm depth revealed that because of high variability in total C and N stocks at greater depths, the 10 to 30 samples per treatment available in this study were inadequate to detect differences in C and N stocks if thh differences were < 26 Mg C ha^{-1}.

Abbreviations: CT, conventional tillage (chisel-plowed) corn–soybean–wheat rotation system with conventional chemical inputs; CT-cover, conventional tillage (chisel-plowed) corn–soybean–wheat rotation with zero chemical inputs and leguminous cover crops; LTER, Long-Term Ecological Research Site; NT, no-till corn-soybean-wheat rotation with conventional chemical inputs.

Soil organic matter plays an important role in the global C cycle and also serves as an index of soil quality and crop productivity (Seybold et al., 1997; Smith, 1999). Thus soil C management is a key component of global climate change studies and sustainable agriculture programs. The net C content in a soil system is a tradeoff between C additions through plant and microbial biomass inputs and C losses through soil respiration and erosion. In agricultural soils, the type and characteristics of implemented management systems have a substantial influence on soil organic matter. However, even within the same management system, soil C sequestration potentials vary in response to many other factors, including but not limited to topography, parent materials, and microclimatic conditions. Success in promoting soil C sequestration depends on a thorough understanding of various factors controlling soil C and of the interactions among these factors. On a scale of a typical agricultural field, topography, soil disturbance by tillage, and amounts of plant residue returned to soil can be regarded as the main factors affecting spatial variations in soil C. The influence of topography can be expected to be either buffered or intensified by different tillage and crop management practices (Bergstrom et al., 2001).

Topography affects soil C through erosion and redistribution of fine soil particles and organic matter across landscape, and through water redistribution leading to varying leaching, infiltration, and runoff potentials (Ovalles and Collins, 1986; Pennock and de Jong, 1990; Kravchenko and Bullock, 2000; Creed et al., 2002). Topography is one of the key factors of soil formation and its effects on soil C have been well documented; many researchers reported a strong relationship between terrain attributes and soil C at a field scale (Moore et al., 1993; Hao et al., 2002; Moorman et al., 2004; Ziadat, 2005; Yoo et al., 2006a; Papiernik et al., 2007).

General topographical influences on soil C are likely to differ in magnitude under agricultural systems with different tillage. Tillage controls soil organic matter dynamics by three major actions, such as periodic disruption of soil structure, incorporating plant residues within soil horizon, and altering soil microclimate (Balesdent et al., 2000). These three major mechanisms in turn influence various soil processes, such as soil aggregation, erosion, mineralization rates, as well as soil moisture, temperature, and aeration regimes (Franzluebbers et al., 1994; Hernanz et al., 2002). Periodic disruption of soil structure due to tillage tends to reduce soil C and N contents. No-till (NT) management is believed to lessen C losses associated with tillage disturbance. In NT, higher organic C at the soil surface leads to higher aggregate stability, reduces erosion, and buffers temperature and moisture fluctuations (Beare et

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al., 1994a, 1994b; Six et al., 2000a, 2000b). Tillage by a chisel plow to a depth of 15 cm was found to incorporate nearly 60% of the residues at a depth of 0 to 6 cm, whereas in a NT system all of the residues remained on the surface (Allmaras et al., 1996). Crop residues on the soil surface in NT generally decompose slower than residues incorporated in soil via tillage because of less contact with microorganisms and differences in soil microclimate (Reicosky et al., 1997). In NT, presence of previous crop residues has been reported to decrease topsoil temperature by 0 to 3°C, increase soil moisture content, and reduce soil aeration (Coote and Malcolm-McGovern, 1989). Based on Rothemsted C model, Balesdent et al. (2000) estimated that for every 2°C decrease in soil temperature the decay rates decrease by a factor of 0.8.

Differences among management systems in terms of plant residue inputs may further affect magnitudes of topographical and tillage effects. Organic based systems with winter cover crops enhance soil C by increasing the amount and diversity of biomass returned to the soil and by increasing the time during which the land is covered by growing plants (Follett, 2001; Teasdale et al., 2007). Benefits of growing winter annual cover crops include increased soil aggregate stability and increased soil N content (McVay et al., 1989; Blevins et al., 1990). However, the beneficial effects of cover crops may differ across the landscape reflecting cover crop growth and performance variability.

Though a substantial number of studies have addressed the relationships between topography and soil C and N and the tillage effects on soil C and N separately, there is less quantitative information on interactions between them. Tillage induced soil losses result in truncated soil profiles in convex slope positions and inverted soil profiles with subsoil material deposited over original surface horizons at convex slope positions (Kosmas et al., 2001; Heckrath et al., 2005; Papiernik et al., 2007). Differences in strength of relationship between topography and soil C under different land use systems were reported by Tan et al. (2004) under cropland, grassland, and forestland in Ohio. In NT, VandenBygaart et al. (2002) observed that after adoption of NT, soil C content increased in upper and middle slope positions more than that of lower slope positions. Bergstrom et al. (2001) mentioned that NT had more soil C than conventional tillage only at well-drained upperslope positions.

The disadvantage of most of the studies that examined topographical effects on soil C in different management systems is lack of replication for management system effects. This leads to confounding of the management and topographical effects.

In this study, topography modifications of total C and N levels under a no-till system, a chisel-plow tillage system, and an organic based tillage system were compared in a replicated long-term field experiment. The large experimental plots and dense elevation data provided reliable estimates of various topographical features within each plot. The objectives of the study were to assess the interactions between topography and management systems on soil C and N; and to compare landform elements in their potential to gain C in different management systems.

