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EFFECT OF TOPOGRAPHY AND SOIL PROPERTIES
ON SPATIAL VARIABILITY OF SOIL CARBON(C)
LOSS IN DIFFERENT CROP MANAGEMENT
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EFFECT OF TOPOGRAPHY AND SOIL PROPERTIES ON SPATIAL VARIABILITY OF SOIL CARBON(C) LOSS IN DIFFERENT CROP MANAGEMENT SYSTEMS OF A LONG-TERM EXPERIMENT

By

Senthilkumar Subramanian

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ABSTRACT

EFFECT OF TOPOGRAPHY AND SOIL PROPERTIES ON SPATIAL VARIABILITY OF SOIL CARBON(C) LOSS IN DIFFERENT CROP MANAGEMENT SYSTEMS OF A LONG-TERM EXPERIMENT

By

Senthilkumar Subramanian

Accurate quantification of total soil C is needed to assess the sequestration potential of different management systems; however the accuracy in estimating soil C to determine best management practices is affected by the inherent variability of soil properties. I hypothesized that spatial variability present in soil C distribution across landscape to a large extent is related to topographical gradients; and that tillage and management practices might further buffer or intensify the influence of topography on C variability. The study was carried out at the Long Term Ecological Research site at Kellogg Biological Station, Michigan. In this work, I analyzed the effects of topographical features, soil properties and different management practices on soil C dynamics and characterized spatial variability pattern in soil C distribution in each management system. Treatments studied were short rotation woody perennial system (poplar) and agronomic systems including chemical input based chisel-plow (CT), no-till (NT) system and organic based chisel-plow system with cover crops (CT-cover). As hypothesized, spatial variability characteristics of the soil C in the agronomic treatments, but not in the poplar systems, were strongly affected by topographical gradients. Within agronomic system, topography effect was stronger in organic based chisel-plow system with cover crops (CT-cover) compared to chemical input

based chisel-plow (CT) and no-till (NT) system. After controlling the topographical effect, the greatest difference in terms of spatial variability characteristics between poplar and agronomic systems was observed in variogram values near the origin. Results indicated that in poplar, C is much more variable at very short distances as compared to agronomic systems. Total C and overall variability in C observed at poplar was found to be similar to that of NT, and slightly greater than CT-cover and differs substantially only with CT. Among the agronomic systems, CT-cover was as efficient as the NT system in restoring C and N and the largest C and N benefits of CT-cover in the landscape were observed in valleys as compared to upper slope positions. The net changes in soil C content that occurred in the past 15-20 years under different agricultural management practices and in never tilled soils were estimated after accounting for the variations in baseline C, soil texture and topographical features among the studied treatments. Results indicated that soil C has decreased by about 10 percent at conventional chisel-plow management soil since 1986. No-till and organic based chisel-plow system neither gained nor lost C as compared to the baseline values (1986-88). Baseline C was found to be negatively related with changes in C content and C loss was found to increase with increase in baseline values. Higher silt and clay contents were associated with greater gains in C in no-till system. Over all results demonstrated that the conservational management practices have prevented total C loss as compared to conventional management but there was no net gain in C over the past two decades in the studied Michigan soils.

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Chapter I

INTRODUCTION

Soil carbon is considered as an index for soil quality and crop productivity and also plays an important role in the global carbon(C) cycle. C content varies across landscape as a result of complex interactions among different factors including topographical attributes, inherent soil properties and land use and management practices. A well replicated long term experiment with known site and management histories and organized along different management intensity gradient based on soil disturbance, chemical inputs and cropping intensity will provide greater advantage for understanding the complex interactions between various factors that control the variability in soil C distribution in a landscape.

Among the various soil forming factors, topography or local relief is one of the major factors contributing to the spatial variability of soil carbon (C) and nitrogen (N) content at the field level. Local relief regulates soil C distribution by means of altering soil moisture, nutrient transport, leaching and mineralization rate. General topographical influences on soil C related processes are likely to differ in magnitude under different tillage and agricultural systems. With the advancement in GIS and GPS technology, topographical information can now be more precisely obtained and even a small depression or a micro level undulation in a field plot can be well represented in digital elevation model (DEM) based on the topographical information. This information provides greater advantage for exploring the relationship between topography effects on soil C variability at a field scale. The overall goal of the present study was to study the effects of topographical features, soil properties and different management practices on soil C dynamics and to characterize spatial variability pattern in soil carbon distribution in each management system.

The first objective was to assess the potential of a short rotation woody perennial (poplar) system in managing soil C as compared to agronomic systems and to characterize the effects of management practices and topographical features on spatial variability patterns at each of the studied systems. The magnitude of spatial variability varies mainly with level of tillage disturbance and cropping intensity. The inclusion of spatial variability characteristics will improve the precision of the treatment estimate, while comparing different management systems.

In the present study, to characterize spatial variability patterns about 600 soil samples from each agronomic treatment and 500 samples from poplar were collected from the surface soil (0-5 cm) during 2003-2004. Treatments studied were chisel plow (CT) and no-till (NT) with conventional chemical inputs, chisel-plow organic management practice with cover crops (CT-cover), and poplar. In addition to surface depth, C measurements were also obtained from the soil samples collected at below plow depth (20-30 cm) during 2006 from CT and CT-cover and compared with the spatial distribution in soil C observed at surface depth (0-5 cm).

Spatial variability for each treatment was characterized using geostatistical techniques. Sample variograms were computed for the raw C, N data and for the residuals obtained from the regression models with topographical features using PROC VARIOGRAM procedure in SAS. Variogram models were fitted using weighted least square in PROC NLIN with spherical, Gaussian, and exponential models and the model that provided the smallest mean square error was selected. Overall treatment variance, sill values, variogram values at 1.5 m distance to sill ratio and spatial correlation range were used to compare the spatial variability pattern among the treatments.

The second objective was to determine interactions between topographical features and tillage and management systems on soil C and N and to identify the landform elements that lead to most rapid and effective C sequestration in each management system. At a field scale, the magnitude of soil C variability depends on the tillage practice and is strongly affected by topography and amounts of plant residue returned to soil. Topography, tillage gradient and C residues inputs may interact in a number of ways on soil C and the influence of topography will be either subsided or intensified by different tillage and crop management practices. Though a number of studies addressed the relationships between topography and soil C and tillage effects on soil C, still there is only limited information on how topography and soil C are related under different tillage practices and different management systems. In this study, relationships between topography and total C and N levels under a no-till system, conventional tillage system, and organic based tillage systems were compared in a replicated long-term field experiment. The study was conducted at the Long Term Ecological Research (LTER) site, at Kellogg Biological Station, in southwest Michigan. Treatments used in the study were conventional tillage (chisel plowed) with conventional chemical inputs (CT), no-till with conventional chemical inputs (NT), and organic chisel plowed system with a winter leguminous cover crop (CT-cover). Interaction effects between topographical features and tillage and management systems on soil C and N was tested first, with wetness index (WI) a compound topographical index as a continuous variable using analysis of covariance (ANCOVA) and second, using topographical information as categorical variable by grouping similar class of terrain attributes into specific landform elements namely, upperslope and valley using discriminant analysis. Then the relationship between soil C and N with topography in different treatments was assessed via a two factor analysis of variance with landform elements as a categorical variable. Landform elements that lead to most rapid and effective C sequestration in each management system were identified.

The third objective was to examine the net changes (gain or losses) in C contents under different management systems that have taken place over a period of 15-20 years from the historic (baseline) C values in Southern Michigan. Various soil properties such as baseline C levels, soil texture, topographical features and climatic factors that drive the change in C content were also explored. Dense geo-referenced historic C values (1986-88) for C measurements were available for both the experimental sites collected prior to the establishment of the experiment, which served as baseline C in this study. Contemporary samples collected during 2006-2007 were compared with historic C values (1986-88) to assess the absolute changes, such as losses or gains in different management systems.

Relationships between the changes in soil C and baseline values were conducted with accounting for the regression to the mean phenomenon (RTM). Changes in soil C and potential differences in relationships between the changes in soil C and the baseline C values under different management systems were studied using analysis of covariance (ANCOVA) with baseline C as a covariate to control the variability in baseline C status and to improve the precision of treatment estimates.

Chapter II

SPATIAL VARIABILITY OF SOIL C, N CONTENT IN POPLAR AND IN DIFFERENT ANNUAL CROPPING SYSTEMS IN A LONG TERM EXPERIMENT

ABSTRACT

Lack of accounting for the spatial variability in soil carbon distribution may cause uncertainty in treatment estimates of soil C gains or losses. In the present work, the relative efficacy of a poplar system in managing soil C was compared to agronomic systems under row crop agriculture and characterized the spatial variability pattern at all the studied management systems. The objectives of the study were to: (i) compare the surface total C content (0-5 cm) of a 15 year old poplar plantation with three commonly practiced annual cropping systems, chisel plow (CT), no-till (NT) with conventional chemical inputs, and a chisel plow organic system with a winter leguminous cover crop (CT-cover); (ii) characterize the effects of management practices and topographical features on spatial variability patterns in soil C with the poplar system and compare its variogram characteristics with those of the agronomic treatments; and (iii) compare the spatial variability patterns in C observed at the soil surface (0-5 cm) and below plow depth (20-30 cm) in CT and CT-cover. The study was conducted at the Long Term Ecological Research site at the Kellogg Biological Station in southwest Michigan. Total C measurements were obtained from the soil samples collected at 0-5 cm depth during 2003-2004 and at 20-30 cm from CT and CT-cover during 2006. Total soil C under poplar management (11.8 g kg $^{-1}$ soil) was significantly greater than that in CT (7.4 g kg $^{-1}$ soil) and CT-cover (10.2 g kg $^{-1}$ soil) however the difference with NT (11.4 g kg $^{-1}$

soil) was not statistically significant ($p<0.05$). The mean N values for poplar (1.1 g kg $^{-1}$ soil) was significantly greater than that of CT (0.67 g kg $^{-1}$ soil) and CT-cover (0.93 g kg $^{-1}$ soil), but not of NT treatment (1.01 g kg $^{-1}$ soil) ($p<0.05$). At the soil surface depth (0-5 cm), overall total C, N variability was found to be closely similar to that of NT followed by CT-cover system and substantially different from that of CT.

Spatial variability for each treatment was characterized using geostatistical techniques. In poplar, variogram values of C at 1.5 m distance to sill ratios were greater compared to agronomic treatments which show that C is highly variable at very shorter distance, compared to other agronomic systems. Variability characteristics of the total soil C in the studied plots were strongly affected by topographical gradients except in the poplar system.

Comparing the variability between surface (0-5 cm) and below plowing (20-30 cm) depth, with CT, spatial correlation range, nugget and sill values at surface depth is substantially greater compared to below plowing depth indicating greater variability in the surface depth compared to below plowing depth. However with CT-cover, variability in C distribution pattern was found to be greater even at below plow depth. Topographical features have a greater effect on controlling the spatial correlation with CT-cover system compared to CT at both studied depths.

In summary, poplar system did not differ substantially with the annual crop no-till system in terms of soil C, N content and in overall C and N variability pattern in a landscape.

INTRODUCTION

Currently the Green House Gas (GHG) reduction initiative has taken a new paradigm of research by testing the feasibility of different crops in energy production as sources for biofuel feedstock. With the growing energy crisis and increased awareness of global warming issues, the spectrum of bioenergy crops may be expanding in the near future. Bioenergy crops have the greatest potential to supply a major portion of U.S and global energy needs while reducing the rate of enrichment of atmospheric CO_2 (Lemus and Lal 2005). They projected about 60 million hectares (Mha) of land are available in US to grow bioenergy crops, which can sequester approximately 318 Million Metric tons or Tg C per year. In this context, growing poplar (*Populus* Sps.) is considered to be one of the conservative land management alternatives that have good potential in enhancing soil quality in marginal lands and mitigating CO_2 emissions. At the same time, poplar is considered to be one of the potential bioenergy crops suitable for North Central region. The U.S. Great Lakes Bioenergy Research Center (GLBRC) included poplar systems as one of the novel production system for biofuel production along with various agronomic systems.

Accurate quantification of total soil C is needed to assess the sequestration potential of poplar along with that of other agronomic systems. Currently only a few studies reported the relative efficacy of carbon sequestration potential of a poplar plantation compared with conventional agricultural system (Coleman et al., 2004; Degryze et al., 2004; Sartori et al., 2006, Grandy and Robertson, 2007). Poplar system of 12- to 18- year-old sequestered 1.6 Mg C ha^{-1} yr^{-1} more C than the adjacent agronomic treatments based on 11 sites across North Dakota, Minnesota, Iowa and Wisconsin (Sartori et al., 2006). In contrast, at North central region on compiling data from 27 study sites, Coleman et al. (2004) reported SOC from poplar fields did not differ significantly from that of agricultural crops except when poplars are placed in marginal soils. Accuracy in estimating C content in poplar systems is greatly hindered by the larger spatial variability in soil C content as compared to agronomic systems. Robertson et al. (1997) mentioned that spatial variability in soil properties in cultivated soils varied substantially from the uncultivated sites both in magnitude and spatial scale. Stoyan et al. (2000) reported that plant root and plant residue patterns are the main factors that control soil heterogeneity at micro scales of about 2 m^2. Based on the study conducted in the same site, Kravchenko et al. (2006) characterized the spatial variability of soil C in agronomic treatments and demonstrated that spatial correlation was strongest in no-till (NT) followed by cover crop based organic tillage (CT-cover) and conventional till (CT). The authors found that lack of soil mixing in NT and greater variability in biomass inputs with cover crop based organic tillage systems contribute to the increase in spatial variability in both treatments. Even though the spatial variability of soil C in individual fields and in different tillage and management system has been assessed in a number of studies (Robertson et al., 1993,1997, Bergstorm et al., 2001; Kravchenko et al., 2006) the information about how the spatial variability of soil C in a perennial system differs from the soils under agricultural treatments is largely unknown. Gathering such information will be useful in improving the precision of the C estimate while comparing poplar system with other agronomic management system and for adopting an efficient sampling strategy.

Poplar systems differ from agronomic treatments in a number of ways. Poplar receives no soil disturbance compared even with no till system, where the soil is subjected to minimum soil disturbance during planting, harvest and herbicide application. Elimination of soil mixing with NT was reported to increase C variability in the topsoil C distribution (Paustian et al., 2000; Kravchenko et al., 2006). Quantity and quality of above ground and belowground biomass produced by poplar system was found to be much different from agronomic crops. Cook and Beyea (2000) reported that poplar produced 8.0 Mg C ha^{-1} yr^{-1} of above ground biomass as compared to 5.4 Mg C ha^{-1} yr^{-1} produced by corn (*Zea mays*). In poplar, the trees are planted up to 4 meters apart as compared to closely and uniformly planted corn or soybean plants in agronomic treatments, which might also substantially influence the spatial distribution of C inputs within the plot. In poplars, the soil surface close to the main tree stem will have a dense network of roots which might receive more C inputs from the root exudates and dead roots compared to the soil surface farther from the trunk. Aboveground C inputs from the leaf litter in poplar will be generally clustered in small pockets within the experimental plot distributed based on the preferential wind directions, as compared to relatively evenly spread of residues on the surface in NT or in conventional tillage systems. This heterogeneity in C inputs will influence the mineralization and C turnover ratio within the landscape/plot which in turn may result in greater variability of soil C in poplar as compared to agronomic systems.

Considering lack of soil disturbance and larger spatial heterogeneity in distribution of both aboveground and belowground C inputs, I hypothesize that overall variability and spatial dependence in soil C distribution in poplar system is greater than that in agronomic systems including NT and organic based conventionally tilled treatment with cover crops. To test this hypothesis, the spatial variability patterns in C, N content (0-5 cm) in the poplar system was compared with 3 agronomic treatments in a replicated long-term (15 years) experiment at Kellogg Biological Station Long Term Ecological Research (LTER) site.

The variability in soil C distribution also expected to be different between the soil and deeper soil horizons. Many long term experiments reported substantial decrement in C content from surface to subsurface depth (Yang and Wander, 1999; Dou et al., 2006). The stratification of C content at different depths is mainly influenced by differences in tillage and cropping intensity. In this study, in addition to the soil surface, the spatial variability pattern at 20-30 cm depth was also examined in CT and CT-cover. Considering the lack of soil disturbance and lesser fluctuations in soil moisture and temperature at below plow depth (20-30 cm) compared to the soil surface, I hypothesize that overall variability and spatial dependence in soil C distribution will be much less at the subsurface depth compared to the soil surface, and the variability pattern at organic based conventionally tilled treatment with cover crops must be greater than the conventional tillage system. To test this hypothesis, the spatial variability in C observed at the soil surface (0-5 cm) was compared with the spatial variability in C observed at below plowing depth (20-30 cm) with CT and CT-cover.

The objectives of this study were :

1. To compare changes in soil C at 0-5 cm depth in a 15-year second ratoon poplar system with three agronomic treatments, namely:

   a. chisel-plowed with conventional chemical inputs (CT),

   b. no-till with conventional chemical inputs (NT), and

   c. organic chisel plowed system with a winter leguminous cover crop and zero chemical inputs (CT-cover).

2. To characterize spatial variability patterns in soil carbon at 0-5 cm depth under a 15-year poplar system and compare its variogram characteristics with those of the agronomic treatments.

3. To characterize spatial variability patterns in soil carbon at 20-30 cm depth under organic conventional system with cover crops (CT-cover) and to compare it with chisel-plowed conventional chemical inputs (CT).

MATERIALS AND METHODS

Test Site

The study was conducted at the Long Term Ecological Research (LTER) site, at Kellogg Biological Station (KBS), in southwest Michigan (85°24' W, 42°24' N) established in 1988. Soils at this site belong to Typic Hapludalfs of the Kalamazoo (fine-loamy, mixed, mesic) and Oshtemo (coarse-loamy, mixed, mesic) series (Mokma and Doolittle, 1993). The site receives approximately 90 cm annual precipitation, with about half as snow and the mean annual temperature is 9°C (Grandy and Robertson, 2007).

Experimental Layout and Agronomic Protocols

The LTER experimental layout is a one-factor randomized complete block design with six replications and seven treatments organized along a management intensity gradient based on tillage intensity, external inputs and net primary productivity (Grandy and Robertson, 2007). The experiment was started at 1989, prior to that the studied site had been conventionally managed in row-crop agriculture for at least a century (Robertson et al., 1997). Treatments relevant to this study include three agronomic annual systems on corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.]–wheat (*Triticum aestivum* L.) rotation and one perennial system under poplar trees (*Populus x euramericana c.v Eugenei.*) The agronomic treatments studied were chisel-plowed with conventional chemical inputs (CT); no-till with conventional chemical inputs (NT); and certified organic chisel plowed system with winter leguminous cover crops and zero chemical inputs (CT-cover). The poplar system consists of short-rotation poplar clones which are grown since 1988 on a 10 year rotation cycle. Among the three studied systems, poplar is subjected to the least soil disturbance and CT-cover management had the greatest amount of mechanical disturbance. CT-cover in addition to chisel-plowing, is subjected to soil disturbance due to weed control achieved by weekly-biweekly rotary cultivations early in the growing season. The cover crops of the CT-cover treatment were hairy vetch (*Vicia villosa* Roth) from 1989 to 1993 and red clover (*Trifolium pratense* L.) from 1994 onwards. The cover crops are generally incorporated in April or May before corn or soybean planting. The complete site description, experimental design, and management protocols are available at the KBS website (Kellogg Biological Station, 2007).

Soil Sampling

Soil sampling was carried out during 2003-2006 and consisted of 2 sample sets. The first set of soil samples was collected at 0-5 cm depth in 2003-04 and the second set of samples was collected at 20-30 cm depth in 2006. The first set included soil samples at 0-5 cm depth collected from replications 1 through 4 during May of 2003 for CT, NT and CT-cover; and soil samples collected from replication 5 and 6 from CT, NT and CT-cover and from all the replications from poplar treatment (except replication 3) in May of 2004. Description of soil sampling during 2003 and 2004 is provided in Table 2.1a.

In poplar treatment soil samples were not collected from replication 3 since the tree population was not well established due to severe erosion during establishment year. In both years CT and CT-cover treatments were plowed approximately 2 weeks prior to sampling. The sampling scheme followed at the agronomic treatments is shown on Fig. 2.1 (Kravchenko et al., 2006). Each experimental plot is about 80 by 100 m in size. To avoid plot boundary effects and the long-term protected portions of the plots restricted to sampling, the sample collection has been limited to the center 60- by 60-m portion in each experimental plot. Approximately 100 georeferenced soil samples were collected from each plot. Among the 100 sampling locations within each plot, 20 samples were collected on a 15- by 18-m triangular grid and the remaining 80 samples were collected at distances 1.0, 2.5, 5.0, and 7.5 m from the grid points. At each sampling point, the sample was taken between the plant rows and was composited from five 2.5-cm-diameter cores collected within a 0.2-m radius.

Table 2.1a. Description of soil sampling data collected during 2003 and 2004

	Time of sampling			
Treatment	**May -2003**	**May-2004**	**Depth**	**N**
CT	Rep 1, 2, 3, 4	5, 6	0-5 cm	600
NT	Rep 1, 2, 3, 4	5, 6	0-5 cm	600
CT cover	Rep 1, 2, 3, 4	5, 6	0-5 cm	600
Poplar		Rep 1, 2, 3, 4, 5, 6	0-5 cm	500
Total				**2300**

CT - Conventional chisel-plow; NT-no-till; CT-cover –Organic chisel plow with cover cropping. Poplar – Poplar trees of 15 years old; N - Number of soil samples collected in each treatment

Table 2.1b. Description of soil sampling data collected at 20-30 cm depth during May 2006

Treatment	**Replication sampled**	**Depth**	**N**
CT	Rep 1, 4	20 - 30 cm	200
CT cover	Rep 3, 4	20 - 30 cm	200
Total			400

N - Number of soil samples collected in each treatment

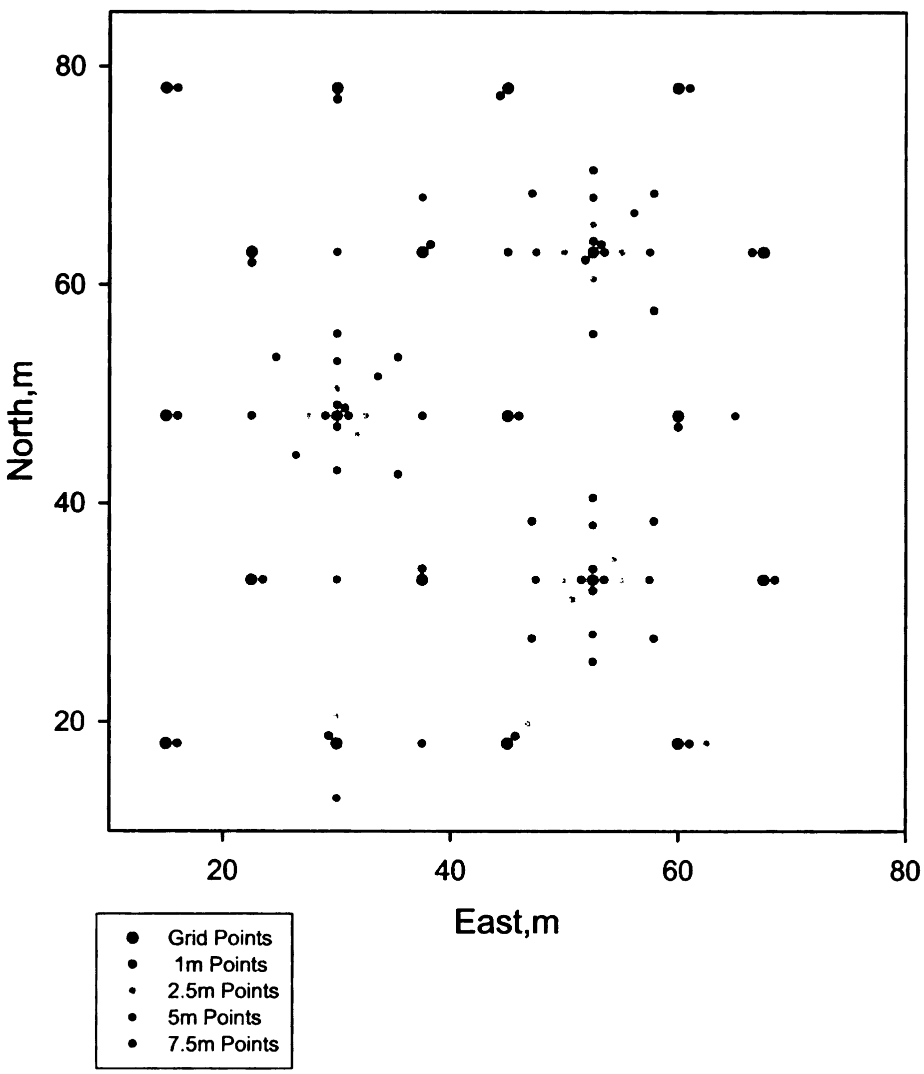


Fig. 2.1. Sampling scheme for each 1-ha plot followed at CT, NT and CT-cover treatments. Images in this dissertation are presented in color.