MATERIALS AND METHODS

Study Site

The study was conducted at Kellogg Biological Station's Long-Term Ecological Research (KBS-LTER) site, in southwest Michigan (85°24′ W, 42°24′ N). The experiment was established in 1988. Before 1988 the site had been conventionally managed in row-crop agriculture for at least a century (Robertson et al., 1997). Soils at the site developed on glacial outwash and belong to Typic Hapludalfs of the Kalamazoo (fine-loamy, mixed, mesic) and Oshtemo (coarse-loamy, mixed, mesic) series (Mokma and Doolittle, 1993). Climate is temperate with cool, moist winters and warm, humid summers. The area receives approximately 90 cm of annual precipitation, with about half as snow. Mean annual temperature is 9°C (Grandy and Robertson, 2007). The general topography of the studied site is a rolling landscape with typical hillslope approximately 100 to 200 m long.

Experimental Layout and Agronomic Protocols

The LTER experimental layout is a one-factor randomized complete block design with six replications and seven treatments. We studied three of the agronomic treatments, namely, chisel-plowed with conventional chemical inputs (CT); no-till with conventional chemical inputs (NT); and an organic chisel plowed system with winter leguminous cover crops and zero chemical inputs (CT-cover). The treatments are in corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.]–wheat (*Triticum aestivum* L.) rotations. The cover crop of the CT-cover treatments from 1989 to 1993 was hairy vetch (*Vicia villosa* Roth) and from 1994 onward red clover (*Trifolium pratense* L.). Typically red clover is frost seeded in wheat and then a year later is incorporated in April or May before corn planting. Weed control in CT-cover for corn and soybean is achieved by weekly/biweekly rotary cultivation from May to early July. For wheat, cultivation before wheat planting is conducted in fall. Each experimental plot is about 90 by 110 m in size. The plots are separated by 10 m wide grass lanes. Due to the grass lanes, the occurrence of the runoff that crosses from one plot to another is extremely rare and there is no erosion from one plot to the next. The complete site description, experimental design, and management protocols are available at the KBS website (Kellogg Biological Station, 2005). The experimental layout along with the elevation map is shown on Fig. 1.

Soil Sampling

Soil sampling was performed over the period from 2003 to 2006 and consisted of two sample data sets. The first set of soil samples was collected at the 0- to 5-cm depth from Replications 1 through 4 in May of 2003 (corn was the previous year crop) and from Replication 5 and 6 in May of 2004 (soybean was the previous year crop). In both years CT and CT-cover treatments were plowed approximately 2 wk before sampling. Approximately 100 georeferenced soil samples were collected at each plot for a total of 500 to 600 samples per treatment. The samples were taken between the plant rows and were composited from five 2.5-cm-diam. cores collected within a 0.2-m radius. Detailed description of this sampling has been reported previously (Kravchenko et al., 2006).

The second set of soil samples was collected at 0- to 15-cm, 20- to 30-cm, and 30- to 40-cm depths in May of 2006 (corn was previous crop) from Replications 1 and 4 for CT and Replication 3 and 4 for CT-cover treatments. These plots were selected for sampling because of their relative proximity to each other and relative topographical diversity of that portion of the LTER site. At each plot approximately 100 samples were collected from the same locations as the 0- to 5-cm samples of 2003. Out of 100 samples, approximately 20 were undisturbed cores of 5.2 cm-diam. obtained using a hydraulic soil core unit from Geoprobe Systems (Geoprobe, Inc., Salina, KS) to a depth of 0 to 40 cm. The portions of 0- to 15-cm depth, 20- to 30-cm, and 30- to 40-cm depths were cut from the cores and used for bulk density measurements and other soil analyses. The cores were collected on a 15- by 18-m triangular grid. The remaining 80 samples were collected using soil core samplers at the 0- to 30-cm depth from between the plant rows and were composited from five 2.5-cm diam. cores collected within a 0.2-m radius circle. Additional undisturbed cores were collected in off-grid positions from the LTER locations that were sampled in 1988 before LTER establishment in Replications 1 to 5 for CT, CT-cover, and NT plots with approximately four to five cores per plot.

Thus the samples at the 20- to 30-cm depth consisted of both samples taken with core samples and the samples cut from the undisturbed cores. The total numbers of samples for the 20- to 30-cm depth were equal to 159 and 182 in CT and CT-cover treatments, and 22 in NT. The samples at the 30- to 40-cm depths were cut from the undisturbed cores. Unfortunately, in several cores the lowest part of the core was lost while pulling out the core. The sample numbers were equal to 28 and 37 in CT and CT-cover treatments, and 10 in NT.

The samples were air-dried at room temperature and all large plant residues were removed manually. Smaller plant material was removed by gentle air blowing and the samples were ground on a shatterbox machine for 1 min to pass a 250-μm sieve. Total C was measured using Carlo-Erba, model NA1500, series 2 Nitrogen-Carbon-Sulfur Analyzer (Carlo-Erba, Milan, Italy). In each plot, about 10% of the samples were replicated thrice for total C and N measurements to account for the variability associated with laboratory measurement error. Previous studies conducted at LTER site reported that inorganic C at the soil surface was found to be negligible thus the values obtained from chemical analysis of total C were considered to be representative of the organic C (DeGryze et al., 2004).

To calculate total C and N stocks on an aerial basis for the 0- to 30-cm and 0- to 40-cm depths we used bulk density values obtained from the undisturbed cores. For 0- to 20-cm, 20- to 30-cm, and 30- to 40-cm segments the bulk densities for stock estimation were averaged by treatment.