The above sampling scheme provided a sufficient number of samples for more accurate spatial variability characterization with minimal sampling effort (Kravchenko et al., 2006). In CT replication-3 plot topography was represented by a deep bowl-shaped depression and distinctly different from the any of the plots in the other treatments in the rest of the LTER site. This distinctly different shape led the data from this plot to differ notably from the rest of the site both in terms of the total C and N values, spatial patterns, and relationships with topography. Since it could not be meaningfully compared with the other treatments the data from this plot were excluded from further analyses.

The sampling layout for poplar was slightly modified from that used in agronomic treatments by taking into account the spatial arrangement of trees and spacing between them. Similar to agronomic treatments, within each plot 20 samples were collected on a 15- by 18-m triangular grid and an additional 80 off-grid points were collected at four distances 1-m, 2.5-m, 5.0-m and 7.5-m from several randomly selected grid points. The sampling scheme followed with the poplar treatment is shown on Fig. 2.2

At the agronomic treatments the off-grid points were randomly selected from eight directions such as north, north-east and east etc. In poplar instead of eight directions, sampling was restricted to four directions namely North, South, East and West such as to be aligned with rows of poplar trees. To reduce the small scale variations due to tree presence and to maintain the same distance from a main trunk, the samples were taken from the middle of the row. The second set of soil samples was collected at 20-30 cm depth in May of 2006 from replications 1 and 4 for CT and replication 3 and 4 for CT-cover (Table 2.1b).

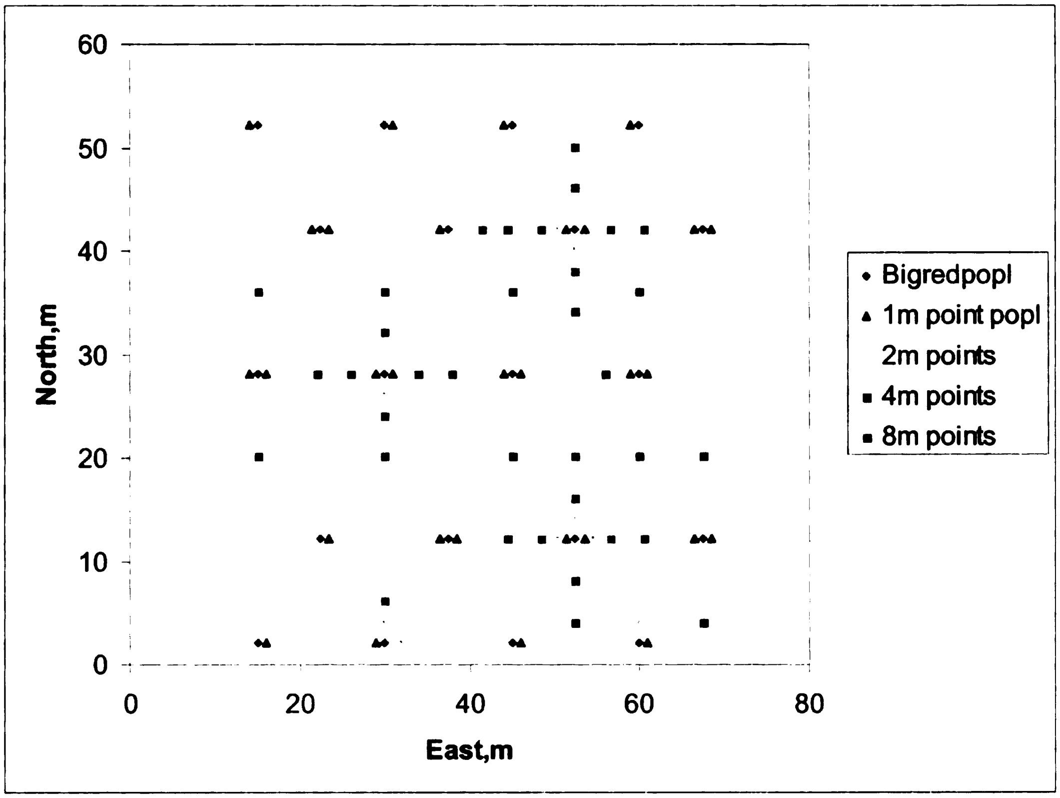


Fig. 2.2. Sampling scheme for each 1-ha plot followed at poplar treatment. Images in this dissertation are presented in color.

These plots were selected for 20-30 cm 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 0-5 cm samples of 2003. Among the 100 samples within each plot, 20 undisturbed cores of 5.2 cm-diameter were obtained using hydraulic soil core unit from Geoprobe systems (Geoprobe Inc. Salina, Kansas) to a depth of 0-40 cm on a 15- by 18-m triangular grid. The samples were air dried at room temperature and cleaned from all plant residue and stones. The samples were air dried at room temperature and cleaned from all plant residues and stones. Proper care was taken to exclude coarse roots, twigs, seeds and other visible plant residues from each sample. Smaller plant material was removed by gentle air blowing and the samples were ground on a shatterbox machine for one minute to pass a 250-μm sieve. Total C was measured using an automatic Carlo-Erba CN analyzer (Carlo Erba Instruments, Milan, Italy).

In each plot, about 10% of the samples were replicated thrice for total C 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 (DeGryze et al., 2002) thus the values obtained from chemical analysis of total C were considered to be representative of the soil organic C. Total C and N contents at 0-5 and 20-30 cm depths were reported in g kg $^{-1}$ of soil which was obtained by multiplying percent of C by 10.

$$C\ (g\ C\ kg^{-1}\ of\ soil) = C\ percent\ (g\ C\ 100g^{-1}\ of\ soil) * 10$$

Terrain Attributes

Topographical survey for measuring elevation data was conducted at the LTER site twice. The first survey was conducted using a land-based laser in 1988 generating 597 elevation measurements (Robertson et al., 1997) and second survey was carried out in 2004 using 12-channel Leica SR530 real-time kinematic DGPS (dual-frequency global positioning system) receiver within measurements collected every 2 m in rows 5 m apart (Kravchenko et al, 2006) at all the treatments. The elevation data from both surveys were merged and converted into a cell-based terrain map on a 4 by 4 m grid using inverse distance weighting with power of two and six nearest neighbors in ArcGIS 9.0 Spatial Analyst (ESRI, 2004). Then topographical features such as terrain slope, aspect, curvature, and flow accumulation were derived from the elevation map using surface and hydrology functions of ArcGIS 9.0 Spatial Analyst. Relative elevation (m) for each cell was obtained by calculating the difference in height of specific cell of interest from the minimum elevation in each plot. A more detailed description of terrain attributes and scale of measurements were provided by Kravchenko and Bullock (2000).

The wetness index (WI) was computed based on flow accumulation and slope data for each map grid cell (Gallant and Wilson, 2000) as:

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

where A_s is specific catchment area derived from flow accumulation, and $\tan\beta$ is a tangent function of slope at percent-rise.

Data Analysis

Data analysis was conducted using SAS (SAS Institute, 2001). First, comparison of total C, N variances was tested using Levene's test (Milleken and Johnson, 1992). Estimation of different variance components due to measurement error, plot and block effects was carried out in PROC MIXED using the restricted maximum likelihood method (SAS Institute, 2001).

Second, to evaluate the variability imposed by topography, multiple regression analysis was carried out between soil C and N with the terrain attributes in each treatment separately using PROC REG procedures (SAS Institute, 2001). The multiple regression models initially included either total C or total N as the response variable and terrain attributes such as elevation, slope, curvature, flow accumulation, aspect, and WI as independent variables. The need for quadratic terms for elevation, slope, curvature, flow accumulation, aspect, and WI were checked separately in each plot and the quadratic terms that were found to be significant ($p < 0.05$) were added to the regression equation. The residuals obtained from the topographical regression models are the variability in total C after controlling the topography effect on soil C changes.

Third, geostatistical analysis was carried out to evaluate the spatial variability in the raw C, N data and the spatial components of the variability that remained after controlling the topographical effects. Here the spatial structure obtained using raw C, N depicts the topography and management practices induced changes in variability pattern in C and N; whereas spatial variability observed using residuals obtained from the regression models with topography is the variability in soil C, N after removing the topographical effect. Sample variograms were computed for the C, N data and for the residuals obtained from the regression models with topography using PROC VARIOGRAM procedure in SAS. Each sample variogram was computed with lag distance of 4 meters and 15 distance classes. Variogram models were fitted using weighted least square in PROC NLIN (Schabenberger and Pierce, 2002) with spherical, Gaussian, and exponential models and the model that provided smallest mean square error was selected. Sill values, variogram values at 1.5 m distance to sill ratio and spatial correlation range were used to compare the spatial variability pattern among the treatments.

RESULTS AND DISCUSSION

Total C (0-5 cm) at 15-year old poplar compared to three agronomic treatments

Total soil C accumulated by poplar (11.8 g/kg) was significantly greater than that in CT (7.4 g/kg) and CT-cover (10.2 g/kg) under annual crop rotation. However the difference with NT treatment (11.4 g/kg) was not statistically significant ($p<0.05$) (Table 2.2). The mean N value for poplar (1.1 g/kg) was significantly greater than that of CT (0.67 g/kg) and CT-cover (0.93 g/kg), but not of the NT treatment (1.01 g/kg) ($p<0.05$).

These results were consistent with other studies who reported greater soil C and N levels with poplar compared with conventional tillage treatments (Sartori et al., 2006). Currently literature comparing poplar with NT is limited. However two other studies conducted in the same site also reported no significant difference between poplar and NT when the poplar trees were 10 to 12- year-old (Robertson et al., 2000; Degrye et al., 2004; Grandy and Robertson, 2007). The lack of significant differences between poplar and NT crop systems might be attributed to the fact that both systems were subjected to

Table 2.2. Treatment mean estimate of total C, N (g C kg $^{-1}$ soil) in CT, NT, CT cover and Poplar treatments of LTER site (standard error in paranthesis).

TRT	Total C (S.E)	Total N (S.E)
CT	7.4 (0.4) a*	0.7 (0.06) a*
NT	11.4 (0.5) c	1.0 (0.06) bc
CT cover	10.2 (0.5) b	0.9 (0.06) b
Poplar #	11.8 (0.6) c	1.1 (0.08) c
Poplar # # (with Rep 6)	12.3 (0.6)	1.2 (0.07)

CT - Conventional chisel-plow; NT-no-till; CT-cover –Organic chisel plow with cover cropping.
Poplar – Poplar trees of 15 years old
* Means within the same column followed by the same letter are not significantly different (α=0.05)
\# - Means estimates of poplar calculated based on the data from plot1, 2, 4 and 5
\# # - Means estimates of poplar calculated based on the data from plot1, 2, 4, 5 and 6

none or very small soil disturbance. In addition, 15 years may be still be not sufficient time for substantial differences in soil C to develop between afforested system and agronomic treatments under temperate conditions. Degryze et al. (2004) hypothesized that 10-40 years may be required to find any significant difference in poplar system compared to agronomic treatments.

These results were consistent with other studies who reported greater soil C and N levels with poplar compared with conventional tillage treatments (Sartori et al., 2006). Currently literature comparing poplar with NT is limited. However two other studies conducted in the same site also reported no significant difference between poplar and NT when the poplar trees were 10 to 12- year-old (Robertson et al., 2000; Degrye et al., 2004; Grandy and Robertson, 2007). The lack of significant differences between poplar and NT crop systems might be attributed to the fact that both systems were subjected to none or very small soil disturbance. In addition, 15 years may be still be not sufficient time for substantial differences in soil C to develop between afforested system and agronomic treatments under temperate conditions.

Degryze et al. (2004) hypothesized that 10-40 years may be required to find any significant difference in poplar system compared to agronomic treatments. Overall total C, N variability observed with poplar was found to be very similar to that of NT and cover crop system and significantly greater to that of CT treatments (Table 2.3a, 2.3b). Total soil C variances at poplar (0.5 g/kg) was significantly greater than that in CT (0.1 g/kg) however the difference with CT-cover (0.4 g/kg) and NT (0.5 g/kg) was not statistically significant (Table 2.3a; $p<0.05$).

Table 2.3. Variances and spatial variability parameters for the (a) total C (b) total N and the residuals of the regression model with topography under poplar and three different agronomic management systems (0-5 cm depth)

a)

		Original Total C				Residuals from topographical regression models			
TRT	**Var***	**Variog model**	**Var1.5 m**	**Sill**	**Range**	**Variog model**	**Var1.5 m**	**Sill**	**Range**
CT	0.1a	Sph	0.05	0.11	20	Sph	0.05	0.1	17
NT	0.5b	Gau	0.18	0.69	30	Gau	0.2	0.55	26
CT cover	0.4ab	Gau	0.09	0.52	38	Gau	0.1	0.26	31
Poplar #	0.5b	Sph	0.31	0.6	35	Sph	0.31	0.6	30
Poplar # #	0.8	Gau	0.28	1.04	32	Gau	0.3	0.9	23

b)

		Original Total N				Residuals from topographical regression models			
TRT	**Var***	**Variog model**	**Var1.5 m**	**Sill**	**Range**	**Variog model**	**Var1.5 m**	**Sill**	**Range**
CT	0.001a	Sph	0.0008	0	16	Sph	0.0008	0	12
NT	0.005ab	Gau	0.0014	0.01	25	Gau	0.002	0.01	26
CT cover	0.003a	Gau	0.0011	0	42	Gau	0.001	0	32
Poplar #	0.006b	Sph	0.0039	0.01	32	Sph	0.004	0.01	28
Poplar # #	0.008	Sph	0.0041	0	28	Gau	0.004	0.01	20

CT - Conventional chisel-plow; NT-no-till; CT cover –Organic chisel plow with cover cropping.
Poplar – Poplar trees of 15 years old
Variog- Variogram Models: sph – spherical; Gau – Gaussian
* Var - Variances followed by the same letter are not significantly different (p< 0.1, Levene's test)
# - Means estimates of poplar calculated based on the data from plot1, 2, 4 and 5
# # - Means estimates of poplar calculated based on the data from plot1, 2, 4, 5 and 6

The variances of total N decreased in the order of poplar~NT~ CT-Cover >CT (Table 2.3b). I hypothesized that overall variance at poplar will be greater than agronomic treatments considering the larger heterogeneity in C inputs and no tillage disturbance, but surprisingly the variance with poplar was found to be very similar to that of the no-till crop system. In the present study, the soil disturbance gradient follows the order of CT-Cover> CT>NT> Poplar. The results show that total C variability increased with lack of soil mixing due to reduction in disturbance level during the past 15-yr period after conversion to poplar and NT. However, CT-cover treatment which is subjected to heavy soil disturbance in this study site (more soil mixing) than CT still showed higher variability than the CT. With the CT-cover system the amount of residue returned from the cover crop and main crop was found to vary over the landscape, which in turn results in greater variability in soil C content. This indicates that apart from the soil disturbance gradient, greater variability in the biomass inputs also increases the variability pattern in soil C.

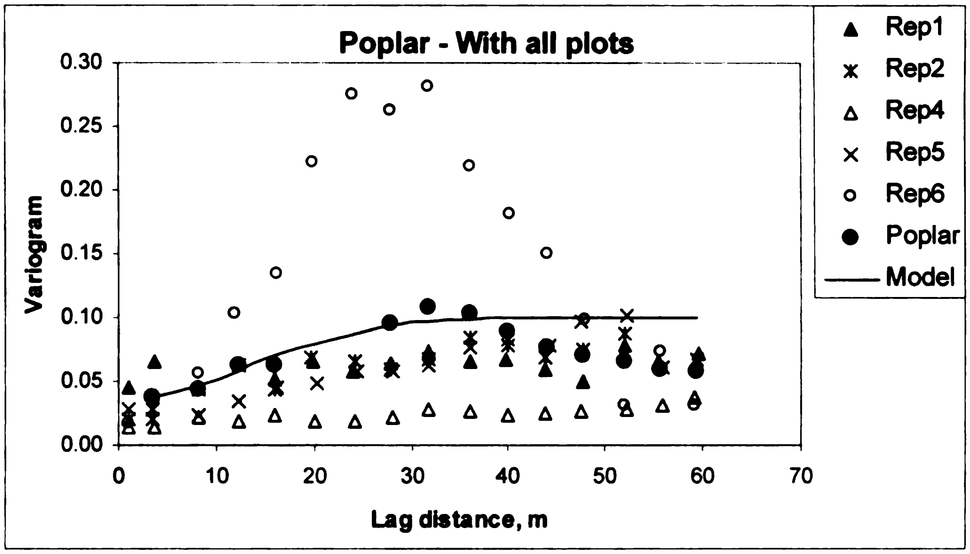
The measurement error variance component for both C and N at poplar was found to be significantly higher over all agronomic crop system ($p<0.05$). Total C variance due to laboratory measurements constituted 0.02, 0.1, 0.05 and 0.2 at CT, NT, CT-cover and poplar respectively. Similarly for N, variance component due to laboratory measurements constituted 0.0003, 0.002, 0.002 and 0.02 at CT, NT, CT-cover and poplar respectively. Here the variance observed with poplar was found to be at least twice that of NT and CT-cover treatment. Possibly because even after removing the smaller plant material by gentle air blowing, there were still very finer pieces of organic material abundant in poplar soil samples compared to agronomic treatments, which might have resulted in greater within sample variance.

Spatial variability pattern in poplar plots

A sample variogram of total C for all the individual plots sampled at poplar is shown in the Fig. 2.3a . The model and sample variogram was obtained by pooling data from all the plots and is depicted by solid circles. The sample variogram from the plot 6 is found to be distinctly different from the other plots in poplar as wèll as with overall sample variogram (Fig. 2.3a). The sample variogram from plot 6 also differed notably from rest of the plots in other treatments. Further the overall C variance from plot 6(0.18) was also found to be much higher compared to plot 1(0.06), plot 2(0.06), plot 4(0.02) and plot 5(0.06). The model and sample variograms obtained combining data from all the plots except plot 6 is found to be well representative of sample variogram of the individual plots (Fig. 2.3b).

Since the spatial pattern observed at plot 6 is found to be totally dissimilar with other poplar plots, for more meaningful comparison the data from this plot 6 were excluded while comparing with other treatments. However the results obtained including plot 6 is also presented but not discussed.

(a)



(b)

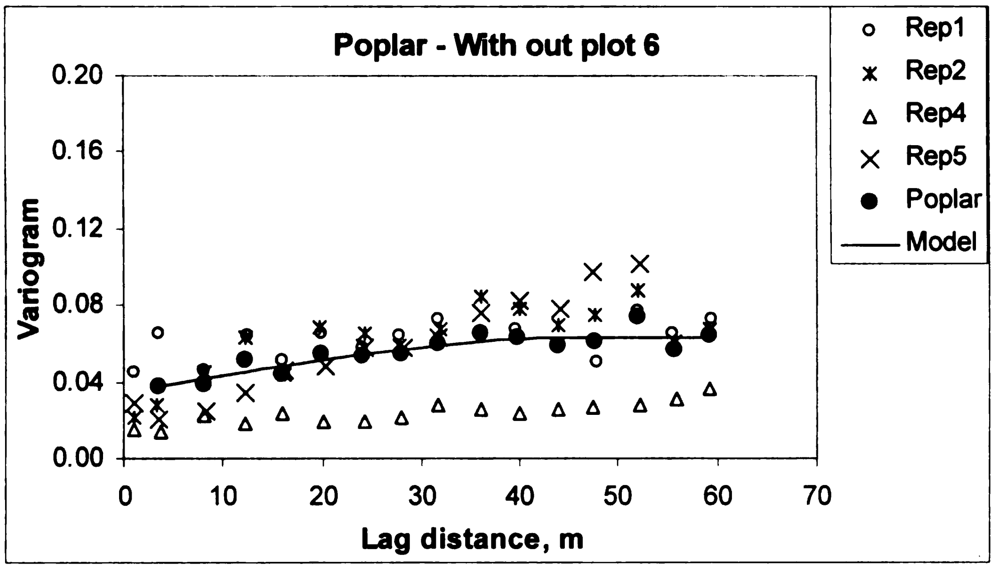


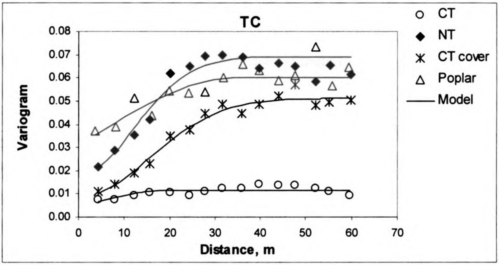
Fig. 2.3. Sample variograms of the total C for all the plots at poplar along with the model and overall sample variogram (green solid circle) obtained including data from all the plots. (a) With all the plots ; (b) With out plot 6

Spatial variability patterns in soil C, N under a 15-year poplar and three agronomic treatments at 0-5 cm

Stronger spatial structure was observed in poplar, NT and CT-cover which is clearly evident from the variograms of original C and N data with all treatments except CT (Fig. 2.4a, Fig. 2.4b). Similar to soil C and N levels and overall variability, spatial variability parameters such as nugget and sill value of C and N with poplar system were slightly greater or equal to that of NT and CT-cover (Table 2.3a, 2.3b). Greater variogram values near the origin with poplar shows that C is highly variable even at very shorter distances compared to agronomic treatments. In this study, to explain the spatial dependence, the ratio obtained by variogram values at 1.5 meters and sill values were used as outlined by Kravchenko et al., (2006). This ratio represents the amount of an unexplainable component in the dataset. The smaller the ratio, the greater the spatial dependence over the range of separation distances modeled.

In this study, the ratio between variogram values at the smallest lag distance (1.5 m) to sill values with poplar was found to be 52 percent whereas at CT, NT and CT-cover were 42, 26 and 18 percent respectively. This trend shows that a larger portion of the variability with poplar is occurring in shorter distance compared to NT and CT-cover. With NT and CT-cover, a larger portion of the overall variability is more spatially structured. The laboratory measurement error constituted 63 percent of variance observed at smallest lag distance of 1.5 m at poplar compared to 45 and 50 percent at NT and CT-cover respectively (Table 2.3a).

a)



b)

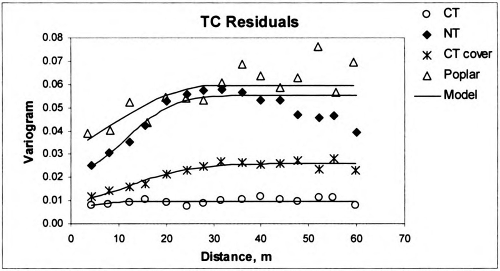


Fig. 2.4. Sample variograms and variogram models for: (a) original soil C data (b) residuals from topographical regression models at poplar and three agronomic management systems. Model parameters are shown in Table 2.3a.

In the present study, topographical features explained a substantial portion of the variability in total C and N distribution in all the studied treatments except poplar. The R^2 value for the topographical regression model for total C ranged from 0.07 (NT-Rep6 and Poplar-Rep1) to 0.73 (CT-cover-Rep1) (Table 2.4a). Similarly for total N the R^2 ranged from 0.08 (NT-Rep6 and poplar-Rep1) to 0.79 (CT-cover-Rep1) (Table 2.4a).

Combining data from all the plots in each treatment, topography was found to explain 26, 18, 38 and 7 percent of the variability in soil C at CT, NT, CT-cover and poplar respectively. The results shows that the relationship between topography and soil C was stronger at organic based system (CT-cover) and weaker at poplar and no till system. Similarly for total N, topography was found to explain 24, 16, 33 and 10 percent of the variability with CT, NT, CT-cover and poplar respectively. Stronger relationships between topography and soil C observed in this study was consistent with the results reported in other studies conducted at the comparable scale (Kravchenko and Bullock 2000; Muller and Pierce 2003; Terra et al., 2004). Compared to agronomic treatments, the topographical effect was less pronounced in poplar due to following reasons. Topography affects soil carbon mainly in two different ways. It influences erosion and redistribution of soil particles and it drives vertical and horizontal water redistribution patterns within the landscape (Creed et al., 2002). With poplar, the general topography soil C relationship is greatly subsided because the distribution of soil particles within the plot is greatly restricted due to dense plant cover and less soil disturbance.

Table. 2.4a Summary of soil and topographical properties of the studied plot. Results of multiple regression for C, N at the 0- to 5 cm depth with topographical variables also shown. For C and N, coefficients of variation (%) are shown in parentheses.

TRT	N	TC§	TN§	Rrelief	Slope degree	WI	R^2‡	R^2‡
Conventional chisel plow (CT)							TC	TN
Rep1	95	6.5 (17)	0.6(18)	1.48	1.41	6.48	0.43**	0.33**
Rep2	92	7.9 (15)	0.8(17)	0.87	0.68	7.15	0.17**	0.17**
Rep3	97	12.6 (21)	1.1(26)	1.11	0.99	7.98	0.73**	0.61**
Rep4	97	8.0 (11)	0.8(19)	0.81	0.86	7.27	0.12**	0.08*
Rep5	100	7.6 (10)	0.7(12)	1.97	1.79	6.83	0.28**	0.19**
Rep6	98	6.0 (20)	0.5(19)	1.66	1.48	6.17	0.14**	0.08*
No till (NT)								
Rep1	96	11.2(14)	1.1(13)	0.73	0.83	7.76	0.35**	0.19**
Rep2	60	11.5(18)	1.1(20)	1.70	1.81	6.33	0.18**	0.09**
Rep3	100	13.7(18)	1.3(20)	0.71	0.79	7.08	0.41**	0.46**
Rep4	100	12.6(28)	1.1(30)	0.45	0.47	7.48	0.70**	0.64**
Rep5	96	10.1(18)	0.8(21)	2.7	2.5	6.18	0.07NS	0.09*
Rep6	95	9.9 (19)	0.7(19)	0.71	0.77	7.12	0.19**	0.15**
Organic chisel plow with cover cropping (CT cover)								
Rep1	98	11.1(28)	1.1(28)	1.01	1.3	6.95	0.73**	0.79**
Rep2	93	9.8(19)	0.9(22)	0.55	0.54	6.89	0.19**	0.10**
Rep3	97	10.7(17)	1.0(17)	0.94	1.17	6.61	0.24**	0.17**
Rep4	98	10.1(15)	1.0(15)	0.56	0.76	6.81	0.70**	0.55**
Rep5	99	10.2(10)	0.9(12)	0.46	0.42	7.79	0.29**	0.26**
Rep6	98	8.8 (18)	0.7(19)	0.96	0.97	6.68	0.31**	0.19**
Poplar								
Rep1	84	11.1(23)	0.1(30)	2.02	1.65	6.31	0.07^{NS}	0.08^{NS}
Rep2	88	12.1(21)	1.1(20)	1.23	1.09	6.72	0.14**	0.15**
Rep4	64	11.0(14)	0.9(16)	1.71	1.18	6.63	0.17**	0.19**
Rep5	49	13.4(18)	1.3(18)	1.69	1.03	7.12	0.40**	0.27**
Rep6	79	14.9(29)	1.5(29)	2.25	2.02	6.51	0.46**	0.43**

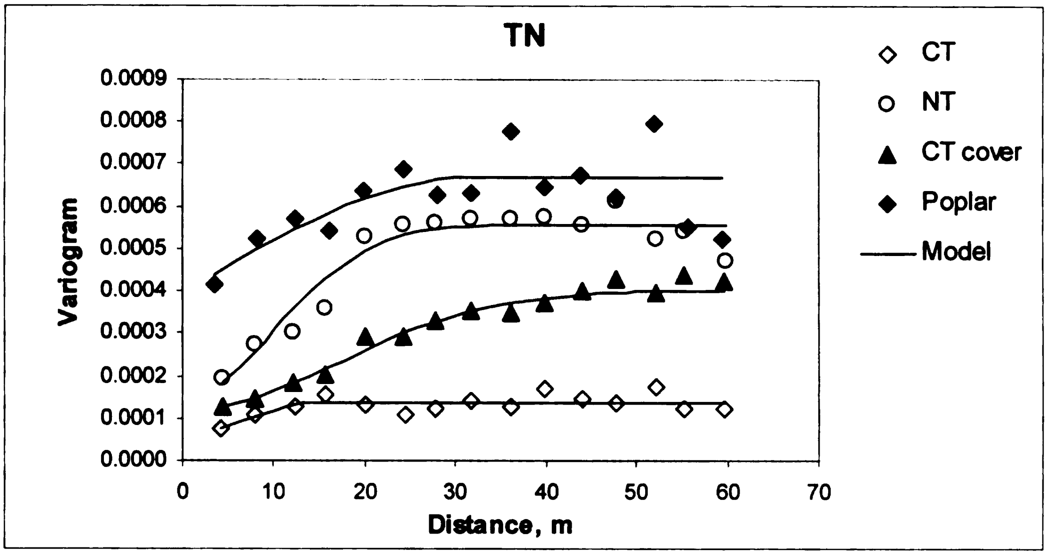
* Significant at the 0.05 probability level. ** Significant at the 0.01 probability level. NS – Non significant at $P \leq 0.05$

‡ Topographical regression models of all plots included linear effects of relative relief, terrain slope, curvature, log flowaccumulation , wetness index and aspect. Quadratic terms were added to the models when found to be significant at 0.05 level.

From the regression results, terrain attributes were found to explain a substantial portion of over all variability in the C and N content in all the treatments. To assess the spatial component of variability remaining after controlling the topography effect variogram of the residuals for total C and N were calculated from the respective multiple regression topographical models. The sill values and spatial correlation ranges obtained from the residual variograms were decreased and the 1.5 m variogram value/sill ratio increased marginally compared to the variogram models of original C, N data at all the studied tillage and cropping treatments except poplar. The 1.5 m variogram value/sill ratio constituted 50, 36, 39 and 56 of the overall variability of the residuals for CT, NT, CT-cover and poplar treatments respectively. With CT-cover, more substantial increase in 1.5 m value/ sill ratio with residual variograms shows stronger influence of topography on total C on these treatments. For example, Kravchenko et al. (2005) reported stronger relationships between topography and crop yield in the CT-cover system compared to CT and NT. Similarly Munos et al., (2008) observed strong relationship between cover crop biomass yields with elevation data collected in the same site. After removing the topography effect, the spatial variability structure greatly dropped with CT-cover, which depicts that the spatial structure in C and N distribution at CT-cover is mainly controlled by topographical gradient (Fig. 2.4b; 2.5b).

With poplar, there is no substantial change in variogram parameters because topography has less impact on soil C distribution in poplar compared to other agronomic treatments. Comparison of variograms based on the raw C data, the variogram values of NT were found to be similar or greater than poplar at most of the lag distances.

a)



b)

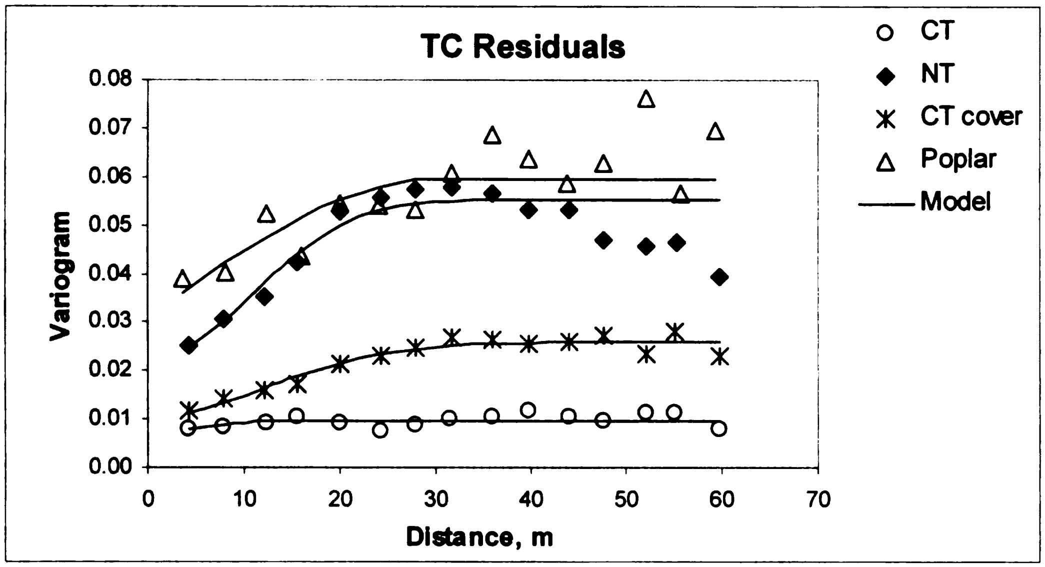


Fig. 2.5. Sample variograms and variogram models for: (a) original N data (b) residuals from topographical regression models at poplar and three agronomic management systems. Model parameters are shown in Table 2.3b.

However after removing the topographical effect, the variogram values with poplar were found to be higher than NT and CT-cover at all the lag distances (Fig. 2.4b). Greater C variability with poplar might be attributed due to the following mechanism. Especially after land use conversion from conventional tillage to any conservative management system, the rapid change in the soil C pool will be mainly attributed from the changes in light fraction and particulate organic matter. Greater variability in soil C distribution in poplar, NT and CT-cover might be attributed due to the increase in particulate organic matter (POM) content after conversion from conventional tillage system. Poplar systems sequester C mainly at the fine intra aggregate particulate organic matter (POM) (Degryze et al., 2004). Fine intra aggregate-POM estimated at poplar in the same study site during 2001 was reported to be greater than NT and CT-cover system (Grandy and Robertson, 2007).

Similarly many previous studies reported NT (Needelman et al., 1999) and CT-cover (Marriott and Wander, 2006) hold 30-40 percent more POM than conventional tillage treatment. POM was found to be more variable than the total C (Burke et al., 1999). Greater overall variability with poplar and NT is attributed due to a greater amount of POM and lesser soil disturbance compared to CT-cover.

Spatial variability patterns in soil C, N at surface (0-5 cm) and below plow (20-30 cm) depth among two management systems

Total C with CT-cover was significantly greater than CT at both the studied depths (Table 2.5a; $p<0.05$). Within each treatment the C content at the surface depth was significantly greater than the subsurface depth.

Table. 2.4b Summary of soil and topographical properties of the studied plot. Results of multiple regression for total C at the 0- to 5 cm and 20-30 cm depth with topographical variables also shown. For total C coefficients of variation (%) are shown in parentheses.

					TC (g C kg^{-1} soil)		R^2 ‡	
TRT	**N**	**R relief**	**Slope**	**WI**	**0-5 cm**	**20-30 cm**	**0-5 cm**	**20-30 cm**
CT								
Rep1	95	1.48	1.41	6.48	6.5(17)	3.0(29)	0.43**	0.23**
Rep4	97	0.81	0.86	7.27	8.0(11)	3.1(20)	0.12**	0.06NS
CT cover								
Rep1	97	0.94	1.17	6.61	10.7(17)	3.7(34)	0.24**	0.39**
Rep4	98	0.56	0.76	6.81	10.1(15)	4.3(50)	0.70**	0.59**

* Significant at the 0.05 probability level. ** Significant at the 0.01 probability level.
NS – Non significant at $P \leq 0.05$
CT - Conventional chisel-plow; CT-cover –Organic chisel plow with cover cropping.
‡ Topographical regression models of all plots included linear effects of relative relief, terrain slope, curvature, log flowaccumulation, wetness index and aspect.

At both 0-5 and 20-30 cm depth, the overall total C variability at CT cover was found to be substantially greater than CT (Table 2.5b). At CT, total C variance (0.12) at the soil surface was twice greater than the subsurface depth (0.05), whereas with CT-cover, C variance at the surface (0.29) and sub-surface (0.30) depth were found to be similar. Total C variability was also strongly spatially structured with CT-cover compared to CT, which is depicted by the variograms of original C data (Fig. 2.6a).

Among the studied depth with CT, variogram values at 0-5 cm depth were found to be greater than the variogram values from 20-30 cm depth at all the lag distances (Fig. 2.5a). This depicts that, C is more spatially variable at the soil surface compared to subsurface depth with CT. With CT-cover, variogram values at surface and subsurface depth were found to be similar in most of the lag distance which indicates greater variability in C even below plow depth (Fig. 2.6a). The spatial correlation range of C at the 20-30 soil depth at CT-cover (27m) was much greater than CT (10m). Compared to the soil surface (0-5 cm) the spatial correlation range of C at 20-30 cm depths was found to be relatively shorter with both CT and CT-cover, which depicts that C values are correlated at larger distances at the surface soil depth compared to below plowing depth (Table 2.5b). Similar to surface depth, at 20-30 cm, relationships between topography and total C were much stronger with CT-cover than CT similar to the surface depth. At CT, topography was found to explain a lesser amount of variability in C at 20-30 cm depth compared to 0-5 cm depth.

However after removing the topographical effect, the variogram values with poplar were found to be higher than NT and CT-cover at all the lag distances (Fig. 2.4b). Greater C variability with poplar might be attributed due to the following mechanism. Especially after land use conversion from conventional tillage to any conservative management system, the rapid change in the soil C pool will be mainly attributed from the changes in light fraction and particulate organic matter. Greater variability in soil C distribution in poplar, NT and CT-cover might be attributed due to the increase in particulate organic matter (POM) content after conversion from conventional tillage system. Poplar systems sequester C mainly at the fine intra aggregate particulate organic matter (POM) (Degryze et al., 2004). Fine intra aggregate-POM estimated at poplar in the same study site during 2001 was reported to be greater than NT and CT-cover system (Grandy and Robertson, 2007).

Similarly many previous studies reported NT (Needelman et al., 1999) and CT-cover (Marriott and Wander, 2006) hold 30-40 percent more POM than conventional tillage treatment. POM was found to be more variable than the total C (Burke et al., 1999). Greater overall variability with poplar and NT is attributed due to a greater amount of POM and lesser soil disturbance compared to CT-cover.

Spatial variability patterns in soil C, N at surface (0-5 cm) and below plow (20-30 cm) depth among two management systems

Total C with CT-cover was significantly greater than CT at both the studied depths (Table 2.5a; p<0.05). Within each treatment the C content at the surface depth was significantly greater than the subsurface depth.

Table. 2.5a. Total C (g C kg^{-1} soil) at surface (0-5 cm) and below plow depth (20-30 cm) at CT and CT-cover treatments.

TRT	0-5 cm	20-30 cm
CT	7.2 (0.6)a*A**	3.1 (0.1) aB
CT cover	10.5 (0.8)b A	4.2 (0.4) bB

* Comparisons of mean effects (Treatment effect within each depth) within the same column followed by the same lowercase letter are not significantly different (α=0.05)
**Comparisons of mean effects (Depth effect within each treatment) within the same row followed by the same upper case letter are not significantly different (α=0.05)

Table 2.5b. Variances and spatial variability parameters for the total C data at surface (0-5 cm) and below plow depth (20-30 cm) and the residuals of the regression model with topography at CT and CT-cover treatments.

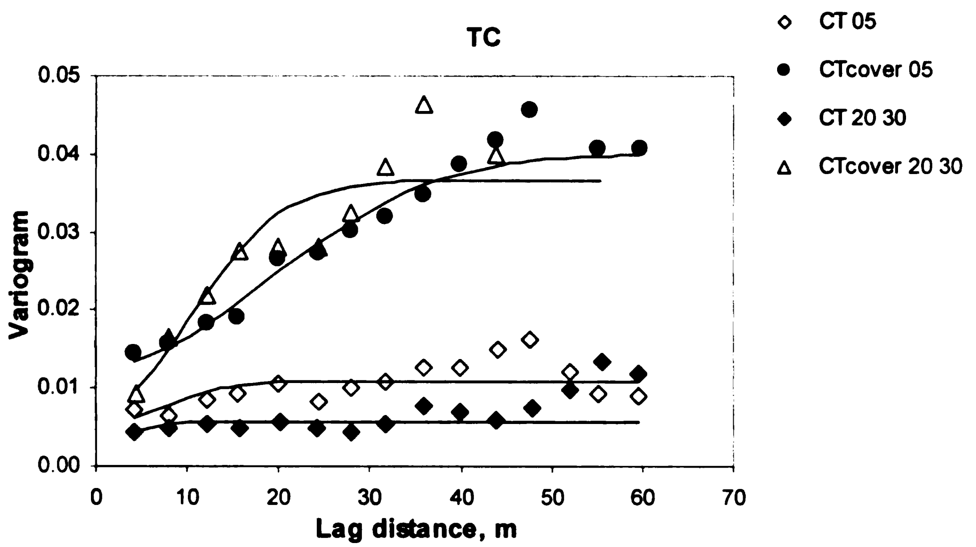
		Original Total C				Residuals from topographical regression models			
TRT	Var #	Variog model	Var at 1.5 m*	Sill	Range	Variog model	Var at 1.5 m*	Sill	Range
				0-5 cm					
CT	0.1a	Sph	0.05	0.11	20	Sph	0.05	0.09	17
CT cover	0.3b	Gau	0.12	0.39	45	Gau	0.12	0.21	31
				20-30 cm					
CT	0.1a	Gau	0.02	0.06	10	Gau	0.02	0.05	8
CT cover	0.3b	Gau	0.11	0.37	27	Sph	0.11	0.2	17

CT - Conventional chisel-plow; CT-cover –Organic chisel plow with cover cropping.
Variog- Variogram Models: Sph – spherical; Gau – Gaussian
* Variogram values at 1.5 m distance
# Variances followed by the same letter are not significantly different (p< 0.05, Levene's test)

However with CT-cover, the amount of variability explained at 20-30 depth was found to be similar to that of 0-5 depth (Table 2.5b). Topographical features explained about 41 percent of variability in total C with CT-cover compared to 10 percent with CT at 20-30 cm depth. The spatial component of variability unexplained by the terrain attributes was calculated from the variogram of the residuals for total C from the respective multiple regression topographical models. The variogram values at 1.5m distance to sill ratio constituted 40 and 55 of the overall variability of the residuals for CT and CT-cover treatments respectively.

At CT-cover, more substantial increase in nugget to sill ratio values and decrease in spatial correlation range with residual variograms show the stronger influence of topography on total C in these treatments. Because with CT-cover, the amount of crop residue inputs is strongly controlled by topography driven redistribution of soil moisture, resulting in a stronger relationship between topography and soil C. Topography in this study generally varied smoothly and had larger correlation ranges. The larger correlation range in CT-cover appears to form in response to topographical gradients. After removing the topography effect, the spatial variability structure greatly dropped at CT-cover compared to CT at both the depths. Still, CT-cover showed greater variability and stronger spatial structure compared to CT at all the lag distance at both the sampling depths.

a)



b)

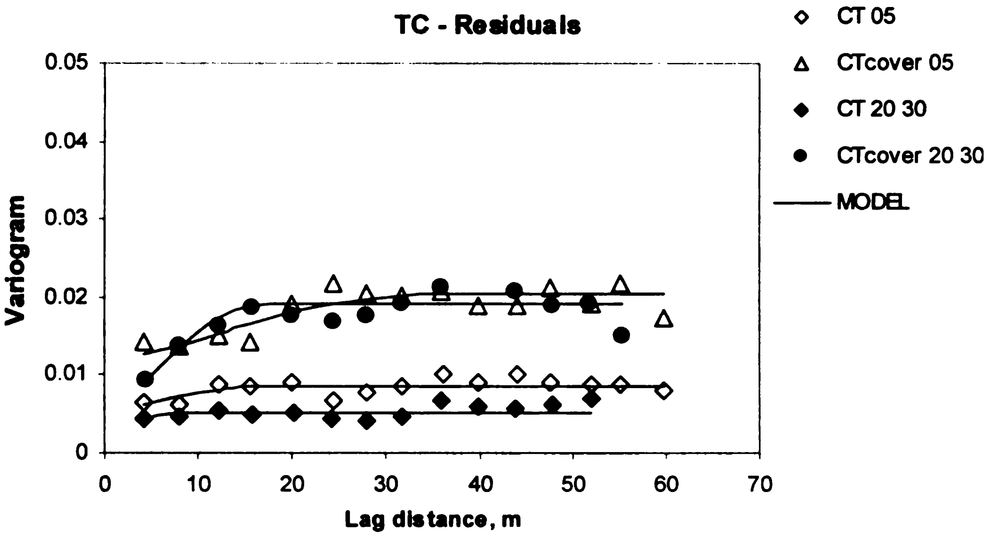


Fig. 2.6. Sample variograms and variogram models at 0-5 cm and 20-30 cm for: (a) original C data (b) residuals from topographical regression models at conventional chisel-plow (CT) and organic chisel-plow with cover cropping (CT-cover). Model parameters are shown in Table 2.5b.