Terrain Attributes

A topographical survey has been conducted at the LTER site using a 12-channel Leica SR530 real-time kinematic DGPS (dual-frequency global positioning system) receiver (Leica Geosystems AG, Heerbrugg, Switzerland) with measurements collected every 2 m in rows 5 m apart. Relative elevation was calculated from the original elevation data by subtracting the minimal original elevation value from the data. Topographical features, including slope, curvature, and flow accumulation were derived from the elevation map using ArcGIS 9.0 (Kravchenko and Bullock, 2000; Pennock and Corre, 2001; Kravchenko et al., 2006). Wetness index (WI) was computed based on flow accumulation and slope data for each map grid cell (Gallant and Wilson, 2000; Huang et al., 2007) as:

$$\mathrm{WI}=\ln(A_s/\tan\beta) \qquad [1]$$

where A_s is a specific catchment area derived from flow accumulation, and tan β is a tangent function of slope. Wetness index is a compound topographical index that integrates information from specific catchment area and slope. Several previous studies used WI as an important covariate while predicting soil C, yield and other soil attributes (Skidmore et al., 1991; Moore et al., 1993; Terra et al., 2004; Kaspar et al., 2006; Huang et al., 2007).

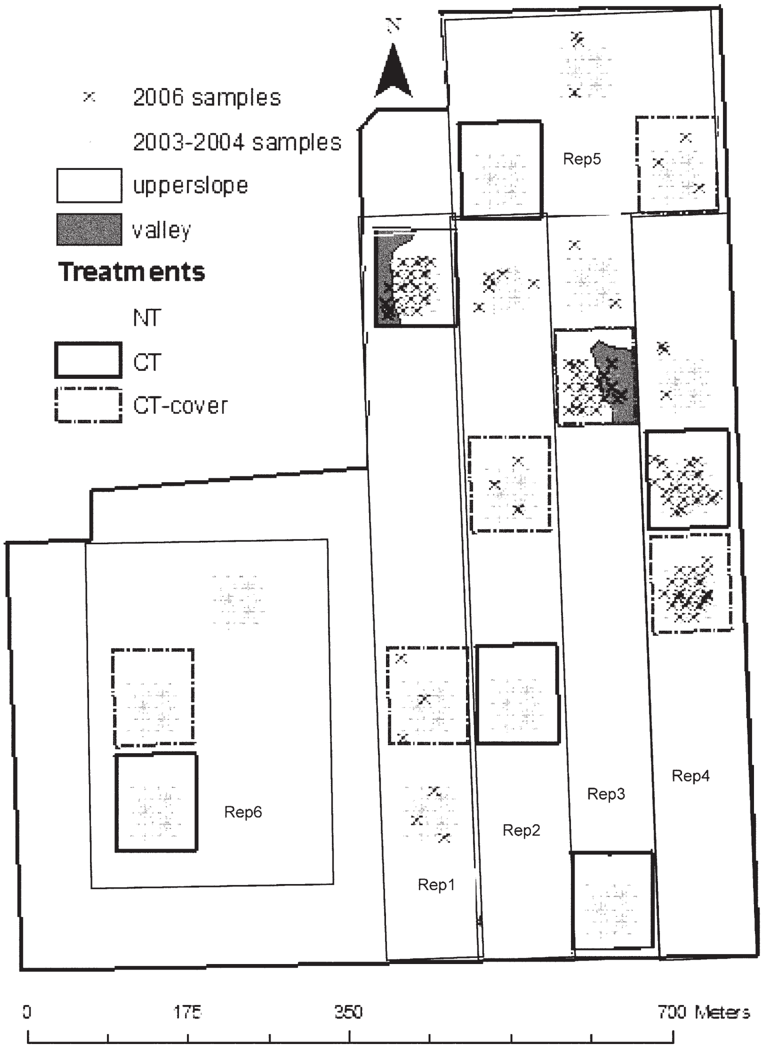

Fig. 1. Experimental layout showing plots that were sampled for this study in 2003 through 2004 and in 2006, and examples of landscape position classification in two of the studied plots.

Data Analysis

Data analysis was conducted using SAS (SAS Institute, 2001). Relationships between terrain attributes and soil C and N were studied using two different approaches.

First, the relationships between soil C and N with the terrain attributes in different treatments were evaluated by treating the terrain attributes as continuous variables via correlation and multiple regression analyses (results not shown) and analysis of covariance (ANCOVA). Preliminary correlation and multiple regression analyses indicated that WI was the terrain attribute that was most consistently related to total C and N as compared with other characteristics. Thus, WI was used as the terrain covariate in the subsequent ANCOVA. The analysis was performed using PROC MIXED procedure in SAS (Littell et al., 2002).

The ANCOVA statistical model included treatments and WI as fixed factors. Replications and plots nested within treatments were treated as random factors and plots were used as an error term for testing the treatment effects. Estimates of linear regression slopes from ANCOVA were obtained for each treatment for both total C and N. When an interaction between treatments and WI was found to be statistically significant ($\alpha = 0.05$), pair-wise comparisons were conducted between the regression slopes of the three treatments.

Table 1. Mean bulk density values at 0- to 15-cm, 20- to 30-cm, and 30- to 40-cm depths and a summary of terrain properties for the three studied treatments.

	Bulk density			Terrain attributes		
Treatment†	0–15 cm	20–30 cm	30–40 cm	Slope	WI	Flow§
	g cm^{-3}			°		
CT	1.45a‡	1.70a	1.69a	1.3	6.8	0.50
NT	1.50a	1.69a	1.69a	1.2	7.0	0.48
CT-cover	1.39a	1.56a	1.62a	0.9	7.0	0.34

† CT, conventional tillage; NT, no-till; CT-cover, conventional tillage (chisel-plowed) corn-soybean-wheat rotation with zero chemical inputs and leguminous cover crop.

‡ Means within each column followed by the same letter are not significantly different (α = 0.05).

§ Flow is the log transformed value of flow accumulation, which is calculated as accumulated weight for all cells that flow into each downslope cell.