Greater variability in subsurface depth with CT-cover may be attributed due to the following mechanisms. Belowground biomass input, which is the major source for soil C at subsurface depth (Ussiri et al., 2006) varies with fertilization, cropping intensity and crop species. In this study, CT is a chemical input treatment and CT-cover is legume based organic tillage treatment. Yield variability with organic based treatments was reported to be higher compared to the conventional chemical input system (Kravchenko et al., 2005; Smith et al., 2007). These greater differences in above ground biomass yields might also produce greater differences at below ground biomass residue return at the lower sampling depth resulting in greater variability at below plow depth in CT-cover. Apart from the amount of C inputs, CT-cover receives greater diversity of biomass returned to the soil through cover crops and weeds compared to CT. Each crop species has varying rooting depths which may cause stratification of C at different depths (Holonda et al., 1988; Lorenz and Lal, 2005).

In CT-cover, among the soil C pools, POM was enriched at least two times compared to any other fraction and POM contributes major proportion to the total C with the organic system compared to CT (Marriott and Wander, 2006). POM contents within the soil profiles will be highly variable (Burke et al., 1999; Hook and Burke, 2000), which might partly contribute to the greater variability in the soil C distribution at deeper layers with the CT-cover system.

In summary, surface soils from 0-5 cm depths in poplar management system was found to be more efficient in maintaining and enhancing C compared to CT and CT-cover cropping systems. However, no substantial differences were observed between poplar and NT cropping systems. Overall total C and N variability and spatial variability patterns observed with poplar were found to be similar to that of NT followed by CT-cover system and substantially different from that of CT. Spatial correlation of total C was strongest with CT-cover followed by poplar and NT and then CT. Variability characteristics of the total soil C in the studied plots were strongly affected by topographical gradients with CT-cover and NT and least with the poplar system.

At the 20-30 cm depth, overall variability in C distribution was much greater in CT-cover compared to CT. Comparing the spatial variability pattern between the studied depth, with CT, spatial correlation range and nugget and sill values at the soil surface were substantially greater compared to below plowing depth indicating greater variability at the soil surface compared to the 20-30 cm depth. However with CT-cover, variability in C distribution pattern was found to be similar at both studied depths.

To conclude, 15 years after land use conversion, total C, N content was greatest at poplar and NT followed by CT-cover and least at CT. In addition to increasing C, N content the land use conversion also affected spatial variability pattern, where the C, N content at poplar and NT was more spatially variable followed by CT-cover and least in CT.

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Chapter III

RELATIONSHIPS BETWEEN TOTAL SOIL CARBON AND TOPOGRAPHY OF DIFFERENT MANAGEMENT SYSTEMS

ABSTRACT

Topography or local relief is one of the major factors affecting spatial variability of soil carbon (C) and nitrogen (N) contents at the field/landscape level. General topographical influences on soil C and N related processes, controlled by soil water contents, are likely to differ in magnitude under different agricultural systems. In the present study, our objective was to examine the interactions between terrain attributes and management systems on soil C and N and to identify the landform elements that were most effective in C sequestration under each management system. The study was conducted at the Long Term Ecological Research (LTER) site, at Kellogg Biological Station, in southwest Michigan. Treatments used in the study were chisel-plow(CT) and and no-till(NT) with conventional chemical inputs and a chisel-plow organic management system with winter leguminous cover crops (CT-cover). Interaction effect between topographical features and tillage and management systems on soil C and N was tested first, with wetness index (WI) a compound topographical index as a continuous variable using analysis of covariance (ANCOVA) and second, topographical information was used as categorical variable by grouping similar class of terrain attributes into specific landform elements namely, upperslope and valley using discriminant analysis. Upperslopes are high relative relief regions in the landscape, characterized by less soil wetness index (water shedding region in a landscape). Valley positions are low lying areas characterized by greater soil wetness index (water receiving region in a landscape).

Interaction between treatment effects and WI was found to be significant at both (0-5, 20-30 cm) the studied depths. The site's topography effect was found to be stronger with the CT-cover treatment compared to CT and NT. Among the landform elements, C and N content was found to be greater at valley areas compared to upperslope position in all the studied treatments. Greater differences in C and N contents between the landform positions were more pronounced at CT-cover followed by conventional CT and NT treatments and the differences were more pronounced at 20-30 cm depth compared to surface depth (0-5 cm).

In overall at 0-30 cm depth, CT-cover and NT were found to accumulate 5.5 and 4.61 Mg more C per ha than CT at upperslope position and 9.12 and 15.39 Mg per ha more C than CT in the valleys. Similarly with N, CT-cover and NT were found to retain 0.73 and 0.84 Mg more N per ha than CT at upperslope position and 0.84 and 1.59 Mg per ha more N than CT in the valleys. In summary, tillage based organic cover crop system (CT-cover) was found to be equally efficient as the NT system in restoring C and N at 0-30 cm depth and the largest C and N benefits of CT-cover were observed in valley position as compared to upperslope position in the landscape.

INTRODUCTION

Soil organic matter (SOM) content is considered an index for soil quality (Seybold et al., 1997) and crop productivity and also plays an important role in the global carbon cycle by acting as a source as well sink for the atmospheric CO_2 emissions and C uptake (Smith et al., 1999). Thus today soil carbon management is a key component in most sustainable agriculture programs and global climate change studies. The net C content in a soil system is a tradeoff between the C additions into the system through crop biomass, cover crops, weeds and microbial biomass and C losses through soil respiration and erosion. The level of soil disturbance in the system has a substantial influence on the magnitude of C losses. Among the agricultural systems even with similar levels of carbon inputs, such as conventional tillage and no till systems, the greater soil disturbance generated by conventional tillage will lead to greater C losses. Even within the same management system, soil C sequestration potentials vary in response to variations in topography, parent materials, and microclimatic conditions. Increasing the carbon content in the soil from its current levels requires a thorough understanding of various factors controlling soil carbon and interactions among these factors. At a field scale, the magnitude of soil C variability depends on the tillage practice and is strongly affected by topography and amounts of plant residue returned to soil.

Topography affects soil carbon mainly in two different ways. It influences erosion and redeposition of fine soil particles, organic matter, and nutrients resulting in accumulation of nutrient rich, finer soil particles at valley regions as compared to soils at upperslope positions in a landscape (Ovalles and Collins.,1986; Pennock and de Jong.,1990; Kravchenko and Bullock, 2000). Topography drives vertical and horizontal water redistribution, resulting in differences in leaching, infiltration rates, and runoff affecting plant growth through varying moisture availabilities (Creed et al., 2002). Effects of topography on SOM have been well documented over the past few decades. Especially in the recent past, with the advancement in GIS and GPS technology, many researchers reported a strong relationship between terrain attributes and soil properties at a field scale (Ziadat, 2005). Topographical features such as landscape position, wetness index (WI)

(Moore et al., 1993; Moorman et al., 2004), terrain curvature (Yoo et al., 2006, Papiernik et al., 2007) and slope (Hao et al., 2002) were considered to be important factors influencing amount and turnover of SOC. In several studies slope and WI were found to account for more than half of the variability in SOM (Moore et al., 1993; Terra et al., 2004). WI is a compound topographical index which depicts the relative likelihood of saturation or wetness. Areas with higher WI were found to have higher soil organic carbon (SOC) due to higher sediment deposition and higher biomass production compared to lower WI zones. Curvature influences SOC by controlling the rate of soil erosion and soil thickness (Yoo et al., 2006). Aspect direction influences SOC by creating local variation in soil temperature and moisture which results in altering the decomposition rates of soil organic matter as well as affecting plant growth and biomass inputs (Yimer et al., 2006).

General topographical influences on soil C related processes 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 rate, wetting and drying cycles, soil moisture, temperature, and aeration (Franzluebbers et al., 1994, Hernanz et al., 2002).

Periodic disruption of soil structure due to tillage tends to reduce C and N content in the soil. No till management was introduced to reduce C loss associated with tillage disturbance, and Conservation Technology information Center (CTIC) reported that land area under no till increased from 2.2 Million hectares in 1973-74 to 21.1 million hectares in 2001-02. In no-till, higher organic carbon at the soil surface leads to high aggregate stability, controls erosion, and buffers temperature and moisture fluctuations. Franzlubbers (2004) in a review of studies that compared no-till with other tillage systems concluded that water-stable macro aggregates tend to be more abundant in soils under no-till as compared to other tillage systems. Increased numbers of water stable aggregates in no-till leads to accumulation of soil organic matter within macro aggregates and protects SOC 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). In heavily disturbed soil such as chisel plowed systems, tillage interferes with the soil aggregation process and exposes more area for microbial decomposition. However the effectiveness on reducing C losses via no-till strongly depends on no-till being maintained for a long time with soils remaining unplowed to protect aggregation and physically stabilized C pools (Grandy and Robertson, 2006).

Tillage affects mixing of aboveground residue and decomposition rate within the soil profile, which in turn influences varying concentration of SOM content with in the soil profile. Tillage by a chisel plow to a depth of 15 cm was found to incorporate nearly 60 percent of the residues at a depth of 0-6 cm, whereas in a no till system all the residues remained on the surface (Allmaras et al., 1996). Crop residue on the soil surface in no-till generally decomposes slower than residue incorporated in soil via tillage because of less contact with micro organisms (Reicoskt et al., 1997) and differences in soil microclimate. This leads to an increase in the particulate organic carbon in no-till over tilled systems (Franzluebbers et al., 2004).

Tillage alters the soil microclimate and creates local variation in soil temperature and moisture conditions (Balesdent et al., 2000). SOC losses through soil respiration greatly depend on soil temperature and soil moisture. In no-till, the presence of previous crop residues have been reported to decrease topsoil temperature, by 0-3° C, increase soil moisture content, and reduce soil aeration (Coote and Macolm-McGovern, 1989). Based on Rothemsted C model (Jenkinson et al., 1992) for every 2°C decrease in soil temperature the decay rates decrease by a factor of 0.8, while the decay rate increases 1.2 to 1.8 times for every 10% increase in soil moisture of the pore space corresponding to a specific range of temperature and moisture conditions (Balesdent et al., 2000).

Organic based systems with winter cover crops (WCC) is one of the potential management systems for increasing soil carbon and protecting soil quality in Midwest agriculture. Organic based systems with WCC were reported to be as effective in sequestering C as no-till despite heavy soil disturbance by tillage in such systems (Teasdale et al., 2007). Systems with WCC enhance SOC 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). Benefits of growing winter annual cover crops include increased soil aggregate stability (McVay et al., 1989) and increased soil N content (Blevins et al., 1990).

It is apparent that the effects of topography, tillage and cover crops on soil C and N may interact in a number of ways and that the soil C relationship with topography may vary in magnitude in different tillage and management systems. The influence of topography can be expected to be either buffered or intensified by different tillage and crop management practices (Bergstrom et al., 2001). Though a substantial number of studies addressed the relationships between topography and soil C and N and the tillage effects on soil C and N separately, there is only limited quantitative information on interactions between management systems and topography and their effects on soil C and N. Tillage induced soil loss or displacement are reported to be highest in crest, shoulder and upperslope positions which may result in truncated soil profiles in convex slope positions and inverted soil profiles with subsoil material deposited over original surface horizons at convex slope position (Kosmos et al., 2001, Heckrath et al., 2005 Papiernil et al., 2007). In no-till systems, VandenBygaart et al. (2002) found that landscape position plays a significant role in the ability of no-till soils to sequester SOC. After adoption of NT, the redistribution of soil particles from upperslope to valley positions was found to be greatly reduced and C content was shown to increase in upper and middle slope positions similar to that of lower slope positions due to increased moisture retention capabilities resulting in better crop yields and greater C inputs to the soil (VandenBygaart et al., 2002). Bergstorm et al. (2001) mentioned that no-till had more SOC than conventional tillage only at well drained upperslope positions. The above studies illustrate that upperslope positions are susceptible to erosion under tillage systems and under no-till systems particle movement is greatly reduced due to lower soil disturbance and more surface crop residues. These findings demonstrate that the topographical effect on soil particle redistribution varies under different management systems. The disadvantage of most of the studies that examined topographical effects on soil C in different management systems is that they were based on data being collected from a limited number of sites without replication for management systems. Thus the effects of management on the relationships between topography and soil C could not be properly separated from the individual characteristics of the specific study sites. In addition, there is only little such information reported studying the relationship between topography and soil C, N in an organic management system (Kasper et al., 2006).

In this study, topography modifications of total C and N levels under a no-till system, conventional tillage system, and organic based tillage systems were compared in a replicated long-term field experiment. The large experimental plots of 1 ha size and dense elevation data provided reliable estimates of various topographical features within each plot.

The objectives of this study were:

(i) To assess the strength of the relationships between topographical features and soil total C and N and study the interactions between topography and management systems on soil C and N;

(ii) To identify the landform elements that lead to most rapid and effective C sequestration in each management system.

MATERIALS AND METHODS

Test Site

The study was conducted at the Kellogg Biological Station's Long Term Ecological Research (KBS-LTER) site, in southwest Michigan (85°24' W, 42°24' N) established in 1988. Soils at the site have been 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 and receives approximately 90 cm annual precipitation, with about half as snow. Mean annual temperature is 9°C (Grandy and Robertson, 2007).

Experimental Layout and Agronomic Protocols

The LTER experimental layout is a one-factor randomized complete block design with six replications and seven treatments organized along a management intensity gradient based on tillage intensity, external inputs and net primary productivity (Grandy and Robertson, 2007). Each experimental plot is about 90 by 110 m in size. The experiment was started at 1989, before that, the studied site had been conventionally managed in row-crop agriculture for at least a century (Robertson et al., 1997). In this study, three LTER agronomic corn-soybean-wheat rotation treatments were studied, namely, chisel-plowed with conventional chemical inputs (CT); no-till with conventional chemical inputs (NT); and organic chisel plowed system with winter leguminous cover crops and zero chemical inputs (CT-cover). The cover crops of the CT-cover treatment was hairy vetch (*Vicia villosa* Roth) from 1989 to 1993 and red clover (*Trifolium pratense* L.) from 1994 onwards. The cover crops are generally incorporated in April or May before corn or soybean planting. Weed control in CT-cover for corn and soybean was achieved by weekly-biweekly rotary cultivation from May to early July. For wheat, cultivation prior to wheat planting was conducted in the fall. Thus CT-cover management had the greatest amount of mechanical disturbance among the three studied systems. The complete site description, experimental design, and management protocols are available at the KBS website (Kellogg Biological Station, 2005).

Soil Sampling

Soil sampling was carried out over the period from 2003-2006 and consisted of 3 sample sets. The first set of soil samples was collected at 0-5 cm depth from replications 1 through 4 in May of 2003 and from replication 5 and 6 in May of 2004. In both years CT and CT-cover treatments were plowed approximately 2 weeks prior to sampling. The sampling scheme for 2003-04 is shown on Fig. 3.1. To avoid plot boundary effects and the long-term protected portions of the plots restricted to sampling, the sample collection area was limited to the middle 60- by 60-m portion in each experimental plot.

Approximately ~100 georeferenced soil samples were collected at each plot for a total of 1714 samples. Among the 100 sampling locations within each plot, 20 samples were collected on a 15- by 18-m triangular grid and the remaining 80 samples were collected at distances 1.0, 2.5, 5.0, and 7.5 m from the grid points (Kravchenko et al., 2006). At each sampling point, the sample was taken between the plant rows and was composited from five 2.5-cm-diameter cores collected within a 0.2-m radius.

In the CT plot, replication-3 (bottom right corner plot in the Fig. 3.1), topography was represented by a deep bowl-shaped valley. As such, it did not have analogues among any of the plots of the other treatments in the rest of the LTER site. This distinctly different shape led the data from this plot to differ notably from the rest of the site both in terms of the total C and N values, their spatial patterns, and relationships with topography. Since it could not be meaningfully compared with the other treatments the data from this plot were excluded from further analyses.

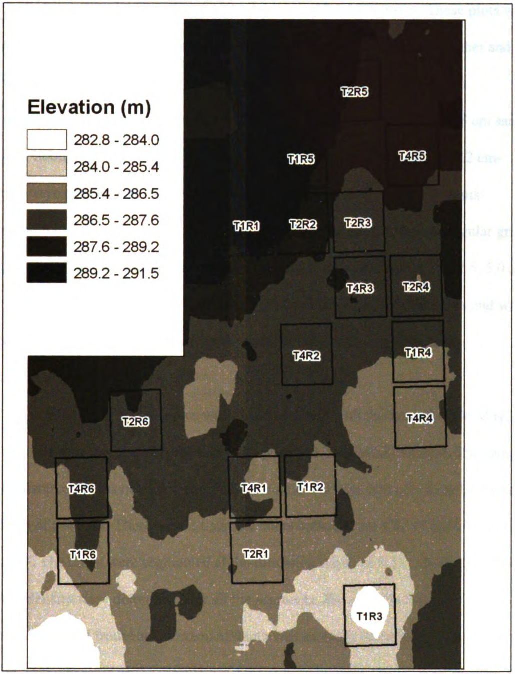

Fig 3.1. Layout of the experimental site along with the locations of the 18 experimental plots used in the study, the 15x15 m interpolated elevation map.

The second set of soil samples was collected at a 20-30 cm depth in May of 2006 from replications 1 and 4 for CT and replication 3 and 4 for CT-cover. These plots were selected for 20-30 cm 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 0-5 cm samples of 2003. Among the 100 samples within each plot, 20 undisturbed cores of 5.2 cm-diameter were obtained using a hydraulic soil core unit from Geoprobe systems (Geoprobe Inc, Salina, Kansas) to a depth of 0-40 cm on a 15- by 18-m triangular grid and the remaining 80 off-grid samples were collected at four distances, 1.0, 2.5, 5.0 and 7.5m, from the grid points at 20- to 30-cm depth from between the plant rows and was composited from five 2.5-cm-diameter cores collected at 0.2-m- radius circle (Kravchenko et al., 2006).

The third set of soil samples was collected along with the second set in May, 2006 from the locations that were sampled in 1988 prior to LTER establishment. The samples were undisturbed cores obtained using the hydraulic soil core unit of 5.2 cm in diameter to a depth of 0-40 cm. There were 11 sample cores collected for CT, 17 for CT-cover and 22 for NT. The cores were segmented at the following depth of 0-15, 15-20, 20-30, 30-40 and bulk density were determined for all the segments. For the bulk density measurements, soil from each horizon of depth was carefully transferred in to polythene bag and total wet mass of the sample weighed. Soil gravimetric water content was determined by weighing, oven drying, and reweighing subsamples.

Based on the moisture content of the subsample, the dry weight of the total sample was calculated for each depth. The bulk density of each soil depth was computed by dividing the oven dry weight into the volume of each segment which is obtained by measuring the length and diameter of tube from which the sample was taken for each depth. The bulk density values were then used to assess soil C and N stocks on an aerial basis. The measurements from the cores that were relevant to this study are the bulk density and total C and N for the depths of 0-15 cm and 20-30 cm.

For 20-30 cm depth, total C and N data from sampling set two and three were combined into a single data set, thus, a total number of samples for 20-30 cm depth were equal to 159 and 182 in CT and CT-cover treatments, respectively, and 22 in NT. The samples were air dried at room temperature and all large plant residues removed manually. Smaller plant material was removed by gentle air blowing and the samples were ground on a shatterbox machine for one minute 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 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 are considered to be representative of the organic C (Degryze et al., 2004). Total C and N contents at 0-5 and 20-30 cm depths were reported as g/100g of soil. Total C and N stocks were calculated on an aerial basis for 0-30 cm depth based on the sampling locations where 20-30 cm data were available.

For 0-20 cm values, in CT and CT-cover, data obtained from 2003-04 samples and 2006 samples were extrapolated to 0-20. In NT, data obtained from 2006 samples at 0-15 cm were extrapolated to 0-20 cm. Bulk density values of 0-30 were derived from bulk density measurements of 2006 samples obtained using the hydraulic soil core unit. Total C and N stocks at 0-30 cm depth were reported in Mg per ha.

Terrain Attributes

A topographical survey for measuring elevation data was conducted at the LTER site twice. The survey was conducted using a land-based laser in 1988 generating 597 elevation measurements (Robertson et al., 1997) and a second survey was carried out in 2004 using a 12-channel Leica SR530 real-time kinematic DGPS (dual-frequency global positioning system) receiver with measurements collected every 2 m in rows 5 m apart (Kravchenko et al, 2006). The elevation data from both surveys were merged and converted into a cell-based terrain map on a 4 by 4 m grid using inverse distance weighting with power of two and six nearest neighbors in ArcGIS 9.0 Spatial Analyst (ESRI, 2004). Then topographical features such as terrain slope, aspect, curvature, and flow accumulation were derived from the elevation map using surface and hydrology functions of ArcGIS 9.0 Spatial Analyst. Previous reports (Kravchenko et al., 2006) on aspect effects on total C at this site showed that the major difference in total C existed between southern aspects (south, southeast, and southwest) and the rest of the aspects. Slope aspects measured in degrees was reclassified into two categories, namely 0 for southern aspect which ranges from 135 to 225 degrees and 1 for the other orientations. Relative elevation (m) for each cell was obtained by calculating the difference in height of specific cell of interest from the minimum elevation in each plot. Slope represents gradient between the land surface and a horizontal plane at a given point. Curvature depicts the measure of convexity or concavity of the land surface in the direction of slope. By convention, convex curvatures are assigned positive values and represents hills in the landscape and concave curvatures are assigned negative values and represents valley areas. Flow accumulation is calculated for each pixel based on the accumulated weight for all pixels that flow into each downslope pixel. More detailed descriptions of each terrain attribute and scale of measurements were provided by Kravchenko and Bullock (2000) and Pennock and Coore (2001). The 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:

$$WI = \ln(A_S / \tan\beta) \qquad [1]$$

where A_S is specific catchment area derived from flow accumulation, and $\tan\beta$ is a tangent function of slope at percent-rise.

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 relationship 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 and analysis of covariance. The purpose of using terrain attributes as continuous variables is to quantify relationships between specific terrain attribute or their combinations with soil C and N and to study how much of variability in soil C and N can be explained by terrain attributes in each treatment.

In the second approach, I grouped locations with similar terrain attributes into specific landform elements using discriminant analysis. Then the relationship between soil C and N with topography in different treatments was assessed via two factor analysis of variance with landform elements as a categorical variable. Each landform element has a distinct set of quantitatively defined range of morphological and positional slope attributes, which in turn results distinct hydrological and soil properties (Pennock and Coore, 2001). The goal of landform segmentation is to find out the landform elements that lead to most rapid and effective C sequestration in each management system.

Terrain attributes as continuous variables

In the first approach, terrain attributes were considered as continuous variables and were related to soil C using correlation, multiple regression, and analysis of covariance (ANCOVA) methods. Correlation analysis and multiple regression were performed separately for each treatment using PROC CORR and PROC REG procedures (SAS Institute, 2001). The multiple regression models initially included either total C or total N as the response variables and terrain attributes such as elevation, slope, curvature, flow accumulation, aspect, and WI as independent variables. Then the model selection was conducted using stepwise regression (α=0.10). Prior to model selection, all variables were checked for normality and presence of outliers and transformed if found necessary. Specifically, slope and flow accumulation was found to be heavily skewed, thus both variables were log-transformed prior to analyses. The need for quadratic terms for elevation, slope, curvature, flow accumulation, aspect, and WI were checked separately in each plot and the quadratic terms that were found to be significant at the $p = 0.05$ level were added to the regression equation. Presence of multicollinearity was examined using variance inflation factors and condition index. Some multicollinearity was anticipated because most of the terrain variables were the primary and secondary derivatives of elevation. Topographical variables that appeared to be collinear and provided the least contribution to the model were excluded from further analysis. The model fit was evaluated by looking at residual plots and presence of outliers was assessed using Cook's D values.

The interactions between terrain attributes and studied agronomic treatments on soil C, N were studied using analysis of covariance. Wetness index is a compound topographical index that integrates information from specific catchment area and slope, and several previous studies used WI as an important covariate while predicting soil C, yield and other soil attributes (Skidmore et al., 1991; Kasper et al., 2006; Huang et al., 2007). In this study, WI was found to be the terrain variable most consistently related to soil C and N. Thus WI was used as the primary terrain covariate in the subsequent ANCOVA and evaluations of the interactions between topography and treatments for soil C and N. The analysis was carried out using PROC MIXED procedure in SAS (Milliken and Johnson, 2002). The relationships between C and N with WI were found to be linear in all treatments, thus higher order terms were not used.

The statistical model included treatments as the fixed factor and WI as a covariate. Replications and plots nested within treatments were treated as random factors and plots 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. 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 (α=0.05), pair-wise comparisons was conducted between the regression slopes for the three treatments.

There was a strong spatial correlation present in C and N data, thus I accounted for spatially correlated residuals (Schabenberger and Pierce, 2002). For that sample variograms for the residuals were examined separately for each treatment and fitted with variogram models using PROC NLIN procedure in SAS. Then the variogram model parameter estimates were used in ANCOVA to describe spatial structure of the correlated residuals. Such an approach ensured easier convergence and helped to reduce the computation time. The decisions on whether models with spatially correlated residuals were warranted were made based on the Akaike Information Criterion (AIC) values with lower AIC values indicating preferable model.

Analysis of landform classes

In this study, landscape within each plot was classified into two landform classes, i.e. upperslopes and valleys. Similar approach was carried out for landform classification at field scale by Macmillan et al. (2000). The land form classification was conducted using discriminant analysis. Discriminant analysis has been employed earlier in predicting soil properties and found to be effective by Bell et al. (1994), Kravchenko et al. (2002) and Bakhsk et al. (2007).

In this study site, landform class information and terrain attributes were available for 258 locations. These landform classes were identified through a direct field survey by traversing along the contour lines in the landscape and the point where we can make a clear judgement about the landform, the specific landform class was recorded using GPS. Among the 258 known landform locations observed, 156 observations were located in upperslope positions and 102 in low lying valleys. This constituted a model dataset. 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 0.15 significance level and used in building the classification rule.

A predictive model developed using the model dataset was then applied to the remaining dataset to place each point into the appropriate landform class. Cross-validation was applied to evaluate the accuracy of landform class prediction. 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). For each data location, discriminant analysis calculated the posterior probability of an observation for each of the landform classes and the specific observation was assigned a landform class that had the highest posterior probability (Johnson,1998 and Khattree and Naik, 2000).

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 interaction between landform elements, treatments and replications as random factors. Plots nested within treatments were used as error terms for testing treatment effects and interaction between landform elements, treatments and replications was used as an error term for testing the landform and landform by treatment interaction effects.

At 20-30 cm, there were only 22 observations in NT as compared to much larger numbers of data points in CT and CT-cover (158 and 182, respectively) which complicated obtaining reliable comparisons between them. Thus for the 20-30 and 0-30 cm depth, I mainly focused on CT and CT-cover treatment results however the results for NT treatments were also shown but not discussed in detail.

RESULTS

Descriptive Statistics and Landform Classification

Total C and N values were significantly different among the studied treatments ($p < 0.01$; Table 3.1) at all the studied depth. In overall, CT-cover and NT had the highest C and N in soil depths from 0 to 30 cm. Relative elevation of these treatment plots ranged from 2.38 to 5.59 meters (Table 3.2). Elevation gradient of about six meters within 50 hectares of the experimental site provided a reasonably large topographical diversity to study the relationship between topography and soil C and N under different management systems. In all three treatments the curvature and WI values were relatively similar, whereas the elevation range, slope and flow accumulation were found to be somewhat lower in CT-cover than in CT and NT treatments. However, the differences among the three treatments in terms of any of the terrain attributes were not

however after removing the topographical effect, the variogram values with poplar were found to be higher than NT and CT-cover at all the lag distances (Fig. 2.4b). Greater C variability with poplar might be attributed due to the following mechanism. Especially after land use conversion from conventional tillage to any conservative management system, the rapid change in the soil C pool will be mainly attributed from the changes in light fraction and particulate organic matter. Greater variability in soil C distribution in poplar, NT and CT-cover might be attributed due to the increase in particulate organic matter (POM) content after conversion from conventional tillage system. Poplar systems sequester C mainly at the fine intra aggregate particulate organic matter (POM) (Degryze et al., 2004). Fine intra aggregate-POM estimated at poplar in the same study site during 2001 was reported to be greater than NT and CT-cover system (Grandy and Robertson, 2007).

Similarly many previous studies reported NT (Needelman et al., 1999) and CT-cover (Marriott and Wander, 2006) hold 30-40 percent more POM than conventional tillage treatment. POM was found to be more variable than the total C (Burke et al., 1999). Greater overall variability with poplar and NT is attributed due to a greater amount of POM and lesser soil disturbance compared to CT-cover.

Spatial variability patterns in soil C, N at surface (0-5 cm) and below plow (20-30 cm) depth among two management systems

Total C with CT-cover was significantly greater than CT at both the studied depths (Table 2.5a; $p<0.05$). Within each treatment the C content at the surface depth was significantly greater than the subsurface depth.

Table 3.1. Mean C and N for all the studied depth at CT, NT, CT-cover crop treatment along with percentages of coefficients of variation in parentheses.

TRT	N	Total C	Total N
		0-5 cm #	
CT	485	7.6(19) a*	0.70(22) a
NT	548	11.5 (24) b	1.01(30) b
CT cover	583	10.3 (20) c	0.91 (22) b
		20-30 cm #	
CT	158	3.1(25) a	0.33 (25) a
NT	22	5.0(59) b	0.50 (50) b
CT cover	182	4.3 (44) b	0.41 (34) b
		0-30 cm # #	
CT	151	26.84(15) a	2.65(20) a
NT	21	39.64(31) b	4.11(26) b
CT cover	167	35.01(19) b	3.45 (17) b

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

- g C kg^{-1} soil

Soil C (Mg C ha^{-1}) = (SOC (g C kg^{-1} soil) /10) x 10,000 (m^2) x depth x bulk density (Mg m^{-3})

Table 3.2. Mean bulk density values for all the studied depths and a summary of terrain properties for the three studied treatment sites.

	Bulk Density (g/cc)			**Terrian attributes**				
TRT	**0-15**	**20-30**	**0-30**	**Elevation range**	**Slope**	**WI**	**Curvature**	**Flow**
CT	1.45a*	1.70a	1.52a	5.59a	1.26a	6.78a	0.047a	0.505a
NT	1.50a	1.69a	1.58a	5.32a	1.15a	7.04a	-0.015a	0.483a
CT cover	1.39a	1.56a	1.43a	2.38a	0.86a	6.96a	0.018a	0.335a

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

Elevation in meters; Slope in degrees; Curvature: Curvature of the terrain, 10^{-2} m.

WI : Wetness index, m^2 m^{-1}.

Flow : Log transformed flow accumulation calculated as accumulated weight for all cells that flow into each downslope cell.

statistically significant ($p<0.05$; Table 3.2). Although bulk densities at all soil depths of the three treatments were not significantly different (Table 3.2), there was a trend toward lower bulk densities for CT-cover treatments.

Mean values of the terrain variables and soil texture for each landform class classified via discriminant analysis are shown in Table 3.3. The upperslope element was characterized by higher relative elevation, lower WI and lower log flow accumulation values and higher sand content. Valley positions are low lying areas characterized by greater soil wetness index, lower relative relief and log flow accumulation. Upperslope element in this study includes geomorphic units such as summit, sideslope, backslope and shoulder. Valley element includes footslope and valleys. Upperslopes are water shedding regions and valleys are water receiving region in the landscape.

Relationship Between Terrain Attributes and Soil C and N at 0-5 cm Depth

Pearson correlation coefficients of total C and N with WI tended to be higher among those studied terrain attributes (Table 3.4). Correlation coefficients varied from treatment to treatment, however in general, total C and N at 0-5 cm depth were negatively correlated with elevation, terrain slope and curvature; and positively correlated with WI and flow accumulation in all three treatments. Positive correlations between soil C and WI and negative correlations between C and elevation and slope, observed in this study, were consistent with results reported by Moore et al., (1993); Florinsky et al., (2002); Muller and Pierce (2003); Terra et al., (2004). Differences in strength of relationship between topography and soil C under different land use system was also reported by Tan et al. (2004) under cropland, grassland, and forestland in Ohio.

Table 3.3. Mean values of the terrain variables and soil texture values for the upperslope and valley positions selected by stepwise discriminant procedure ($P \leq 0.10$) in the study site.

Landform Class	N	Rel. Elevation	Flow	WI	Sand #	Silt #	Clay #
Upperslope	1111	0.704	0.217	6.40	413	453	134
Valley	505	0.18	0.924	8.09	322	517	160

N – number of samples; Elevation in meters ; WI : Wetness index, $m^2 m^{-1}$. # - g kg^{-1} soil
Flow : Log transformed flow accumulation calculated as accumulated weight for all cells that flow into each downslope cell.

Table 3.4. Pearson correlation coefficients between the total C and N at 0- to 5-cm depth with terrain attributes significant at 0.05 level.

	TC (0-5 cm)					TN (0-5 cm)				
TRT	Elev	Slope	Curv	Flow	WI	Elev	Slope	Curv	Flow	WI
CT	NS	-0.38	-0.13	0.17	0.38	-0.13	-0.37	-0.12	0.14	0.34
NT	-0.24	-0.22	-0.12	0.16	0.26	-0.30	-0.18	-0.11	0.15	0.23
CTcover	-0.18	-0.18	-0.11	0.37	0.44	-0.16	-0.11	-0.11	0.33	0.36

NS - Not significant at $P \leq 0.05$

Terrain attributes explained about 26, 11 and 26 percent of variation in total C and 21, 12 and 21 percent of variation in total N in CT, NT and CT-cover treatments, respectively (Table 3.5). Topographical models were significant in all the studied plots ($p < 0.05$). At 0-5 cm depth, the relationship between total N and terrain attributes followed the same trend as that for total C in all the three treatments. The amount of variability explained by terrain attributes for total C and N was found to be relatively higher in tillage treatments (CT and CT-cover) as compared to the NT treatment. Significant positive contributions of WI to the regression equations for total C were observed in all three treatments. Contributions of the other topographical variables were significant in some but not other treatments.

Based on the correlation and regression results, I decided to run ANCOVA with WI as a covariate. Several previous studies also used WI as a variable representing topography when discussing topographical effects on total C (Moore et al., 1991, Kasper et al., 2006). These ANCOVA results demonstrated significant interactions between treatment effects and WI ($P<0.01$) (Table 3.6). The regression slopes of both tillage treatment i.e., CT-cover crop and CT for total C were significantly greater than that of the NT treatment for total C (Table 3.6).

The regression slope for CT-cover WI was numerically higher than that of the CT, though not significantly different ($p<0.05$). For total N, the regression slope estimate of the organic based treatment (CT-cover) was significantly higher than that of both chemical input treatments (CT and NT).

Table 3.5. Results of multiple regressions for total C, N at the 0 to 5cm depths with terrain attributes ($P \leq 0.05$)

	Total C (0-5 cm)			Total N (0-5 cm)		
Variables	**CT**	**NT**	**CT cover**	**CT**	**NT**	**CT cover**
Intercept	0.465	0.88	0.56	0.062	0.094	0.05
Elevation-						
Linear	-0.047	NS	NS	NS	-0.011	0.006
Quadratic	-0.023	0.14	NS	NS	NS	0.021
Slope	-0.077	NS	NS	-0.011	NS	NS
Flow	NS	NS	NS	0.006	NS	NS
Aspect	0.061	NS	NS	0.005	0.01	NS
WI	0.033	0.036	0.06	NS	NS	0.005
MSE	0.117	0.259	0.176	0.013	0.027	0.018
R^2	0.26	0.11	0.26	0.21	0.12	0.21

Elevation in meters; Slope in degrees; Curvature: Curvature of the terrain, 10^{-2} m.
Aspect: Reclassified aspect South = 0 (135-225 degrees); North =1
WI : Wetness index, $m^2 m^{-1}$.; Flow : Log transformed flow accumulation calculated as accumulated weight for all cells that flow into each downslope cell. ;
R^2 : Coefficient of determination for multiple regression, including only the variables significant at 0.05 significance level.

Table 3.6. Linear regression slopes, intercepts, r^2 and MSE resulting from ANCOVA of total C, N at 0- to 5-cm with wetness index as covariate.

TRT	N	Slope (SE)	Intercept (SE)	R^2	MSE
		Total C			
CT	485	0.015*a**(0.005)	0.658 (0.056)	0.14	0.13
NT	548	0.003 b NS(0.005)	1.164 (0.056)	0.07	0.26
CT cover	583	0.017*a (0.005)	0.902 (0.059)	0.19	0.19
		Total N			
CT	485	0.001NS(0.001)	0.068(0.007)	0.12	0.01
NT	535	0.0005NS (0.001)	0.101 (0.007)	0.06	0.03
CT cover	548	0.002* (0.001)	0.080 (0.007)	0.13	0.02

* Regression slopes are significantly greater than zero (α=0.05).
** Regression slopes in the equations followed by the same letter are not significantly different from each other (α=0.05).
NS - Regression slope of NT is not significantly greater than zero

Table 3.7. Total C and N content at 0- to 5-cm for the upperslope and valley positions in CT, NT and CT-cover.

	TC (g C kg^{-1} soil)		TN (g N kg^{-1} soil)	
TRT	**Upperslope**	**Valley**	**Upperslope**	**Valley**
CT	7.44 a*	7.71 a*	0.69 a*	0.72 a*
NT	11.4 c	11.5 b	0.99 b	1.03 b
CT cover	9.94 b	10.6 b	0.89 c	1.01 b

*Means followed by same letter within each column are not significantly different at $P<0.05$.

Even though relationships similar to those observed here between terrain attributes and soil C and N have been reported before (Moore et al., 1993; Moorman et al., 2004; Terra et al., 2004), this present study highlights that the magnitudes of the observed relationships were found to be different among the treatments. At 0-5 cm depth, the terrain attributes appeared to affect C stronger in CT-cover and CT than in NT treatments.

Among the landform classes, as expected, C and N contents in valleys were substantially higher as compared to those in upperslope elements, Table 3.7. The interactions between the landform elements and treatments for both C and N were not statistically significant. Contrast estimation was carried out to better assess the differences in C and N contents between upperslope and valley positions at different treatments. Differences in C contents at 0-5 cm depths (Table 3.8) between upperslope and valley was numerically greater with CT-cover (0.7 g kg^{-1} soil) followed by CT (0.3 g kg^{-1} soil) NT (0.1 g kg^{-1} soil). However, these differences were not significantly different among the treatments. The above trend shows that at 0-5 cm depth, topography tended to have a stronger effect in the CT-cover and CT treatments as compared to NT. The greater numeric differences in total C in CT-cover and lower differences in NT between upperslope and valley positions were in agreement with greater regression slopes observed in ANCOVA with WI for CT-cover and CT and a smaller slope from ANCOVA for NT.

Table 3.8. Total C and N difference between upperslope and valley landform positions for CT, NT and CT-cover.

Depth	Total C*			Total N*		
	CT	NT	CT cover	CT	NT	CT cover
		g C kg^{-1} soil			g C kg^{-1} soil	
0-5 #	0.3 a**	0.1 a	0.7 a	0.03 a	0.04 a	0.12 a
20-30	0.2 a	4.2 b	2.0 b	0.00 a	0.34 b	0.14 b
			Mg C ha^{-1} soil			
0-30 ##	1.6 a	12.3 b	5.2 b	0.25 a	1.0 b	0.36 b

* C, N values for 0-5 and 20-30 were measured in g kg^{-1} soil and for 0-30 cm in Mg ha^{-1} soil
**Means within each row followed by the same letter are not significantly different (α=0.05)
C differences at CT (0-5 cm) = C at valley (0-5 cm) – C at upperslope (0-5 cm)
(Similarly differences in values are obtained for all treatments at all the three studied depth)
Soil C (Mg C ha^{-1} soil) = (SOC (g kg^{-1}) /10) x 10,000 (m^2) x depth x bulk density(Mg m^{-3})

Table 3.9. Pearson correlation coefficients between the total C and N at 20- to 30-cm depth with terrain attributes significant at 0.05 level.

TRT	TC (20-30 cm)					TN (20-30 cm)				
	Elev	Slope	Curv	Flow	WI	Elev	Slope	Curv	Flow	WI
CT	NS	-0.23	-0.19	0.26	0.30	-0.17	-0.24	-0.20	0.25	0.30
NT	-0.52	-0.53	NS	NS	0.38	-0.55	-0.54	NS	NS	0.39
CTcover	-0.32	-0.21	NS	0.43	0.47	-0.19	-0.16	NS	0.41	0.43

NS - Not significant at $P \leq 0.05$

Similarly, for total N, the differences between the upperslope and valley positions were found to be numerically greater with CT-cover (0.12 g kg $^{-1}$ soil) followed by NT (0.04 g kg $^{-1}$ soil) and CT (0.03 g kg $^{-1}$ soil) although the differences were not significantly different among the treatments. Greater numeric differences in total N in CT-cover and lower differences in CT and NT between upperslope and valley positions were in agreement with greater slopes observed in ANCOVA with WI for CT-cover and an insignificant slope from ANCOVA for NT and CT.

Relationship Between Terrain Attributes and Soil C and N at 20-30 cm Depth

Similar to the results at 0-5 cm depth, Pearson correlation coefficients between total C and N and the terrain attributes varied from treatment to treatment and correlation coefficients with WI tended to be higher than those with the other terrain variables(Table 3.9). Unlike the results for 0-5 cm depth, terrain attributes explained larger portions of variability in total C and N at CT-cover (34% and 21%) as compared to CT (9 % and 13%). The R^2 values and regression coefficients from step-wise multiple regression for soil C and N with topographical variables are shown in Table 3.10. The r^2 values of NT treatment was based on the 22 samples as compared to that of CT(158) and CT-cover(182) which makes comparisons with the other two rather difficult. So for the 20-30, I mainly focused on CT and CT-cover results.

Based on the ANCOVA results with WI as the covariate (Table 3.11), the interaction between treatments and WI for total C was found to be significant ($P<0.01$), implying that relationships between WI and soil C at 20-30 cm depth were different under different management systems. The regression slope for the CT-cover was significantly greater than that of the CT treatment. In NT the regression slopes was not significantly different from zero, most likely reflecting the small sample size. For total N the regression slopes of CT-cover and CT were not significantly different.

Soil C and N contents at 20-30 cm depth for different landscape positions for CT, NT and CT-cover are shown in Table 3.12 ($P<0.05$) and Fig. 3.2. There was a significant interaction between the landform elements and treatments for both C and N. As expected, C and N contents in valleys were higher than in upperslope areas. At upperslope positions, there was no significant difference between total C and N of the CT, CT-cover and NT treatments. However at valleys, CT-cover and NT had higher C and N than CT.

Contrast results carried out with the differences in C and N contents between upperslope positions and valleys of each treatment are shown in Table 3.8. Unlike 0-5 cm, at 20-30 cm the difference in C content between upperslope and valleys was greater with CT-cover as compared to the CT treatment. Differences in C and N contents obtained between the two landforms were about ten-fold greater in CT-cover as compared to CT (Table 3.8). This depicts that topography effects were more pronounced at 20-30 cm depth as compared to 0-5 cm and much stronger in CT-cover compared to CT. These relative gains in C and N content at 20-30 cm, while adopting cover crop treatment over CT were significantly higher at upperslope positions compared to valleys. The greater differences in total C and N with CT-cover over CT were in agreement with greater regression coefficient values and greater slope from ANCOVA with WI for CT-cover compared to CT.

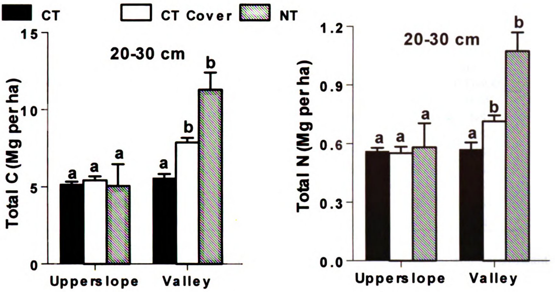

Fig. 3.2. Total C and N content at 20- to 30-cm at upperslope and valley positions in CT, NT and CT-cover. The same letters within each landform positions shows that treatments are not significantly different from each other (p<0.05).

Table 3.10 Results of multiple regressions for total C, N at the 20- to 30-cm depth with terrain attributes ($P \leq 0.05$)

Variables	Total C (20-30 cm)			Total N (20-30 cm)		
	CT	NT	CTcover	CT	NT	CTcover
Intercept	0.30	0.77	0.30	0.03	0.06	0.04
Elevation-Linear	NS	NS	0.20	-0.001	NS	NS
Quadratic	NS	NS	0.34	NS	NS	NS
Slope	NS	-0.15	0.06	NS	-0.02	NS
Flow	NS	NS	NS	NS	0.002	NS
Aspect	NS	NS	NS	NS	0.003	NS
WI	0.02	NS	NS	NS	0.003	NS
R^2	0.09	0.29	0.34	0.13	0.3	0.21

R^2 : Coefficient of determination for multiple regression, including only the variables significant at 0.05 significance level.
Elevation in meters; Slope in degrees; Curvature: Curvature of the terrain, 10^{-2} m.
Aspect: Reclassified aspect South = 0 (135-225 degrees); North =1
WI : Wetness index, $m^2\ m^{-1}$; Flow : Log transformed flow accumulation calculated as accumulated weight for all cells that flow into each downslope cell.

Table 3.11. Linear regression slopes, intercepts, r^2 and MSE resulting from ANCOVA of total C, N at 20- to 30-cm with wetness index as covariate.

TRT	N	Slope(SE)	Intercept (SE)	R^2	MSE
		Total C (20-30 cm)			
CT	158	0.014*(0.005) a**	0.206 (0.035)	0.09	0.07
NT	21	0.048NS(0.033) ab	0.111 (0.240)	0.15	0.30
CT cover	182	0.046 * (0.006) b	0.045 (0.054)	0.22	0.16
		Total N (20-30 cm)			
CT	158	0.0017*(0.001) a	0.021 (0.005)	0.18	0.01
NT	21	0.0043NS (0.003) a	0.022 (0.20)	0.15 NS	0.03
CT cover	182	0.0024* (0.001) a	0.025 (0.006)	0.18	0.01

* Regression slopes were significantly greater than zero (α=0.05).
** Regression slopes in the equations followed by the same letter are not significantly different from each other (α=0.05).
NS - Regression slope of NT is not significantly greater than zero

Table 3.12. Total C and N content at 20- to 30-cm at upperslope and valley positions in CT, NT and CT-cover.