For the second step of the analysis we grouped the locations with similar terrain attributes into specific landform elements using discriminant analysis (Bell et al., 1994; Kravchenko et al., 2002; Bakhsh et al., 2007). Each landform element had a distinct set of quantitatively defined topographical features (Pennock and Corre, 2001). In this study, we used two landform classes, for example, upperslopes and valleys, similar to the study by Macmillan et al. (2000). The upperslopes consisted of such geomorphic units as summit, sideslope, backslope and shoulder. The valleys included footslope and valleys.

In this site, landform class information and terrain attributes were available for 258 locations, which constituted a model data set for discriminant analysis. The landform classes at these locations were identified through a direct field survey by traversing along the contour lines in the landscape and along the points where a clear judgment could be made about the landform class; the specific landform class was recorded using global positioning system (GPS). Among the 258 locations, 156 were located in upperslope positions and 102 in valleys. Using the model dataset, classification rule was developed to predict each landform class for all the other locations that had terrain attribute data but where the landform class was unknown. Stepwise discriminant procedure, STEPDISC (SAS Institute, Cary, NC) was used to select the topographical variables that had significant contribution to landform class prediction. Relative elevation, WI, and flow accumulation were the variables found to be significant at $p = 0.15$ level and used in building the classification rule. A predictive model developed using the model dataset was then applied to the remaining data to place each point into the appropriate landform class. For that, the discriminant analysis determined the posterior probability for each observation to belong to each of the landform classes and the specific observation was assigned the landform class with the highest posterior probability (Johnson, 1998; Khattree and Naik, 2000). Cross-validation was applied to evaluate the accuracy of landform class predictions. For cross-validation each value from the model data set was eliminated in turn and, then, estimated using information from the rest of the data (Khattree and Naik, 2000; Kravchenko et al., 2002).

The relationship between soil C and N with topography in different treatments was assessed via two factor analysis of variance (ANOVA) with landform elements as a categorical variable. Effects of treatments and landform elements on total C and the interaction between them was quantified via PROC MIXED procedure. The statistical model included the treatments, landform elements, and their interaction as fixed factors; and replications, plots, and the interactions between the landform elements and treatments with replications as random factors. Plots nested within treatments were used as error terms for testing treatment effects. Interaction between landform elements, treatments, and replications were used as an error term for testing the landform effect and the landform by treatment interaction effect.

Table 2. Mean values of selected terrain attributes and soil texture characteristics for upperslope and valley landscape positions.

Landform class	Terrain attributes			Soil texture at					
				0–15 cm		20–30 cm		30–40 cm	
	Relative elevation	WI	Flow	Sand	Silt	Sand	Silt	Sand	Silt
	m	m^2 m^{-1}		g kg^{-1} soil					
Upperslope	0.7	6.4	0.2	420	420	440	290	590	190
Valley	0.2	8.1	0.9	320	490	450	290	470	330

RESULTS

Overall, there were no pronounced differences in terrain attributes of the studied treatments, but CT-cover sites tended to be slightly flatter than those of the other two treatments (Table 1). Bulk densities of the three treatments at all three studied depths were not significantly different from each other ($p > 0.2$).

As expected, the two landform classes obtained via discriminant analysis differed in their terrain characteristics and soil texture (Table 2). The upper slopes had higher relative elevation, lower WI, and lower flow accumulation values than the valleys. Upperslopes tended to have coarser texture with higher sand and lower silt contents, while finer texture characterized the valleys.

In ANCOVA with WI as a continuous covariate we observed significant interactions between treatment and WI for both C and N at the 0- to 5-cm depth ($p < 0.01$; Table 3). For both total C and N, the regression slope for CT-cover was higher than that of both chemical input treatments (CT and NT; $p<0.05$). In upperslope positions both total C and N were different among the three studied treatments with the highest values observed in NT followed by CT-cover and then CT, while in valleys CT-cover and NT were not significantly different from each other but greater than those of CT (Fig. 2a). There were no significant differences in both C and N contents between upperslopes and valleys in any of the three treatments (Table 4).

At the 0- to 15-cm depth, for total C the regression slope with WI in CT-cover was higher than that of CT, however, for total N there was no significant difference in regression slopes observed among the treatments (Table 3). In CT-cover both total C and N were higher than those of CT, while not significantly different from NT (Fig. 2b). However, the differences between them were lower in upperslope than in valley positions. Total C of NT was higher than that of CT in valleys, while there was no significant difference in total C between CT and NT in the upperslope positions. Total N of NT was higher than that of CT in both valley and upperslope positions. Unlike the 0- to 5-cm depth, the effect of position was statistically significant with higher total C and N observed at valley positions in both CT-cover and NT. However, there was no difference between the positions in CT treatment (Table 4).

At the 20- to 30-cm depth, for both total C and N the regression slopes with WI in CT-cover and NT were higher than in CT treatments. In upperslope positions, there were no significant differences among the three treatments in terms of both total C and N (Fig. 2c). However in valleys, CT-cover and NT had significantly higher C and N than CT. Similar to the 0- to 15-cm depth, at 20 to 30 cm there was a significant difference in C and N contents between upperslope and valleys in CT-cover and NT while not in CT treatment (Table 4).

For the 30- to 40-cm depth, positive regression slopes with WI were observed in NT for both total C and N ($p < 0.1$), while the slopes were not different from zero in either CT or CT-cover (Table 3). In upperslope positions there was no significant difference among the treatments in both total C and N. In valleys total C of NT was higher than that of CT and CT-cover ($p < 0.1$) (Fig. 2d). In NT, total C and N tended to be higher in the valley than in upperslope positions, while there was no difference between the two positions in either CT or CT-cover (Table 4).