	TC (g C kg $^{-1}$ soil)		TC (g C kg $^{-1}$ soil)	
TRT	**Upperslope**	**Valley**	**Upperslope**	**Valley**
CT	3.04 a*	3.22 a*	0.33 a*	0.33 a*
NT	2.87 a	7.05 b	0.33 a*	0.67 b
CT cover	3.34 a	5.29 b	0.34 a	0.48 b

*Means followed by same letter within each column are not significantly different at P<0.05.

Table 3.13. Pearson correlation coefficients between the total C and N at 0- to 30-cm depth with terrain attributes significant at 0.05 level.

		TC (0-30 cm)					TN (0-30 cm)				
TRT	**N**	**Elev**	**Slope**	**Curv**	**Flow**	**WI**	**Elev**	**Slope**	**Curv**	**Flow**	**WI**
CT	151	-0.49	-0.68	-0.31	0.34	0.52	-0.45	-0.57	-0.24	0.26	0.42
NT	21	-0.59	-0.58	-0.41	NS	0.39	-0.56	-0.55	-0.45	NS	0.43
CT cover	167	NS	-0.16	NS	0.43	0.44	NS	-0.14	NS	0.43	0.43

NS - Not significant at P $\leq$ 0.05

Relationship between Terrain Attributes and Soil C and N at 0-30 cm depth

Total C and N stocks at 0-30 cm depth were strongly negatively correlated with elevation and terrain slope; and positively correlated with WI, log flow accumulation and curvature in all the three treatments (Table 3.13). For both C and N, correlations with slope and WI were found to be significant in all the three treatments. At 0-30 cm, the proportion of variability explained by terrain attributes in multiple regression was higher with CT compared to CT-cover (Table 3.14). No single variable was consistently significant in multiple regression in all the three treatments. WI was used as a primary terrain covariate in the subsequent ANCOVA analysis for consistency purpose.

There was no significant interaction between treatment effect and WI for total C and N (Table 3.15). Total C and N contents at different landscape positions for CT, NT and CT-cover are shown in Table 3.16 ($P<0.05$) and Figure 3.3. The ANOVA results, demonstrated a significant interactions among the landform elements and treatments for both C and N. CT-cover had higher C and N than CT at both landscape positions. In valleys, NT had higher C and N than CT but was not significantly different from CT-cover. In upperslope positions for NT were not significantly different from either CT or CT-cover. The differences in C content between upperslope positions and valleys at 0-30 cm were 1.55, 12.33, and 5.17 Mg/ha for total C and 0.25, 1.0, and 0.36 Mg/ha for total N with CT, NT and CT-cover, respectively.

Table 3.14. Results of multiple regressions for total C, N at the 0- to 30-cm depth with terrain attributes ($P \leq 0.05$)

	Total C (0-30 cm)			Total N (0-30 cm)		
Variables	**CT**	**NT**	**CT cover**	**CT**	**NT**	**CT cover**
Intercept	0.68	0.85	0.78	0.068	0.088	0.075
Elevation	-0.01	-0.16	NS	-0.002	-0.013	NS
Slope	-0.10	-0.045	-0.01	NS	NS	NS
Flow	0.032	NS	NS	NS	NS	0.004
Aspect	0.03	NS	NS	NS	NS	0.004
WI	NS	NS	0.094	0.002	NS	0.003
R^2	0.54	0.35	0.24	0.39	0.31	0.22

R^2 : Coefficient of determination for multiple regression, including only the variables significant at 0.05 significance level.
Elevation in meters; Slope in degrees; Curvature: Curvature of the terrain, 10^{-2} m.
Aspect: Reclassified aspect South = 0 (135-225 degrees); North =1
WI : Wetness index
Flow : Log transformed flow accumulation calculated as accumulated weight for all cells that flow into each downslope cell.

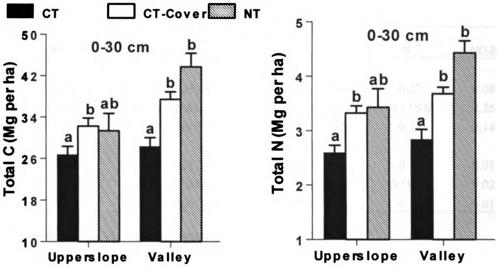

Fig. 3.3 Total C and N content at 0- to 30-cm at upperslope and valley positions in CT, NT and CT-cover. The same letters within each landform positions shows that treatments are not significantly different from each other (p<0.05).

Table 3.15. Linear regression slopes, intercepts, r^2 and MSE resulting from ANCOVA of total C, N at 0- to 30-cm with wetness index as covariate.

TRT	N	Slope(SE)	Intercept(SE)	R^2	MSE
		Total C			
CT	151	0.021* (0.005) a**	0.430 (0.053)	0.27	0.08
NT	21	0.038NS (0.019) a	0.566 (0.137)	0.15NS	0.25
CT cover	167	0.023 * (0.009) a	0.649 (0.072)	0.19	0.14
		Total N			
CT	151	0.002* (0.001) a**	0.044 (0.007)	0.18	0.01
NT	21	0.004NS (0.003) a	0.058 (0.014)	0.19NS	0.02
CT cover	167	0.003* (0.001) a	0.064 (0.007)	0.18	0.01

* Regression slopes are significantly greater than zero (α=0.05).
** Regression slopes in the equations followed by the same letter are not significantly different from each other (α=0.05).
NS - Regression slope of NT is not significantly greater than zero

Table 3.16. Total C and N content at 0-30 cm at upperslope and valley positions in CT, NT and CT-cover.

	TC Mg/ha (0-30 cm)		TN Mg/ha (0-30 cm)	
TRT	**Upperslope**	**Valley**	**Upperslope**	**Valley**
CT	26.74 a*	28.29 a	2.59 a	2.84 a
NT	31.35 ab	43.68 b	3.43 ab	4.43 b
CT cover	32.24 b	37.41 b	3.32 b	3.68 b

*Means followed by same letter within each column are not significantly different (P<0.05)
TC ($Mg\ C\ ha^{-1}$) = (SOC ($g\ C\ kg^{-1}$ soil) /10) x 10,000 (m^2) x depth x bulk density($Mg\ m^{-3}$)

For both C and N, the differences with CT-cover and NT were significantly greater than those with the CT treatment. Thus the results at 0-30 cm indicate that topography produced a greater effect on total C and N in CT-cover than in the CT treatment and the potential benefits of adopting cover crops were found to be greater in the valleys compared to upperslope positions.

DISCUSSION

In this study, at the surface depth (0-5 cm), the relationship between topography and total C were regarded to be affected primarily by tillage disturbance. Total C and N contents were strongly related to topography in the tillage treatments, CT-cover and CT, than in NT as indicated by higher multiple regression coefficients and greater regression slopes from ANCOVA with WI. This effect can be attributed to the greater influence of moisture and particle redistribution that occurs under constant soil disturbance by tillage at 0-5 cm depths. It has been shown in a number of studies that over a time, tillage leads to soil losses or displacements from upper landscape positions and its accumulation at lower landscape positions (Li and Lindstorm, 2001; Ritchie et al., 2004, Kaspar et al., 2006). After conversion to no-till, topography influence on soil erosion and particle redistribution can be expected to be greatly reduced due to lower soil disturbance, increased water permeability and a larger amount of crop residues remaining on the surface.

Moreover it has been noted that after implementation of NT, landforms susceptible to erosion, such as upperslope regions, may also improve in soil quality due to increased moisture retention characteristics and improved soil structure, leading to greater C accumulations along the downsloped positions within the landscape (VandenBygaart et al. 2002). Both reductions in topography-driven material transport and improved soil C sequestration at upperslope positions were consistent with the observed weaker relationship between soil C and topography in NT at 0-5 cm depth, including lower correlation and regression coefficients; lower slope from ANCOVA with WI; and lower difference between upperslope and valley soil C values.

The greater regression slope between total N and WI from ANCOVA in CT-cover probably reflects the effect the cover crop. CT-cover is a zero chemical input treatment, where soil nitrogen inputs come mainly from decomposition of crop and cover crop residues. The presence of cover crops affects N processes as compared to CT and NT due to differences in quantity and quality of residues and differences in plant rooting pattern and activities (Power et al., 1998; Villamil et al., 2006). Red clover and rye residues have narrower C/N ratio (11 to 37) than main crop residues (57 to 80) (Brady and Weil., 2002). Cover crop residues with narrow CN ratio provide a positive priming effect on N mineralization rate as well as an increase in microbial biomass turnover in the rhizophere by plant rhizodeposition (Kuzyakov et al., 2000) and symbiotic N-fixation from red clover. In the studied area, water redistribution along the landscape and water availability to plants affects the cover crop performance along with that of the main crops. Thus, in dry years lower located sites have a substantially greater cover crop stand than upperslope areas. The cover crop stand within the studied landscape is strongly controlled by topography driven redistribution of soil moisture, reflected in WI (Munos et al., 2008), thus explaining why the regression slope for N relationship with WI at CT-cover was greater than those of CT and NT. The smaller regression slopes in CT and NT may be due to the fact that, N was supplied via chemical fertilizers, thus uniform external N fertilization intensity prevailed over topography effect. Moreover, among the landform elements valleys had numerically higher C and N compared to upperslopes in CT and CT-cover. These higher levels may be due to the fact that, in a landscape position, valleys are generally fine textured (Table 3.2) and subject to less erosion compared to upperslopes (Franzluebbers., 2004). Furthermore C loss due to soil respiration which is speculated to be higher during spring from the drier, coarse textured soil of the upper slope positions compared to wetter, colder fine textured soils at footslope positions (Parkin and Kaspar, 2003, Kasper et al., 2006) contributes to the higher C and N in valleys relative to upperslopes.

At 20-30 cm, relationships between topography and total C and N were much stronger with CT-cover than CT. Since in a chisel plow system the tillage zone lies within the 0-20 cm depth, at 20-30 cm the C and N contents can be hypothesized to be driven by quantity and quality of below ground biomass inputs rather than by the tillage disturbance gradient. The stronger relationship between C, N and topography with CT-cover compared to CT may be attributed due to following mechanisms. First, with CT-cover, as mentioned earlier the amount of cover crop residue inputs is strongly controlled by the topography driven redistribution of soil moisture, resulting in stronger relationship between topography and soil C. Moreover, upperslopes were characterized by coarser textured soil (Table 3.3) with unfavorable moisture conditions with low inherent organic matter content, which might have restricted rooting pattern and activities (Villamil et al., 2006) to a much shallower depth. This would produce lower belowground biomass and C inputs at 20-30 cm in upperslopes compared to dense and deeper rooting pattern with more C inputs in valley positions which explain the lack of differences in carbon content between CT-cover and CT at upperslope positions. Fine textured soils in the valleys have a higher inherent level of macroaggregates inspite of heavy soil disturbance due to the cohesive nature of the reactive clays (Franzluebbers., 2004). The additional biomass with a narrow CN ratio that comes from winter cover crop roots and weeds in CT-cover might have enhanced the water stable aggregates and aggregation process resulting in more carbon and nitrogen sequestration with less soil C and N losses. CT-cover tends to have lower bulk density values at both 0-5 and 20-30 cm depths even though it was not statistically significant over CT and NT, and the lower bulk density in the cover crop treatment might have resulted in enhanced total porosity, which leads to increased macropores and micropores. Increases in macropore and micropores reduces moisture tension and increases plant available water capacity resulting in better crop stands and subsequently more C inputs in CT-cover. Similar results in a chisel plowed treatment with winter cover crops were reported by Villamil et al. (2006).

At 0-30 cm depth (Table 3.15), CT-cover and NT were reported to accumulate 5.5 and 4.61 Mg per ha more C than CT on the upperslopes and 9.12 and 15.39 Mg per ha more C than CT in the valleys. CT-cover and NT were found to retain 0.73 and 0.84 Mg per ha more N than CT in the upperslopes and 0.84 and 1.59 Mg per ha more N than CT in the valleys. Other studies reported a winter cover crop effect resulting in more soil mineral nitrogen content at 0-30 cm depth compared to chisel till treatment without cover crop Varco et al ., (1987) and Sainju and Singh (2001). Similar results in an organic based tillage system that include winter cover crops were reported to be as effective in gaining organic C as NT despite the heavy soil disturbance by tillage (Teasdale et al., 2007). In this study the site topography effect was found to be stronger with CT-cover treatment compared to CT and NT and; the CT-cover treatment and NT system were more efficient in restoring C and N at 0-30 cm than the CT system. The potential benefits of adopting cover crop treatment found to be greater at valleys compared to upperslope positions.

SUMMARY AND CONCLUSIONS

Tillage and management practices significantly interacted with topographical features as represented by WI with both C and N. Topography was found to explain larger proportion of variation in C at organic based tillage treatment compared to the chemical input based no-till (NT) and chisel plow (CT) systems. Among the landform elements, C and N content was found to be greater at valley areas compared to upperslope position in all the studied treatments. At 0-30 cm depth, CT-cover and NT was found to accumulate 2.2 and 1.81 Mg more C per acre than CT at uphill position and 3.7 and 6.2 Mg per acre more C than CT in the depressions. In overall, CT-cover was found to be equally efficient in maintaining C and N content as compared to NT treatments. Largest C and N benefits of CT-cover in the landscape were observed in valleys as compared to uphill position in the landscape. This may be attributed to greater gradients in spatial distribution of plant nutrients in organic management as well as greater influence of moisture redistribution through the landscape, which in CT-cover affects not only the main crop but as well performance of the cover crops. The results indicate that CT-cover has greater potential for C sequestration at lower landscape positions.

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Chapter IV

CONTEMPORARY EVIDENCE FOR SOIL C LOSS UNDER DIFFERENT CROP MANAGEMENT SYSTEMS IN A LONG TERM EXPERIMENT IN THE US CORN BELT

ABSTRACT

Monitoring soil carbon (C) plays an important role in understanding the influence of different land uses and management practices on C sequestration. Changes in C content vary across landscape as a result of complex interactions among different factors including historical soil C (baseline) levels, soil texture, topographical attributes, and land use and management practices. Recent changes in global temperature patterns may enhance or mediate the changes in soil C by interacting with different land use and management practices. In this study, first I reported the changes in soil total C contents that occurred in the past 15-20 years in soils under agricultural management and in non agricultural soils of Southern Michigan, USA, and, second, the relationships between these changes with soil properties such as baseline C levels, soil texture and topographical features was explored.

The data were collected from two long-term experiments namely; Long Term Ecological Research (LTER) Interaction site and Main site established in 1986 and 1988, respectively. Geo-referenced samples were collected from both experiments prior to establishment and then the locations were resampled in 2006-2007. Studied agricultural treatments included conventional chisel plowed management with and without N fertilizing, conventional no-till management with and without N fertilizing, and organic chisel plowed management. The non-agricultural treatment was a never tilled soil kept at

present under grass vegetation. Total C in the conventional chisel plowed fertilized management system has decreased by 1.15 g/kg and 0.22 g/kg at main site and interaction site respectively. At the interaction site within the conventional tillage system, C losses were found to be greater with unfertilized (1.54 g/kg) compared to fertilized (0.22 g/kg) treatments.

In comparing management practices at Main site, soil C under no-till (9.9 g kg $^{-1}$ of soil) management and under organic management (9.8 g kg $^{-1}$ of soil) with cover crops tends to be higher than that of the conventional management (8.2 g kg $^{-1}$ of soil) however; it has not changed as compared to 1988. That is, the conservation management practices appeared to have prevented total C loss as compared to conventional management but they did not lead to gains in absolute amount. Likewise, total C in the never tilled grassland soil has decreased by 7.4 (g kg $^{-1}$ of soil) since 1986. Increased decomposition rate as a result of winter warming in Michigan might be one of the major factors that drive soil C losses in this study site. Baseline C was found to have a negative relationship with changes in C content and C loss was found to increase with increase in baseline values. Increase in silt and clay content leads to positive changes (gain in C) in C content in no-till system. Topographical effect was not found to have a significant relationship between changes in C content, probably due to small sample size and low variations in topography. In summary, none of the studied treatments showed an increase in C content from the baseline values during the past two decades.

INTRODUCTION

Soil carbon is considered one of the major reservoirs for the carbon stocks on earth. It holds about 1550 Gt as organic carbon (1Gt = 10^{15} g) and 950 Gt as inorganic C (Lal, 2004). Currently there is growing concern that rising global temperature might possibly affect C content in the soil and influences the global C cycle (Bellamy et al., 2005). Reduction in global soil C stock due to global warming phenomenon has been already addressed by number of authors (Jenkinson et al., 1991; Schimel et al., 1994; Jones et al., 2005). If the rising global temperature were to cause even a little increase in the release of stored organic carbon as CO_2 to the atmosphere it may further intensify the present global warming potential.

Recently, Bellamy et al. (2005) and Schipper et al. (2007) reported widespread soil C losses across all land uses, soil types and management systems when comparing the contemporary C values with the baseline C values. Bellamy et al. (2005) reported C losses of about 0.12 kg C m^{-2} yr^{-1} with a net C loss of about 15 g kg^{-1} (~2.93 kg C m^{-2}) across England and Wales during the past 25 years. The study was based on the data obtained from more than 2000 sites sampled at 0-15 cm depth. Similarly Schipper et al. (2007) reported soil C losses of about 2.1 kg C m^{-2} during last 20 years based on 31 whole soil profiles sampled at 1 meter depth in the pasturelands of New Zealand. The findings of Bellamy *et al.* (2005) and Schipper *et al.* (2007) of losses in soil C occurring at a wide range of soils, land uses and management practices and appearing to accelerate over past couple of decades point to possible effect of the recent increases in global temperature.

Increase in global temperature affects soil C by influencing soil organic matter decomposition rate (Knorr et al., 2005), soil and root respiration (Kirschbaum, 2004; Jones et al., 2005) and mineralization rate (Davidson et al., 2000). Data analysis based on 12 soil warming experiments showed that an increase in soil temperature by up to 3°C increased soil respiration rate by 20 %, mineralization rate by 46 % and the plant productivity by 19 % (Rustad et al., 2001; Richter et al., 2007). Rising global temperature effect on soil C losses has been reported to be higher in temperate regions as compared to C stored in the warmer regions, since the temperature sensitivity of organic matter decomposition decreases with increase in temperature (Kirschbaum, 1995, 2000). For instance, increase in global temperature by 1° C could lead to a loss of over 10 percent of soil C in regions with an annual mean temperature of 5° C whereas the same temperature increase in tropical climate could lead to C loss of only 3 percent (Kirschbaum, 1995).

On a regional scale, Michigan's mean winter temperature was found to be increasing during the past few decades. Global warming effect on soil C changes at Michigan was earlier predicted with equilibrium analysis using Century model by Paustian et al. (1995). In this context, changes in temperature patterns may enhance or mediate the changes in soil C by interacting with different land use and management practices. For monitoring the dynamics of soil C in agricultural soils many long term studies have been established under different management practices. In the following sections, I discussed land use and management driven changes in soil C content.

Land Use Control on Soil C Changes

Among the land use induced C changes, conversion from natural vegetation to arable agriculture leads to a rapid depletion of soil carbon. Major decline in soil C content was reported at Morrow Plots (established at 1876) in Illinois and Sanborn field (established at 1888) at Columbia on conversion from native prairie to arable agriculture (Huggins et al., 1998). Global meta data analysis of the studies carried out under different climatic regions and soil types revealed that land use conversion from forest to agricultural crops results in average loss of C up to 24% (Murty et al., 2002).

Management Control on Soil C Changes

Management induced soil C changes depend on factors such as tillage disturbance, amount of crop residue return, cropping pattern and cropping intensity.

Tillage

Conventional tillage system affects soil C by disrupting the soil structure and aggregation, influencing soil microclimate and finally mixing of crop residues within the soil matrix (Balesdent et al., 2000). No till (NT), where the soil disturbance is minimal provides an overall positive effect on soil C sequestration compared to conventional tillage system. Global meta data analysis based on results compiled from long term studies revealed that the adoption of NT leads to an increase in soil C as compared to conventional tillage treatments (Franzluebbers, 2004; Puget and Lal, 2005). However to maintain or enhance the soil C storage, NT has to be maintained continuously without tillage (Grandy et al., 2006).

Crop residues

Crop residues are the main source of C input into the soil. The quantity and quality of crop residue returned within a management system varies according to the cropping pattern, cropping intensity and crop rotation. Many long-term studies reported gradual increase in soil C with increase in C inputs across treatments (Paustian et al., 1997). Removal of crop residues results in a decline in soil organic matter content. Huggins et al., (1998) reported a drastic decline in C content in Morrow Plots at Illinois and Sanborn field plots as a result of removal of crop residues during the initial 50 years of the experiment. However losses were slightly reverted after the initiation of annual return of straw and stover during 1950s and 1960s. An increase in C content was observed after continuously returning the crop residues for 17 years at Sanborn plots and at Morrow plots the loss was slower or leveled off after beginning of residue returns.

Organic based systems

Organically managed tillage systems are reported to accumulate more SOM content compared to the conventional tillage systems (Pulleman et al., 2000; Stockdale et al., 2001). Marriott and Wander (2006) reported a 14 % increase in soil organic C in organically managed CT when compared with the conventional tillage systems in a 10 years period. Similarly Teasdale et al., (2007) reported greater C contents at chisel plow based organic cover crop system compared to no-till system in a nine year old study under corn soybean wheat rotation conducted in a coarse and fine loamy Typic Hapludult soils. Based on KBS-LTER results, Robertson et al. (2000) reported that C levels at organic based cover crop system in the KBS-LTER were midway between the conventional and no till systems 10 years after treatment initiation. Differences in C content between organic based CT and conventional CT is mainly driven by quantity and quality of organic inputs (Stockdale et al., 2002). Inclusion of winter cover crops (WCC) in the crop rotation increases the amount and diversity of biomass returned to the soil. Leguminous cover crop residues with narrow CN ratio and rich in protein promote mycorhiza which in turn results in increased microbial communities, production of polysaccharides and aggregate stabilization (Haynes and Beare 1996).

General land use and management practices effect on soil C related processes are likely to differ in magnitude under different baseline C contents and soil textures. Local variations in soil properties such as changes in baseline C content and soil texture interact with different land use and management practices may enhance or mediate the changes in soil C.

Relationship Between Changes in C and Baseline C

Baseline soil C levels might be one of the critical factors influencing the rate of change in soil carbon under any land use or management practice (Jansen et al., 1998; Bellamy et al., 2005). For instance, VandenBygaart et al. (2002) observed negative relationship between the baseline C content and the change in C after 15 years of no-till treatment. No-till was found to generate a greater increase in soil C at eroded locations with lower baseline soil C than in the depositional areas with higher baseline C. Puget and Lal (2005) reported no change in C content in a NT experiment carried out in a soil which has high baseline C and high clay content.

Relationship between baseline C levels and the change in C content might be controlled by soil's saturation with C. C saturation capacity is defined as the maximum amount of C that can be sequestered by a soil under specific climatic and management conditions (Hassink 1997; Six et al., 2002). Saturation capacity depends on the sizes of protected and unprotected soil C pools. In soils with lower baseline carbon content, the sites able to protect soil C might be under-saturated with C. In this case adoption of NT or a high C input system will show greater increase in C content, which is supported by VandenBygaart et al. (2002) data. At higher baseline carbon content, most of the sites, where C could be protected are saturated and additionally a lot of C is stored in unprotected forms as light fractions and POM. This limits the increase in protected C pool which is supported by Puget and Lal (2005) experiment. The amount of unprotected C being held at equilibrium is affected by environmental conditions for decomposition which prevents substantial increases in C storage in unprotected forms. Limited or no increase in soil C with increased organic residue inputs observed in soils with relatively high baseline C in several experiments support the saturation capacity hypothesis (Hassink and Whitmore,1997; Six et al., 2002).