For both total C and N for the entire 0- to 30-cm depth and for the 0- to 40-cm depth the stocks were positively related to WI, however the interaction between WI and treatments was not statistically significant. In both upperslope and valley positions, soil C at 0 to 30 cm was higher in CT-cover as compared with CT, while no significant differences were observed with NT treatment (Fig. 2e). There was no difference among the treatments in terms of either C or N stock across both positions at the 0- to 40-cm depth (Fig. 2f). For both total C and N the differences between upperslopes and valleys were not significantly different from zero in either of the treatments (Table 4).

At the 0- to 5-cm depth the variances for total C and N were the highest at NT with variances for total C and N in NT being equal to 7.5 and 0.083 respectively, followed by CT-cover and CT (variances for CT and CT-cover are shown in Table 5). These results are consistent with the results obtained previously from Replications 1 to 4 at the 0- to 5-cm depth (Kravchenko et al., 2006). The variances for total C of CT-cover were higher than those of CT at the 20- to 30-cm and the 30- to 40-cm depths. The coefficients of variation for total C tended to be lower in 0- to 5- and 0- to 15-cm samples but increased at the 20- to 30-cm and the 30- to 40-cm depths.

Analysis of spatial variability characteristics indicated that in the studied area total C and N contents of CT-cover were much stronger spatially structured than those of CT at all studied depths (Fig. 3, results for total N are not shown). At all studied depths, the variogram values at short lag distances constituted approximately 20% of the overall variability in total C and N from CT-cover, while short range variability constituted more than 70% of the overall variability in CT.

DISCUSSION

The ANCOVA with WI results indicate that at the soil surface (0–5 cm) presence or absence of fertilizer and cover crops affects the relationship between topography and total C and N. As expected, the regression slopes with WI were positive reflecting the overall tendency for higher total C and N in lower located areas. However, total C and N contents were more sensitive to topography in the organic treatment with cover crops (CT-cover) than in CT and NT as indicated by greater regression slopes. The overall results of comparisons between the conservational management practices and CT did not differ in upperslope and valley positions and in both landforms NT and CT-cover had higher total C and N than CT. The greater regression slopes with WI in CT-cover could in part be explained by more intensive tillage that is implemented in this treatment for weed control as compared with CT and NT practices. It has been shown in a number of studies that over time, tillage leads to soil displacement from upper landscape positions and soil accumulation at lower landscape positions (Li and Lindstrom, 2001; Ritchie et al., 2004, Kaspar et al., 2006). In this experiment in early summers of corn and soybean years, CT-cover undergoes weekly/biweekly weed control cultivations which might contribute to greater soil particle redistribution across landscape.

Table 3. Regression slopes obtained in ANCOVA for total C and N with wetness index (WI) as a covariate.

Treatment†	Number of samples	Total C	Total N
	Depth 0–5 cm, g kg^{-1}		
CT	485	0.23 a‡§	0.019 a
NT	548	0.38 a	0.014 a
CT-cover	583	0.69 b	0.047 b
	Depth 0–15 cm, g kg^{-1}		
CT	159	0.31 a	0.035 a
NT	22	0.32 ab	0.040 a
CT-cover	156	0.54 b	0.049 a
	Depth 20–30 cm, g kg^{-1}		
CT	158	0.16 a	0.015 a
NT	21	0.46 ab	0.037 ab
CT-cover	182	0.66 b	0.048 b
	Depth 30–40 cm, g kg^{-1}		
CT	28	0.05NS a	0.01NS a
NT	10	1.13 b	0.11 b
CT-cover	37	0.11NS a	0.02NS a
	Depth 0–30 cm, Mg ha^{-1}		
CT, NT, CT-cover	31, 15, 29	0.64	0.072
	Depth 0–40 cm, Mg ha^{-1}		
CT, NT, CT-cover	22, 5, 21	0.57	0.093

† CT, conventional tillage; NT, no-till; CT-cover, conventional tillage (chisel-plowed) corn-soybean-wheat rotation with zero chemical inputs and leguminous cover crop.

‡Regression slopes not followed by NS are significantly greater than zero ($\alpha = 0.05$).

§ Regression slopes in the same depth group followed by the same letter are not significantly different from each other ($\alpha = 0.05$).

After conversion to NT, topographical influence on soil erosion and particle redistribution is reduced as a result of lower soil disturbance, increased water permeability, and larger amount of crop residues remaining on the surface. Increased soil aggregation in NT is one of the mechanisms reducing erosion and increasing soil C. In a review of studies that compared NT with other tillage systems, Franzluebbers (2004) concluded that water-stable macroaggregates tend to be more abundant in soils under no-till as compared with other tillage systems. Increased numbers of water stable aggregates in NT lead to accumulation of soil organic matter within macroaggregates and protects soil C from faunal action and microbial consumption (Beare et al., 1994a, 1994b; Six et al., 2000a) producing aggregates enriched in fine particulate organic matter which are more resistant to decomposition (Six et al., 2000b). It has been noted that after implementation of NT, landforms susceptible to erosion, such as upperslopes, may improve soil quality more due to improved moisture retention characteristics and soil structure, leading to greater C accumulations than in depression areas (VandenBygaart et al., 2002). Greater difference in organic C between NT and conventional tillage at shoulder positions than any positions has been observed by Elliott and Efetha (1999) in Saskatchewan. Our observations of the highest soil C and N at the 0- to 5-cm depth observed in NT at upperslope positions as compared with valleys, where NT was not greater than CT-cover (Fig. 2a) are consistent with the previous reports.

The same tendency for greater regression slopes with WI in CT-cover persisted at the entire 0- to 15-cm depth and at the 20- to 30-cm depth. However, unlike the 0- to 5-cm depth, there

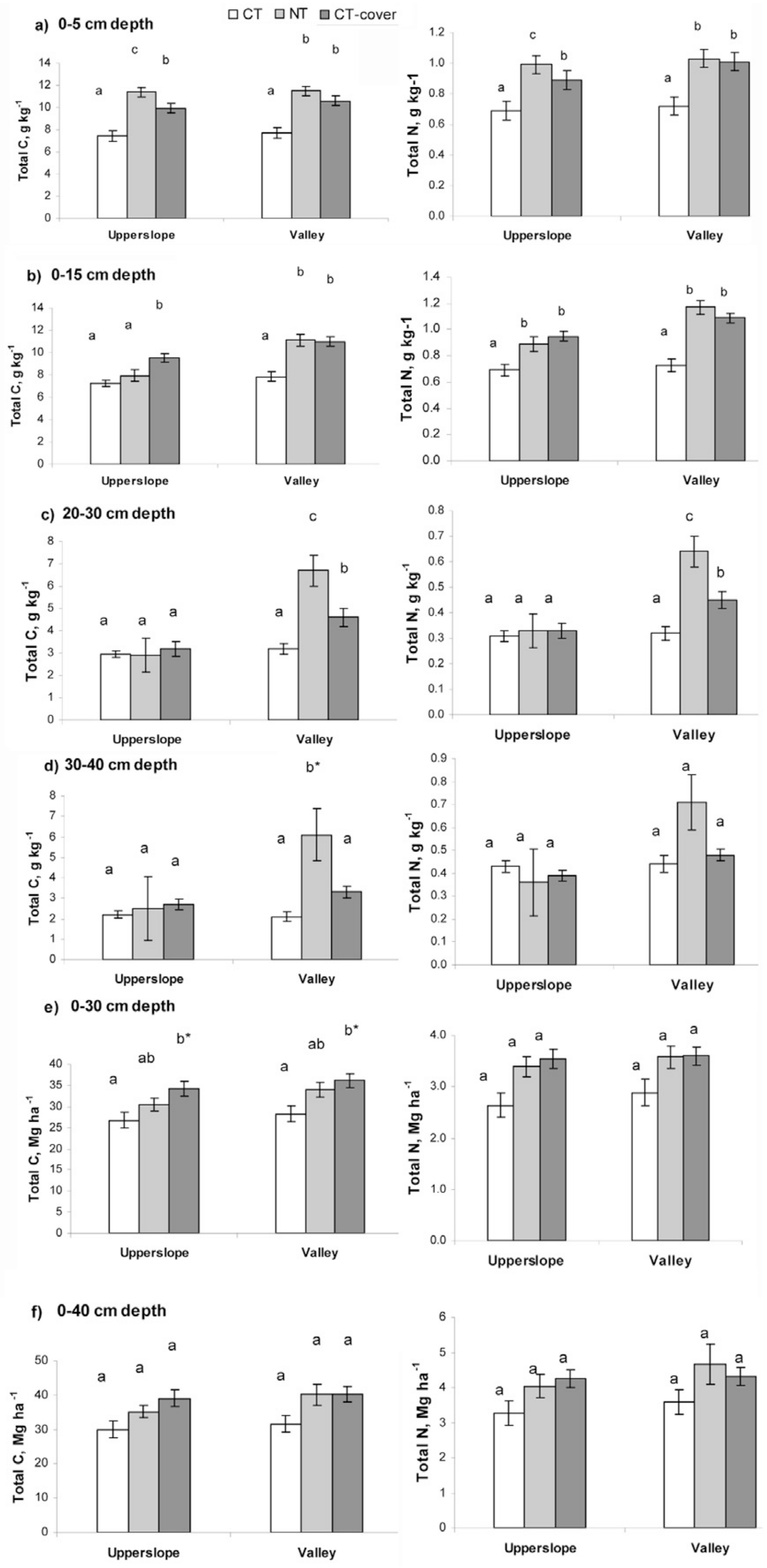

Fig. 2. Total C and N contents at upperslope and valley landscape positions in the three studied agronomic management practices at (a) 0- to 5-cm, (b) 0- to 15-cm, (c) 20- to 30-cm, and (d) 30- to 40-cm depths and total C and N stocks at (e) 0- to 30-cm and (f) 0- to 40-cm depths. Management practices within the same landscape position with the same letter are not significantly different from each other ($p < 0.05$). The means within the same landscape position that were different from each other with $0.05 < p < 0.1$ are marked with *.

was a significant interaction between landform position and management practice. The interaction first became visible at the 0- to 15-cm depth and then became very pronounced at the 20- to 30-cm depth. At the 0- to 15-cm depth total C in CT-cover was only slightly higher than that of CT, while in valleys both CT-cover and NT had much greater total C than CT. At the 20- to 30-cm depth, there was no difference between the treatments in upperslopes while conservational practices had much higher total C and N in the valleys. Since in a chisel plow system the tillage affects only the top 0 to 20 cm of soil, at 20 to 30 cm, the C and N contents are driven by quantity and quality of below ground biomass inputs. The stronger topographical effect in CT-cover at 20- to 30-cm depth might be explained by substantially better growth conditions provided to cover crops at valleys as compared with upperslope positions. Upperslopes are characterized by coarser-textured soil (Table 2), less favorable moisture conditions, and lower inherent organic matter content, which might have restricted cover crop rooting patterns and activities to a much shallower depth (Villamil et al., 2006). Water redistribution and water availability along the landscape affects performance of both main and cover crops. Analysis of cover crop growth patterns in the fields adjacent to the LTER experiment indicated that in the studied area in dry years valley sites have a substantially better cover crop stand and larger N inputs from cover crops than upperslope areas (Munos et al., 2008). Thus lower belowground biomass and lower C inputs occurred at the 20- to 30-cm depth in upperslopes as compared with dense and deeper rooting patterns and greater C inputs in valley positions.