Soils with both low and high baseline C values on subjected to unfavorable conditions, such as increase in temperature or heavy soil disturbance will lose C. High baseline C soils, that have more unprotected C will lose more C compared to lower baseline C soils. Bellamy et al. (2005) reported relative loss in soil C in top soil increased with increase in baseline values.

Relationship between Changes in C and Soil Texture

Soil texture plays an important role in influencing soil C changes directly and indirectly in many different ways. Soil texture controls SOM decomposition rate where the decomposition rate will be greater at coarse textured soil compared to fine textured soil. Increases in clay content interact with SOC and forms complexes and microaggregates, which provides greater physical protection to the SOC stored in the soil (Tisdall and Oades, 1982; Amato and Ladd et al, 1992). Positive relationship between soil C and clay content has been reported in many previous studies (Hassink, 1997; Hao and Kravchenko., 2007).

Magnitude of soil C and texture relationship may depend on the degree of saturation of C in silt and clay protected soil C pools (Hassink and Whitmore, 1997). Silt+clay content increases soil C indirectly by increasing the physically protected storage capacity. As a result, fine textured soils will have more protective capacity and retain more organic matter than coarse-textured soils even on applying the same level of C inputs (Kortleven, 1963; Jenkinson, 1988).

However the general relationship between SOC and soil texture vary as a function of tillage and management systems. For instance, Campbell et al. (1996) reported stronger positive relationship between clay and C contents at NT as compared to that in CT management at three sites in western Canada. In contrast, Paustian et al. (1997) observed no relationship between texture and the effects of tillage on SOM contents while analyzing data from 27 long-term tillage trials. The relationship between silt+clay content with soil C varies with management system because apart from silt+clay protection, C is also protected in other forms such as microaggregate protected C, biochemically protected C and unprotected C. In tilled treatments the silt+clay protected C will be reduced due to tillage disturbance resulting in weaker relationship between C and soil texture at tillage treatments.

Most of the C studies examine the differences in soil C between different management systems at specific time points after initiation of the experiment. The changes in soil C are thus assessed on a relative scale via comparison with a control treatment, which is typically the conventional management practice. Contemporary samples are rarely compared with baseline values (VandenBygaart et al., 2002; Bellamy et al., 2005; Scipper et al., 2007) since geo-referenced soil C and N data are not available in most of the long term sites. However, to monitor temporal trends in soil C dynamics, not only relative but also absolute changes in soil C over time must be assessed.

Contemporary samples are desirable to compare with historic values to know the impact, such as losses or gains in different management systems, including the system used as a control. Bellamy et al. (2005) and Scipper et al. (2007) on comparing the contemporary C values with baseline values raised a concern that there are widespread losses in C occurring across all land uses, soil types and management systems common to temperate regions. It is important to determine whether soils in temperate regions of the US also experience similar C losses.

This study examines the changes in C and N contents under different management systems that have taken place over a period of 15-20 years in Southern Michigan. The two long-term experiments studied were Long Term Ecological Research (LTER) site and the Interaction study site located at Kellogg Biological Station. Both experiments have dense geo-referenced baseline data and hence resampling the baseline locations can be done at any point of time with an accuracy of <0.5 meters in identifying the sampling sites. Moreover, for some of the locations, the archived baseline samples are still available and could be reanalyzed using newer techniques to reduce experimental errors. The large size of LTER experimental plots provided a diverse range of topographical and soil characteristics for studying interactions between managements and soil properties on the SOC dynamics.

The objectives of this study are to:

1) Examine the changes that have taken place in soil C under different tillage and management practices and in never tilled grassland over the past two decades in Southern Michigan.

2) Analyze the relationships between the changes in soil C and baseline soil C and soil texture under different tillage and management systems and in never tilled grassland.

Materials and Method

The study was conducted at two long-term experiments from Kellogg Biological Station's Long Term Ecological Research (KBS-LTER) site in Southwest Michigan (85°24' W, 42°24' N). Climate is temperate with cool, moist winters and warm, humid summers with approximately 90 cm annual precipitation about half of which is snow. Mean annual temperature is 9°C (Grandy and Robertson, 2007). Detailed description of soil properties for the study site is presented in Chapter 2. Soil sampling for the main site and interaction site were carried out during May of 2006 and May of 2007, respectively. The sampling protocol and treatments sampled at both the sites are discussed below.

Main Site

The LTER main site experiment is a one-factor RCBD with seven treatments organized along a management intensity gradient based on tillage intensity, external inputs, and net primary productivity (Grandy and Robertson, 2007). All the agronomic treatments are under corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.]–wheat (*Triticum aestivum* L.) annual rotation. The experiment was started at 1988. Prior to that, the site had been conventionally managed under row-crop system for at least a century (Robertson et al., 1997). A set of 417 total C measurements was obtained from the area that became blocks 1-5 of the main site experiment in 1988. Among the 417 sampling locations, 192 sample locations were selected using stratified unaligned grid design (Webster and Oliver 1990) based on 50 * 50 m sampling cells and the remaining samples were collected randomly as singlets, doublets and triplets (Robertson et al., 1997). Doublets and triplets were separated by 1m from one another. Two 0-15-cm deep soil cores were collected using a 7.5 cm diameter root sampler (Elkjamp,Wageningen, The Netherlands) during late May of 1988 and composited into a single sample for each location. The locations were geo-referenced using laser stratigraphy that also provided elevation information for each location (Robertson et al., 1997). Year prior to the initiation of experiment, entire site was planted with corn, followed by fall-planted rye (*Lolium* sp.). The 1988 data will be referred from now on as baseline samples for the main site.

In May of 2006, 50 of the locations sampled in 1988 were found using GPS (Trimble Receiver Type Pro XRS model 33302-51) and re-sampled. The sample locations chosen for re-sampling were those located within central portions of the plots of the present LTER experiment. Three of the LTER management systems were studied, namely, chisel plowed (CT) and no-till (NT) with conventional chemical inputs, and certified organic chisel plowed system with a winter leguminous cover crop and zero chemical inputs (CT-cover). Overall, 11, 22 and 17 locations suitable for re-sampling were found in CT, NT and CT-cover treatments, respectively, with approximately 3-4 locations per each plot.

At each sampling location a hydraulic soil core unit from Geoprobe systems (Salina, Kansas) with 4.2 cm diameter cylinder was used to collect an undisturbed soil core of 0 - 40 cm depth. The cores were segmented into 0-15, 15-20, 20-30, 30-40 cm depths and bulk density was determined for all the segments. The measurements from the cores that will be reported in this study are the bulk density and total C and N data for the depth of 0-15 cm. The samples were air dried at room temperature and all plant residues and stones were removed. Smaller plant material was removed by gentle air blowing and the samples were ground on a shatterbox machine (Shatterbox model 8530) to pass through 250-μm sieve. Total C were measured using an automatic Carlo-Erba CN analyzer (Carlo Erba Instruments, Milan, Italy) and soil texture analyses were carried out using the hydrometer method. Bulk density measurements were obtained on dry weight basis and then used to assess soil C stocks on an areal basis.

The 2006 sampling was carried out during same period of time as that of 1988 sampling (May) with corn being previous year crop in both 1988 and 2006. This allowed reducing errors associated with seasonal effects and crop residue effects. Soil sampling information for data collection during 1988 and 2006 for LTER main site is provided in Table 4.1.To minimize the errors associated with differences in laboratory procedures, the 1988 archived samples from all 50 locations were reanalyzed for total C and N using the same procedure that was used for the analysis of 2006 samples. The changes in soil C and N are reported based on the reanalyzed 1988 data.

Interaction Site

The LTER Interaction site is a RCBD experiment with four replications. The two studied factors are the fertilization with two levels, fertilized and unfertilized, and tillage with two levels, tilled and no tilled. Each experimental plot is 27 by 40 m in size. All the agronomic treatments are under corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.]–wheat (*Triticum aestivum* L.) annual rotation. In the fertilized plots, during wheat years Urea (NH_2-C0-NH_2) is applied as a source of N (40 pounds per acre) and during corn years liquid N (28 percent active ingredient) is applied as per Michigan recommended fertilizer rates for corn. No fertilizer is applied when soybeans are grown. During the last five years no phosphorous (P) or potassium (K) was applied even at the fertilized plots. The experiment was started at 1986, before that, the tilled portions of the studied site have been conventionally managed at least from 1950 prior to that it was under native vegetation (oak-hickory (*Quercus-Carya* spp.) forest) (Robertson et al., 1993).

Table 4.1. Summary of data collection in 1988 and 2006 for LTER mainsite and in 1986 and 2007 for the Interaction site.

TRT	N	Sampling depth		Sampling time		Previous crop		C N analysis method	
				Main site					
		1988	2006*	1988	2006	1988	2006	1988	2006
CT	11		0-15					Carlo-	
NT	22	0-15	15-20	May	May	Corn	Corn	Erba CN	Carlo-Erba
CT cover	17		20-30					analyser	CN analyser
				Interaction site					
		1986	2007	1986	2007	1986	2007	1986	2007
CT F	14								
CT NF	10								
NT F	12	0-20	0-20	May	May	Soybean	Soybean		
NT NF	11							Walkley-	
Never								Black	Carlo-Erba
tilled	13							method	CN analyser

N - Number of samples collocated at each treatment

* At main site during 2006, samples were collected from 0-15, 15-20 and 20-30 at CT, NT and CT-cover

Several never tilled grassland sites are located near the interaction experiment. In the never tilled grassland, mowing was done every year during late Fall since 1960 and the residues were left at the surface.

A set of 256 samples from the tilled portions and 65 samples from the never tilled portions of the site were collected in May 1986 prior to the Interaction experiment establishment. Stratified unaligned sampling design based on 15*18 sampling cells was adopted to select the sampling locations and provided a sufficient number of samples separated by relatively small distances (< 15 m). For geooreferencing the sampling locations, the most South-West corner cell of the rectangular grid was assigned the starting value of (0,0) and set as a reference point. Then coordinates of each sampling location was calculated based on the distance from the set reference point. For instance, if sampling location has coordinates as (5,3) then the specific sample will be located 5 meters from East and 3 meters from North of the reference point (0,0).

At each sampling point, five 2.5-cm-diameter cores were collected at 0-20 cm depth within 15 cm radius circle and composited into single homogenous sample (Robertson et al., 1993). In the year prior to soil sampling, the tilled portion of the site has been planted with winter cover of annual ryegrass (*Lolium* sp.) without tillage. Carbon measurements were carried out with triplicates subsample from each sampling point following Walkley and-Black wet combustion technique during 1986 (Nelson and Sommers 1982). Soil sampling information for data collection during 1986 and 2007 for LTER interaction site is provided in Table 4.1.

Unlike mainsite, at the interaction site archived samples were not available to reanalyze the baseline samples with our current procedure. The 1986 data will be referred from now on as baseline samples for the interaction site.

During 2007, we collected a total of 57 samples from 1986 sampled locations. At each sampling point, the sample was taken between the plant rows and was composited from three 2.5-cm-diameter cores collected within a 0.2-m radius to a depth of 20 cm. Soybean was grown during 2006, i.e., year prior to the contemporary soil sampling. Approximately, 2-4 samples were collected in each plot of the Interaction experiment. Locations for resampling were selected in such a way that they were located in central portions of the plots.

The procedures for sample cleaning, processing, and analyses were the same as those used for the main site and described earlier. Smaller plant material was removed by gentle air blowing and the samples were ground on a shatterbox machine (Shatterbox model 8530) to pass through 250-μm sieve. Total C and N were measured using an automatic Carlo-Erba CN analyzer (Carlo Erba Instruments, Milan, Italy). Subsample of 20 g was used for particle size analysis. Soil was dispersed in 5 % sodium hexametaphosphate solution and kept in a mechanical shaker for about 16 hours. Sand content was then isolated by passing the dispersed sample through a 53-μm sieve. For the interaction site, silt+clay content was obtained by subtracting sand content from the total weight of soil used for analysis. Bulk density measurements were obtained on dry weight basis and then used to assess soil C stocks on an areal basis.

Data analyses

Assessing treatment effects and relationships between changes in C content and baseline C, soil texture and topographical features in different treatments

Data analysis was conducted using SAS (SAS Institute, 2001). Changes in soil C and potential differences in relationships between the changes in soil C and the baseline C values, silt+clay content and relative elevation under different management systems were studied using analysis of variance (ANOVA) and analysis of covariance (ANCOVA) approaches in PROC MIXED (Milliken and Johnson, 2002). For the LTER main site, the statistical model included treatments as a fixed factor, and blocks and plots nested within treatments as random factors with plots used as an error term for testing the treatment effects. For the Interaction site, the statistical model included fixed effects of tillage, fertilization, and their interaction and random effects of blocks and plots. Baseline C was used as a continuous covariate in both experiments. When interactions between fixed factors and covariates were found to be statistically significant (α=0.05), comparisons were conducted at several different covariate levels. In both experiments normality of the residuals and homogeneity of variances assumptions were checked and analysis with heterogeneous variances was conducted, if found necessary, using REPEATED /GROUP statement in PROC MIXED. When the fixed effects were found to be statistically significant (α=0.05), the comparisons between the treatments were conducted using t-tests.

Reanalyzing the baseline values from the main site

Correspondence between soil C measurement on 1988 samples conducted in 1988 and reanalyzed in 2006 was assessed using simple linear regression. The R^2 was equal to of 0.51 (Fig. 4.1). Noticeable scattering of the data might be due to differences in sample processing and analytical procedures. Reanalyzing the archived samples with the current procedure will serve as a robust method for detecting changes and provide more credence to our reported results. Hence for the analysis of changes in C content in different treatments, I used the baseline values obtained using our current procedure from archived samples to overcome any errors associated with sampling and instrumental variation.

For interaction site, archived samples were not available for reanalysis, hence I reported the changes in C content calculated using the baseline values as measured in 1986.

Regression to the Mean (RTM) correction

Regression analysis of the relationships between the changes in soil C and baseline values was conducted with accounting for the regression to the mean phenomenon (RTM). Lark et al. (2006) mentioned that while relating a change in value in any soil properties with its baseline value, at least part of the relation will include regression to the mean (RTM) effect. RTM occurs when unusually large or small measurements obtained by chance during baseline sampling are followed by the measurements that are less extreme and closer to the mean in the subsequent sampling.

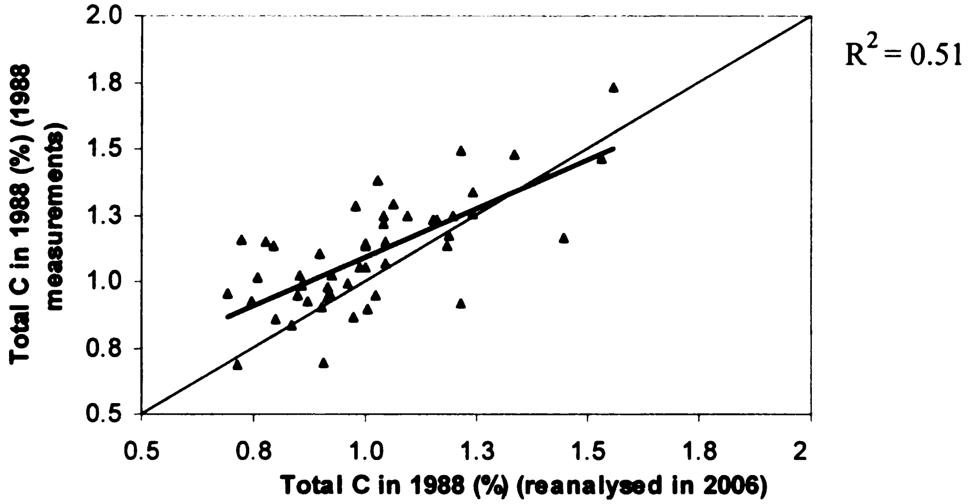

Fig. 4.1. Comparison of baseline C values obtained from KBS database value with baseline samples reanalyzed using current procedure for the LTER Main site along with 1:1 line

Thus even in the absence of the real relationship between the changes and the baseline levels, larger changes are often associated with more extreme baseline values leading to negative sample correlation (Barnett, 2005). The proportion of RTM effect may be more, when we resample only portion of the original sites in the subsequent sampling. In our study both the main site and interaction site, only a portion of the baseline points were resampled, so I used a method proposed by Blomqvist (1977) for overcoming the RTM effect to get unbiased regression slope estimates and confidence intervals for regressions between changes in soil C and baseline values (Lark et al., 2006). The sample regression slope obtained from an ordinary simple linear regression between the change and the baseline, $\hat{\beta}$ is adjusted as following (Blomquist, 1977)

$$\hat{\beta}_{adjusted} = \frac{\hat{\beta} + (1 - V)}{V} \quad [1]$$

where $V = 1 - (S_u^2/S_z^2)$,

$\hat{\beta}_{adjusted}$ is the adjusted regression slope obtained after accounting for RTM effect.

S_u^2 is the independently determined estimate of the variance for the baseline data which is due to all the sources of uncertainty in baseline measurements, i.e., those associated with analytical error and the spatial variability between the nominal and true location of resampling array (Lark et al., 2006). To obtain the S_u^2 values, I calculated sample variograms for the baseline values using PROC VARIOGRAM and fitted the variograms model with PROC NLIN. The value of S_u^2 was set to be equal to the variogram value at 3 meters distance as obtained from the fitted variogram models. This value was considered to be representative of the spatial variability of the baseline C data within 3 meters area around the sampling site. This area was assumed to provide a conservative estimate of the errors in identifying the precise location of the baseline sampling sites. Being a cumulative estimate, S_u^2 evaluates the error associated with relocating the sample sites plus the variability occurring at distances less than 3 m, that is, accounts for analytical errors as well (Lark et al., 2006). S_z^2 is the overall sample variance obtained from the 1988 baseline samples used in this study. Substituting S_z^2 and S_u^2 in Eq. [1] I obtained adjusted regression slopes and confidence intervals for the adjusted regression slope as

$$C.I = \hat{\beta}_{adjusted} \pm t_{(\alpha/2)(n-1)df} * S.E \qquad [2]$$

Here the $t_{(\alpha/2)(n-1)df}$ is the tabulated t-value obtained for the (n-1) degrees of freedom at significance level($\alpha = 0.05$) and S.E is obtained as

$$Var(\hat{\beta}_{adjusted})/(1+\hat{\beta}_{adjusted})^2 \approx Var(\hat{\beta}_{Initial}')/(1+\hat{\beta}_{Initial}')^2 + (v/(1-v))^2[CV^2(S_u^2)+CV^2(S_z^2)] \qquad [3]$$

$$CV(S_u^2) = std(S_u^2)/E(S_u^2) \qquad [4]$$

$$CV(S_z^2) = std(S_z^2)/E(S_z^2) \qquad [5]$$

Here $CV(S_u^2)$ and $CV(S_z^2)$ represent the dispersion in the value of independently determined estimate of the variance for the baseline data and the true sample variance respectively. CV (S_u^2) and CV(S_z^2) were calculated using Eq. [4] and Eq. [5]. For CV(S_u^2), standard deviation of S_u^2 is assumed to be about 6 % of the mean of S_u^2, since about 6 percent variability in C was associated with analytical errors and spatial variability within 3 meters. For $CV(S_Z{}^2)$, standard deviation of $S_Z{}^2$ is about 21% and 45% of the mean of $S_Z{}^2$ at main site and interaction site respectively which is obtained based on true sample variance. To obtain the intercept, the regression line with $\hat{\beta}_{adjusted}$ is passed through the point of mean baseline C value, $\bar{x}$ and the mean 2006 C value, $\bar{y}$. Then the intercept is obtained from the following equation.

$$\overline{Y} = \hat{\beta}_{adjusted}\,\overline{X} + \hat{\beta}_0 \qquad [6]$$

Relationships between the changes in soil C and baseline values presented and discussed were the results obtained after accounting for the regression to the mean phenomenon (RTM) effect.

RESULTS AND DISCUSSION

Long Term Trends in Changes in Soil C under Different Management Systems

No single treatment showed increase in C content over the baseline C level (1986-88) at both main site and interaction site. In LTER Main site, the mean baseline C (1988) values were found to be somewhat lower in CT (9.3 g C kg $^{-1}$ soil) than in CT-cover (10.1 g C kg $^{-1}$ soil) and NT (10.6 g C kg $^{-1}$) treatments even prior to management implementation (Fig. 4.2). Mean C content of contemporary samples (2006) under NT(9.9 g C kg $^{-1}$ soil) and CT-cover(9.8 g C kg $^{-1}$ soil) were significantly greater than CT(8.2 g C kg $^{-1}$ soil) (Table 4.2a). Mean changes in C (2006-1988) adjusted for the common level of baseline C values was equal to -1.15, -0.71 and -0.16 g C kg $^{-1}$ soil for CT, NT and CT-cover, respectively.