Many studies reported no gains or even losses in organic matter at below soil surface after switching to NT (e.g., Dick and Durkalski, 1998; Wander et al., 1998; Dolan et al., 2006; Hermle et al., 2008). Reduction in supply of plant residue inputs to greater depths in the absence of tillage is believed to be the main reason for the observed phenomenon. The upperslope position results for total C and N contents of this study are consistent with these reports. However, an opposite trend of greater C and N at greater depths in NT also has been reported (e.g., Deen and Kataki, 2003; Terra et al., 2005; Dou et al., 2007; Yoo et al., 2006b). Huggins et al. (2007) observed a substantially lower C under moldboard plow treatment than under NT at the 30- to 45-cm depth in one of the studied cropping systems, the continuous corn. This trend is consistent with our observations from valley positions. Leaching of soluble organic compounds from the surface layer is one of the mechanisms that contribute to C increases in NT at lower depths. Dou et al. (2007) observed higher levels of dissolved organic

C under NT as compared with CT in sorghum–wheat–soybean rotations up to the depth 55 cm in a 20-yr-old experiment in silty clay loam soil in Texas. Dissolved organic C levels are often found to be proportional to the overall soil organic matter content (Gregorich et al., 2000; Chantigny, 2003), thus being higher in the surface soil at NT they could then be transported to greater depths rather quickly in the relatively coarse-textured soil of this study. In valley soils the higher organic inputs to greater depths through either roots or as dissolved organic C are subjected to overall slower decomposition rates. A commonly observed tendency under NT is lower temperatures and greater soil moisture contents (e.g., Johnson and Lowery, 1985). This tendency can be expected to be much stronger in valleys, thus further reducing decomposition rates. Thus, our study indicates that numerous inconsistent results of no-till/tillage comparisons for soil C at below-plowing depths reported in literature are in some measure reflecting the presence of the interaction between tillage and topography.

Total C and N stocks at the 0- to 30-cm depths were significantly greater in CT-cover than in CT in both upperslopes and valleys. These results are consistent with results from multiple studies who reported systems with cover crops having greater C and N levels (Varco et al.., 1987; Sainju and Singh, 2001; Villamil et al., 2006). Teasdale et al. (2007) found that organic based tillage system with winter cover crops was as effective in gaining C as NT despite the heavy soil disturbance by tillage. Their observation is strongly supported by our data.

Lack of statistically significant differences among the treatments for 0- to 40-cm stocks is related to smaller sample size (Table 3) and greater variability in C and N measurements at greater depths. For example, the coefficients of variation for total C were equal to 18, 25, and 20% for CT, NT, and CT-cover treatments at the 0- to 15-cm depth, while they increased respectively to 29, 73, and 36% at the 30- to 40-cm depth.

Table 4. Differences in total C and N between valley and upperslope landform positions for conventional tillage (CT), no-till (NT) and CT (chisel-plowed) corn-soybean-wheat rotation with zero chemical inputs and leguminous cover crop (CT-cover treatments).

	Total C			Total N		
Depth, cm	CT	NT	CT-cover	CT	NT	CT-cover
		g C kg^{-1} soil			g C kg^{-1} soil	
0–5	0.3	0.1	0.7	0.03	0.04	0.12
0–15	0.6	3.2*†	1.5*	0.07	0.25*	0.11*
20–30	0.2	3.9*	1.4*	0.01	0.31*	0.12*
30–40	–0.1	3.6	0.6	0.00	0.35	0.09
			Mg C ha^{-1} soil			
0–30	2.2	3.6	2.1	0.25	0.19	0.06
0–40	1.6	4.9	1.1	0.31	0.62	0.06

† The differences that are significantly different from zero are marked with '*' ($p < 0.05$).

Table 5. Variances/coefficients of variation for total C and N in conventional tillage (CT) and in chisel-plowed corn–soybean–wheat rotation with zero chmical inputs and leguminous cover crop (CT-cover) treatments at th studied depths.

	Total C, g kg^{-1}		Total N, g kg^{-1}	
Depth	CT	CT-cover	CT	CT-cover
0–5 cm	1.8/19a†	4.2/20b	0.023/22a	0.042/22b
0–15 cm	1.5/17a	3.0/17b	0.019/18a	0.023/15a
20–30 cm	0.6/25a	3.1/44b	0.005/23a	0.018/36b
30–40 cm	0.4/29a	1.2/36b	0.011/24a	0.013/26a

† Variances within the same depth followed by the same letter are not significantly different from each other ($p < 0.05$).

To assess the size of the differences in total C and N stocks at the 0- to 40-cm depth that could be detected as statistically significant in our study we conducted a post-hoc power analysis using the variance estimates from the studied data and probabilities of Type I and Type II errors of 0.05 and 0.10, respectively. The estimates of variances due to plots, landscape positions within the plots, and individual samples within the plots (residual variance) for C stock were equal to 11.0, 2.0, and 12.0, respectively. With this amount of observed variability and the number of available soil samples the difference in total C stocks between two treatments that could be detected as statistically significant is equal to

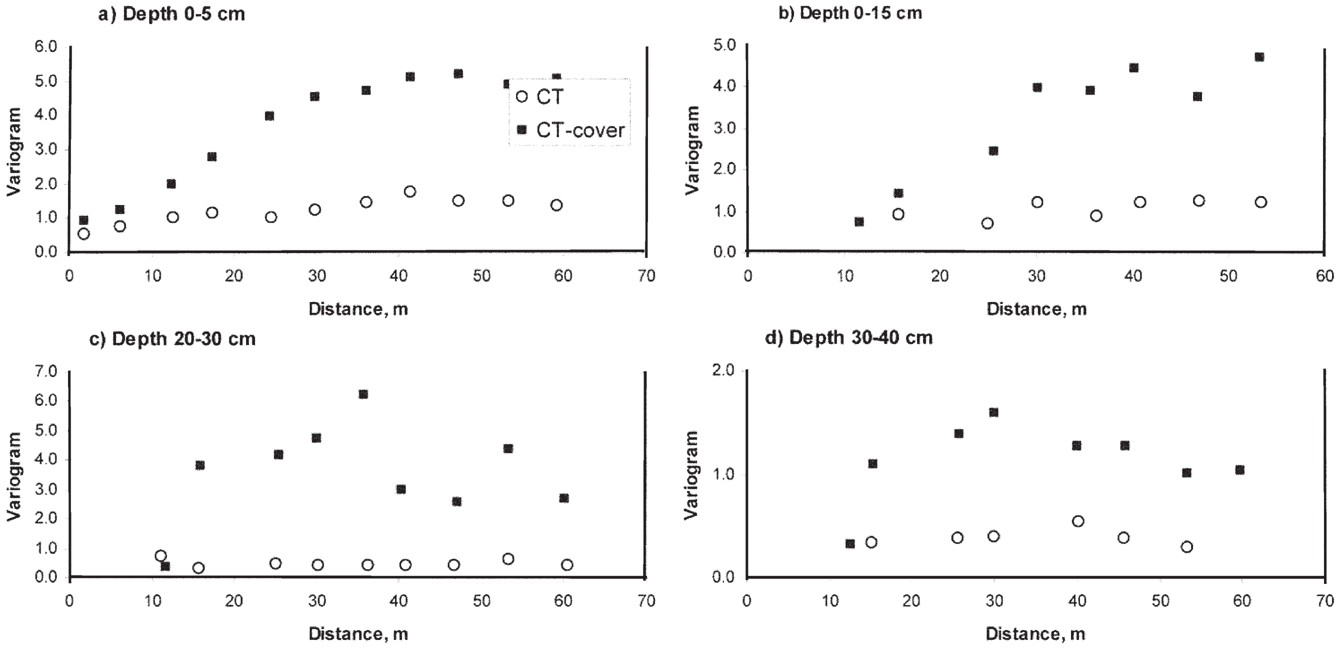

Fig. 3. Sample variograms for total C content data from conventional tillage (CT) and CT-cover treatments.

26 Mg C ha^{-1} soil. This is almost doubling the observed C stock levels and it would be highly unrealistic to expect such a marked increase in soil C stock after <20 yr of an agricultural experiment. Estimates of variance components for N 0- to 40-cm stock were equal to 0.208, 0.001, and 0.122 and the minimal detectable difference between the treatments was as high as 3.2 Mg C ha^{-1} soil. Obviously, a substantially greater number of samples would be necessary to be able to detect smaller differences among the treatments at the 0- to 40-cm depth, if such smaller differences indeed existed in the study.

The spatial variability analysis results at the 0- to 5-cm depth were consisted with those reported by Kravchenko et al. (2006) for Replications 1 through 4 data. The spatial structure of CT-cover was notably greater than that of CT indicating that patterns in spatial distribution of total C across the landscape were more pronounced in CT-cover management system. A tendency for stronger spatial patterns in CT-cover persisted at the 20- to 30- and at the 30- to 40-cm depths. The greater spatial diversity of total C in CT-cover appears to be related to variations in topography. In the CT-cover plants do not received chemical fertilizers and thus are more susceptible to stresses, including those related to topography driven variations in moisture and nitrogen. Stronger spatial patterns in plant biomass inputs are likely to lead to stronger patterns in soil C.

SUMMARY AND CONCLUSIONS

For both C and N tillage and management practices significantly interacted with topographical features as represented by WI. Regression slopes with WI were greater at organic based tillage treatment than in the chemical input based no-till and chisel plow systems. At the 0- to 5-cm depth total C and N contents of NT and CT-cover managements were greater than that of CT in both upperslopes and valleys. At the 0- to 15-, 20- to 30-, and 30- to 40-cm depths the treatment effects on soil C and N contents varied markedly depending on the landscape position. The treatment effects were lower or negligible in upperslopes while larger differences among the treatments were observed in valleys. In valleys, C and N contents tended to be substantially higher in NT and CT-cover than in CT. Our study indicates that the interaction between tillage and topography is one of the possible explanations of the contradictory results of no-till/tillage comparisons at below-plowing depths reported in numerous studies. For example, consistent both with those who did and did not observe the increase in soil C concentration at below plow depths, in our study at the 20- to 30-cm depth we saw no difference between CT and NT in upperslopes as well as soil C being greater in NT than CT in valleys.

Total C and N stocks at the 0- to 30-cm depths tended to be the highest in CT-cover followed by NT and then by CT in upperslopes and valleys. Overall, the organic-based management with legume cover crops (CT-cover) was found to be as efficient in maintaining C and N content as no-till with conventional chemical inputs. Note that the variations in topography at the studied site were relatively minor. The fact that a number of significant topographical and treatment/topography interaction effects were observed even in such relatively flat landscape indicates the importance of accounting for interacting topographical effects in evaluating C sequestration performance of different land use and land management practices.

Power analysis indicated that the number of samples collected in this study was inadequate to detect the differences among the treatments in terms of the 0- to 40-cm profile C and N. Given higher variability in total C and N stocks at greater depths, the 10 to 30 samples per treatment available in this study would only be sufficient for detecting the changes in C and N if the differences between treatments were as high as 80% (26 Mg C ha^{-1}). However, such sample size would be useless for detecting any smaller differences.

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