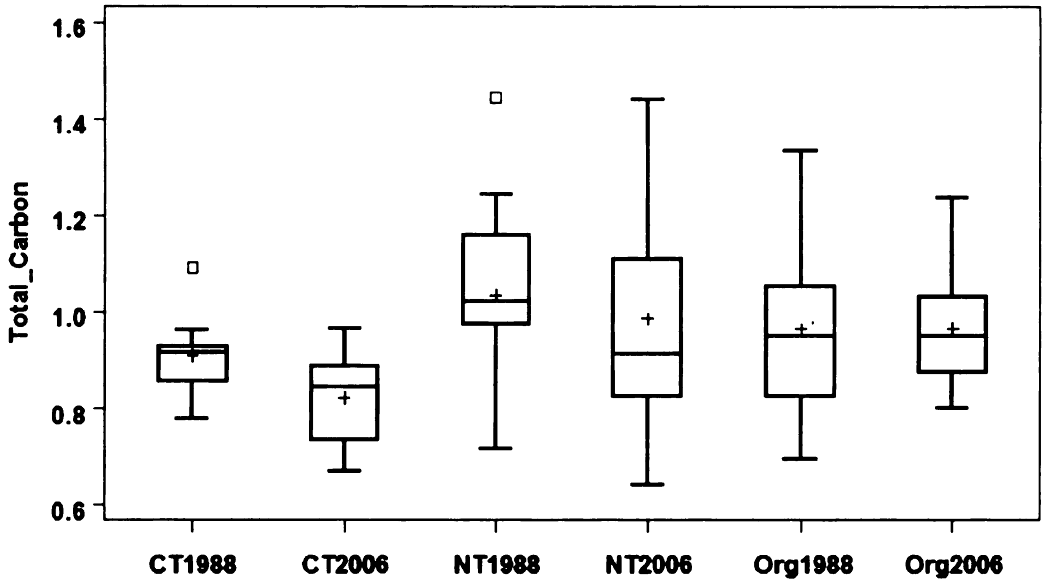

Fig. 4.2 Baseline C (1988) and contemporary (2006) soil C content (0-15 cm) in CT, CT-cover(organic) and NT treatments at the LTER main site

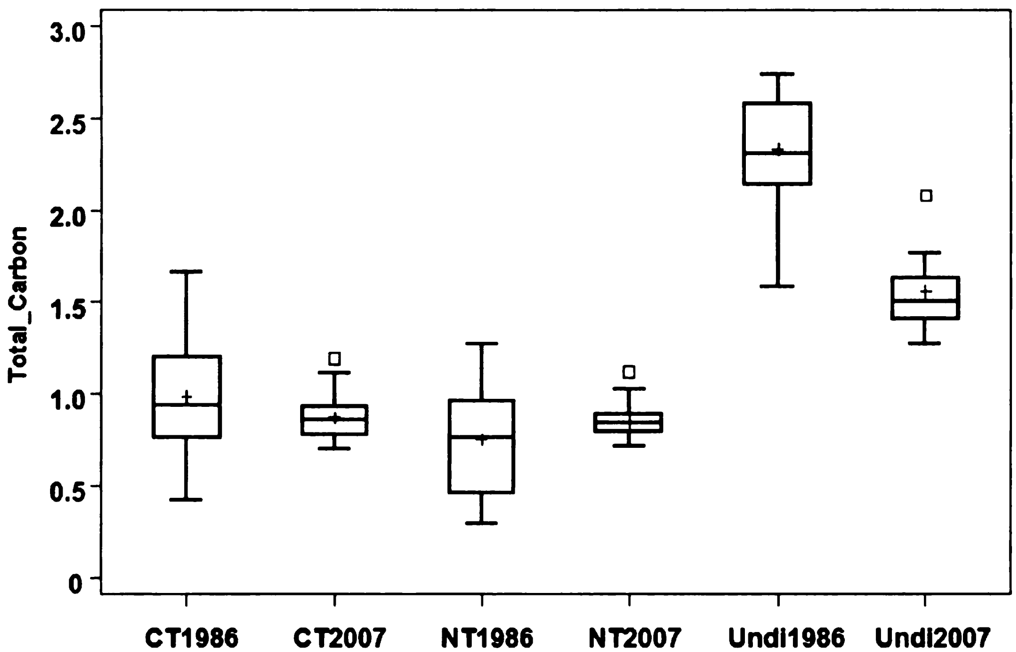

Fig.4.3. Baseline (1986) and contemporary (2007) soil C content (0-20 cm) in CT, NT and Never tilled grassland plots (undisturbed) at the long term interaction site experiment.

Table 4.2a. Mean baseline(1988) C and contemporary(2006) C in CT, NT and CT-cover at LTER main site. Standard errors are shown in parentheses.

TRT	Baseline C	2006 C
	g kg $^{-1}$ of soil	
CT	9.3 (0.7) a*	8.2 (0.3) a*
NT	10.6 (0.5) a	9.9 (0.5) b
CT-cover	10.1 (0.5) a	9.8 (0.3) b
P value	0.43	0.02

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

Table 4.2b. Mean changes in C content adjusted for standardized baseline C content along with raw means (unadjusted for baseline) in CT, NT and CT-cover at LTER main site. Standard errors are shown in parentheses.

Treatment	Raw data	Adjusted for standardized TC1988
		g kg $^{-1}$ of soil
CT	-1.15*(0.36) a**	-1.15*(0.27) a**
NT	-0.71NS(0.52) a	-0.71NS (0.48) a
CT-cover	-0.17NS (0.49) a	-0.16NS (0.29) a
P value	0.35	0.14

NS - the value is not significantly different from zero (p<0.05)
TC1988 – baseline C value during initiation of the experiment at 1988
* Means that were significantly different from zero at p<0.1
** Means within the same column followed by the same letter are not significantly different (α=0.05)

At NT and CT-cover the mean changes in C value were not different from zero indicating no change in C content over the baseline values, while in CT the mean change is significantly lower than zero indicating C losses prevailing at CT. The studied treatments, CT, NT and CT-cover were not significantly different from each other in terms of changes in C content ($p<0.05$) (Table 4.2b). In the Interaction site, mean baseline C (1986) were somewhat different among the treatments prior to treatment implementation, e.g. C in NT(8.2 g C kg^{-1} soil) tended to be lower than that in CT(9.8 g C kg^{-1} soil). Baseline C values of never tilled sites (20.4 g/kg) were much higher than those of the agronomic part of the experiment (Fig.4.3). Mean C content of contemporary samples(2007) under NT(8.6 g C kg^{-1} soil) were similar to that of CT(8.8 g C kg^{-1} soil) (Table 4.3a).The variability in the Interaction site baseline (1986) C data was found to be much higher as compared to that in 2007.

For example, C variances in samples collected from NT and CT plots in 1986 were equal to 0.07 and 0.07, respectively, while they were equal to 0.03 and 0.01 in 2007 measurements. The difference could be attributed to different measurement procedures used in 1986 (Walkley-Black) and 2007 (Carlo-Erba) and differences in sample preparation and processing. There was a significant interaction effect between tillage and fertilization for the change in C content ($p<0.1$) and the main effect of tillage also was found to be significant (Table 4.3b; $p<0.05$). Mean changes in C values(2007-1986) for the CT-F, CT-NF, NT-F and NT-NF were equal to -0.22, -1.54, 0.31 and 0.97 g C kg^{-1} soil, respectively (Table 4.3b). The mean C change in CT-NF was less than zero and less than those of both NT-F and NT-NF treatments. The mean C changes of CT-F, NT-F and NT-NF were not different from zero and not different from each other either.

Table 4.3a. Mean baseline C (g kg $^{-1}$) and contemporary (2007) C content at fertilized and unfertilized plots of CT and NT at LTER-interaction site treatments from 0-20 cm depth. Standard errors are shown in parentheses.

Treatment	Baseline C	2007 C
Main effects		
CT	9.8 (1.2) a*	8.6 (0.3) a*
NT	8.2 (1.2) a	8.6 (0.3) a*
P Value	0.11	0.61
Interaction effect		
CT-F	9.8 (1.4) a*	9.5 (0.5) a*
CT-NF	9.8 (1.4) a	8.2 (0.5) a
NT-F	7.4 (1.4) a	8.3 (0.5) a
NT-NF	8.9 (1.4) a	8.9 (0.5) a
P Value	0.48	0.07

* Comparisons of mean effects (either among marginal means or among cell means) within the same column followed by the same letter are not significantly different (α=0.05

Table 4.3b. Mean changes in C values (g kg $^{-1}$)adjusted for the standardized baseline C content in CT and NT of LTER-interaction site treatments. Standard errors are shown in parentheses.

Treatment	Raw data	Adjusted for standardized TC1986
Main effects		
CT	-1.15^{NS} (0.9) a**	-0.88* (0.34) a**
NT	0.94^{NS} (0.9) a	0.64^{NS} (0.35) a
P value	0.08	0.013
Interaction effect		
CT-F	-0.28^{NS} (1.1)a **	-0.22^{NS} (0.46) ab**
CT-NF	-2.02^{NS} (1.2)a	-1.54* (0.51) a
NT-F	0.79^{NS} (1.1)a	0.31^{NS} (0.48) b
NT-NF	1.08^{NS} (1.2)a	0.97^{NS} (0.51) b
P value	0.36	0.07

CT-F , Conventional tillage, Fertilized; CT-NF , Conventional tillage, non fertilized;
NT-F , No tillage, Fertilized; NT-NF , No tillage, non fertilized;
TC1986 – baseline C value content during initiation of the experiment at 1986
* Means that were significantly different from zero at p<0.1
** Comparisons of mean effects (either among marginal means or among cell means) within the same column followed by the same letter are not significantly different (α=0.05)

Mean changes in C content at CT and NT across both fertilization treatments were equal to -0.9 and 0.6, g C kg $^{-1}$ soil, respectively. The change in C at CT was significantly less than zero representing C losses at CT. However the change in NT was not different from zero indicating no change in C content over the baseline values, similar to the results from the main site. Decline in soil C content over the baseline status at CT at 0-20 cm depth was previously reported by Hendrix et al. (1998) in a 16 year old experiment carried out in a fine loamy soil in Georgia and by Doran et al. (1998) at 0-30 cm in a 22-27 year old experiment in a silt loam soil in Nebraska. Both studies reported that the magnitude of C losses was greater in CT as compared to NT. No change in C content at NT was similar to the results reported in other previous studies reported by Puget and Lal (2005) at 0-30 depth in a 8 year old experiment carried out in a Mollisol of central Ohio; and by Eynard et al.(2005) at 0-20 cm in a 6-16 years old long-term experiments studied in Ustolls in South Dakota.

C losses at never tilled sites were equal to 1.7 kg C m $^{-2}$ (0-20 cm) and were the highest as compared to all treatments from the Interaction site and the main site. Occurrence of greater C losses in New Zealand grasslands of about 2.1 kg C m $^{-2}$ from one meter depth during the past 2 decades was also reported by Scipper et al. (2007). Summarizing the Main site and Interaction site results, I conclude that changes in C content varied with the management system. Total C at conventional chisel plowed management has decreased by 1.15 g C kg $^{-1}$ soil and 0.22 g C kg $^{-1}$ soil at main site and interaction site respectively (treatment CT-F is used here for comparing CT of main and interaction sites). When compared at present (in 2006 and 2007), total C values under no-till management with conventional chemical inputs and under organic management with cover crops are higher than those of the conventional management ((Table 4.2a, Table 4.3a). However, examination of the changes since 1986 and 1988 revealed that there has not been a net gain in C under these systems. The observed differences with conventionally tilled systems are reflecting C losses sustained by its soil. C in never tilled soil kept for past >25 years under grass vegetation has decreased on 7.4 g C kg^{-1} soil since 1986. Within the conventional tillage system, the C losses were found to be greater in unfertilized compared to fertilized treatments.

Rate of change in C content and the size of the C pool in any management system depend on the balance between soil C inputs through plant residues and C losses which occur mainly through decomposition. The balance exists for particular environmental settings affecting decomposition rates, including air and soil temperatures and moisture availability. It appears that the observed C losses in never tilled sites might be due to increased decomposition rate. The increased decomposition rate could be driven by rising winter temperatures in Michigan. Two recent studies also linked widespread soil C losses at England and Wales (Bellamy et al., 2005) and at pasturelands at New Zealand (Scipper et al., 2007) with the increase in global climate change.

Latest report from the Intergovernmental Panel on Climate Change (IPCC) predicts the average increase in global temperature of about 1.4-5.8° C for the period of 1990 to 2100 (Luo et al., 2001). Organic matter decomposition is very sensitive to rise in temperature (Knorr et al., 2005; Conant et al., 2008). It is expected that the temperature effect on changes in soil C will be greater in temperate regions than in tropical regions. In temperate regions, rising temperatures will increase organic matter decomposition rates but will not lead to substantial changes in net primary productivity (NPP) (Kirschbaum, 1995). The greater sensitivity for organic matter decomposition to rising temperature as compared to that of NPP will play an important role affecting the balance between C inputs and C outputs.

In Michigan, over the last century, the mean temperature has increased from 46.6°F (1876-1905 average) to 47.7°F (1962-1991 average; US EPA,1997). Over the next century, based on IPCC and United Kingdom Hadley Centre's climate model (HadCM2), it was projected that by 2100, Michigan's temperature might increase by 4°F in all seasons with range of 2-8°F (US EPA,1997). Data from KBS weather stations indeed indicate that the number of days per year with temperature daily average minimum above freezing has been increasing during the past 15 years (Fig. 4.4).

Potential effects of global warming on soil C storage under CT and NT management practices in KBS-LTER were reported earlier by Paustian et al. (1995). They evaluated soil C storage projections under the scenario of the mean annual temperature increasing by 2° C by 2050 based on IPCC estimates using Century model. The simulation assumed that no changes in management or in C input levels were made in conventional tillage system. Model predicted a decline in C storage from the baseline status at CT by taking baseline C values as 3 kg C m^{-2} for 0-20 cm observed at mid 1980's. Results from our current measured C levels support these model predictions.

In soils under agricultural management, soil C losses due to increase in decomposition rate is partly compensated by increase in agricultural productivity due to improvement in crop varieties and usage of external chemical inputs.

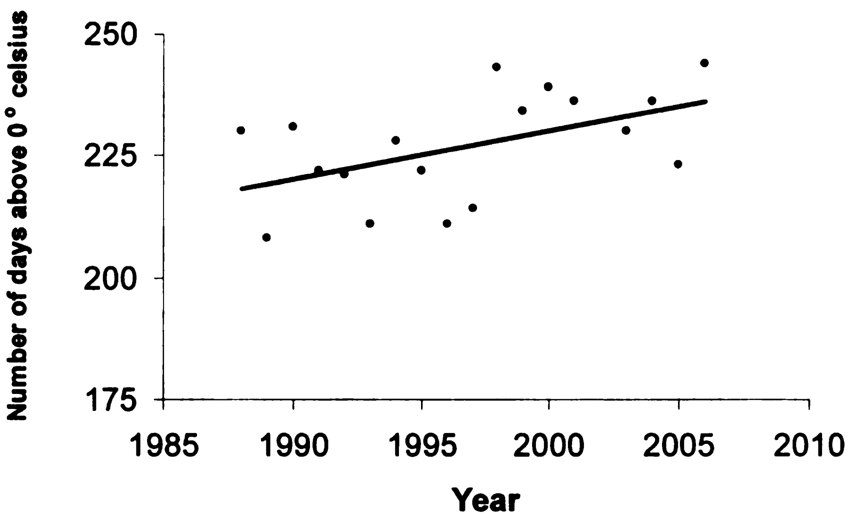

Fig. 4. 4. Decadal pattern of number of days above freezing point at the KBS-LTER site (R^2 = 0.27).

In Michigan, the annual agricultural productivity was reported to increase by about 2.6 percent per year during 1960-1999 (http://www.ers.usda.gov/Data/AgProductivity). At never tilled sites, the productivity might be more stable and might have not increased over this time period unlike that in the agricultural systems. Hence at undisturbed sites, due to winter warming C loss through decomposition will be exceeding the amount of C from the inputs that can be stored in soil under new temperature balance.

Pautian et al., (1995), predicted that the baseline C can be sustained or marginally increased if the agricultural productivity increases annually by 1.4 percent which might result in 40 percent more residue return as compared to present residue return rate. Our study results from NT and CT-cover shows that C content has not changed since 1986-1988. With the projected increase in global temperature, at practical standpoint, at least adoption of NT or inclusion of cover crops in the crop rotation may be one of prerequisites to sustain the present soil C levels. With the growing bioenergy market, increased removal of crop residues for the biofuel feedstock may have serious negative impact on the soil quality causing increase in soil C losses, in turn increasing the global warming potential.

Climate induced soil C changes are likely to differ in magnitude under different tillage and management systems. Moreover, within each management system local variations in soil properties also influence C change values. Greater C losses at CT and no change in C content at NT are mainly driven by difference in disturbance gradient at these treatments. In this study, NT receives the least soil disturbance compared to CT, however C inputs through annual residue return reported to be same under both CT and NT (Robertson et al., 2000). Though both the treatments receive the same level of C inputs, C losses due to organic matter decomposition might be relatively greater at CT compared to NT. At CT, due to tillage disturbance the aggregate turnover rate will be faster which in turn increases organic matter decomposition by means of exposing more of relatively young and labile organic matter to microbial attacks (Pautian et al., 2000). Moreover, in CT faster aggregate turnover also inhibits formation and stabilization of more recalcitrant organic matter fractions which has longer mean residence time (Six et al. 1999). Lack of soil disturbance in NT increases the number and stability of soil aggregates which in turn protects SOC from rapid oxidation by encapsulating C within the stable aggregates (Puget and Lal, 2005). NT also promotes the formation of recalcitrant SOC within micro and macro aggregates and increases the mean residence time (MRT) of the organic matter fractions compared to CT (Pautian et al., 2000).

The difference in changes of C content between CT-cover and CT are driven by difference in quantity and quality of residue inputs from the primary crops and cover crops of these treatments. At CT-cover, despite of heavy soil disturbance, magnitude of soil C changes was found to be similar to that of NT. Similar results showing organic based systems with cover crops to be as effective as no-till (Teasdale et al., 2007) and more efficient than CT in maintaining C was also reported earlier in other long term studies (Pulleman et al., 2000; Marriott and Wander 2006).

Legume based organic tillage system enhances or maintains soil C storage due to following mechanisms. C inputs from cover crops have narrow CN ratio and thus enhance soil C storage by means of improving the soil physical properties such as increase in the total porosity and wet aggregate stability (Villamil et al., 2006). Mycorrhizae associated with the leguminous cover crop secretes proteineous substance called glomalin which acts as cementing agent in binding the soil particles and is found to be effective in providing short term stabilization of large aggregates (Brady and Weil, 2002). Inclusion of cover crops in the crop rotation reduces the frequency of bare fallow period in crop rotations, which in turn reduces organic matter decomposition rates. Thus additional inputs from the cover crop and greater aggregate stabilization offset soil C losses due to heavy tillage disturbance in an organic CT system.

Relationship between Changes in C content and Baseline C

At main site, baseline C content was found to have significant negative relationship with the change in C values at CT-cover however at CT and NT the relationship found to be insignificant (Table 4.4). At the interaction site, significant negative relationship was observed between baseline C values and the change in C values from 1986 to 2007 C values in all the studied treatments (Table 4.5).

Precision of the treatment estimates were also improved after adjusting with the baseline value, which is reflected in lower standard error and lower *p*-values compared to the unadjusted mean values (Table 4.2b). Negative relationship between baseline C and change in C content reported in the study were consistent with the results reported in literature (Bellamy et al., 2005; VanderBygaart et al., 2002). One possible mechanism behind the negative relationship between baseline C levels and the change might be related to soil's saturation with C (Hassink 1997, Six et al., 2002).

Table 4.4. Results of observed and RTM adjusted slope estimates for baseline C effect on changes in C content in the LTER-mainsite treatments.

TRT	Observed slope	Adjusted slope
CT	-0.64*±0.56	-0.41^{NS}±0.91
NT	-0.47^{NS}±0.50	-0.31^{NS}±0.81
CT-cover	-0.73±0.28	-0.58*±0.45

NS - Regression slopes that were not significantly lesser than zero (α=0.05).
* Regression slopes that were significantly less than zero at p<0.05

Table 4.5. Results of observed and RTM adjusted slope estimates for baseline C effect on change in C content of LTER- interaction site treatments

TRT	N	Observed slope	Adjusted slope
CT-F	14	-0.95*±0.35	-0.93*±0.49
CT-NF	10	-0.82*±0.18	-0.76*±0.28
NT-F	12	-0.89*±0.18	-0.85*±0.26
NT-NF	11	-1.04*±0.15	-1.05±0.22
Never tilled	13	-0.88*±0.41	-0.84*±0.58

CT-F , Conventional tillage, Fertilized; CT-NF , Conventional tillage, non fertilized;
NT-F , No tillage, Fertilized; NT-NF , No tillage, non fertilized;
Native: Annually mowed, never-tilled grassland.
* Regression slopes that were significantly different from zero (p<0.05)

In our study, the baseline C content at the Native sites was relatively higher than the conventional tillage system. The major proportion of the higher baseline C content in the never tilled sites will be occupied at the protected C sites and additionally a lot of C is stored in unprotected forms as light fractions and POM. The amount of unprotected C being held at equilibrium at never tilled sites, on subjected to change in environmental conditions such as increase in temperature might have experienced greater losses as a result of increased decomposition rate. At conventional tillage system, most of the labile state C that comes from the native vegetation might have already been depleted and the baseline C (1988) mentioned in this study might be the equilibrium state of most stable C. These most stable, low baselines C at conventional tillage system would have been occupied in the protected sites and only small amount of C is present at unprotected C pools which resulted in relatively lower soil C losses. Similar to the results reported in our study, Bellamy et al. (2005) observed lower soil C losses in cultivated lands and greater C losses in grasslands.

Relationship Between Changes in C and Soil Texture (silt+clay)

Among the studied treatments, significant positive relationship between changes in C content and silt+clay content was observed only at NT with r^2 value of 0.32 at the main site (Table 4.6) and 0.13 for the interaction site. Increase in SOC with increase in silt+clay content in NT was consistent with the previous studies (Needelman et al., 1999; Hao and Kravchenko., 2007). Silt +clay content increases SOC possibly because NT favors formation of micro- and macro-aggregates which provides greater stability to the silt and clay associated C stored as the protected pool.

Table 4.6. Relationships between changes in C, N and silt+clay content at 0- to 15-cm depth for the LTER main site.

TRT	Regression model	R^2
CT	$\Delta C = -0.11 - 0.00003$ Silt+Clay ^{NS}	0.01
NT	$\Delta C = -0.68 + 0.01$ Silt+Clay ***	0.32
CT-cover	$\Delta C = -0.12 + 0.002$ Silt+Clay ^{NS}	0.01

ΔC = 2006 C -1988 C ;
NS - Regression slope is not significantly greater than zero (α=0.05).
Regression coefficient that were significantly less than zero p<0.01(***)

Table 4.7. Relationships between changes in C and silt+clay content at 0- to 20- cm depth for the LTER interaction site.

TRT	Regression model	R^2
CT F	$\Delta C = -1.8 + 0.03$ Silt+Clay ^{NS}	0.14
CT NF	$\Delta C = 1.22 - 0.023$ Silt+Clay ^{NS}	0.29
NT F	$\Delta C = -0.24 + 0.003$ Silt+Clay ^{NS}	0.003
NT NF	$\Delta C = -4.3 + 0.08$ Silt+Clay ***	0.44
Never tilled	$\Delta C = -0.49 + 0.004$ Silt+Clay ^{NS}	0

CT F , Conventional tillage, Fertilized; CT NF , Conventional tillage, non fertilized;
NT F , No tillage, Fertilized; NT NF , No tillage, non fertilized;
Never tilled: Annually mowed undirturbed grassland.
ΔC – 2007 C -1986 C
NS - Regression slopes that were not significantly greater than zero (α=0.05).

In NT, changes in C content were found to be positively correlated with silt+clay content which shows that protective capacity of our soils has not been saturated.

In CT and CT-cover, relationships between changes in C content and silt+clay were not significant. Conventionally tilled soils have limited potential to protect C in the aggregates since the aggregate formation is greatly disrupted by plowing (Puget et al., 1995; Paustian et al., 1997). For example, Beare et al., (1994) mentioned that the pool of physically protected C in macroaggregates accounts for 10 % of soil C stocks in the tilled soil and 19% in the no-tilled soils.

In previous studies, greater C content in organic based systems is mainly attributed to increases in POM. Organic based system is reported to have 30-40 percent more POM than the conventional system (Marriott and Wander, 2006). Earlier studies reported that POM content is not directly related with soil texture (Plante et al., 2006; Franzluebbers and Arshad ,1997). Soil C at CT and CT-cover is protected mainly through physico-chemically stabilization (Krull et al., 2003) rather than physical stabilization alone (Hao and Kravchenko, 2007). Above results shows that soil texture information might explain greater amount of variation in soil C changes in NT soils compared to CT and CT-cover.

SUMMARY

In summary, increase in winter temperature at Michigan might be one of the major factors that cause soil C losses in this site. Baseline C was found to have negative relationship with changes in C content, and C loss was found to increase with increase in baseline values. Increase in silt and clay content leads to bring positive changes (gain in C) in C content in no-till system. The effect of relative relief was not found to have any relationship between changes in C content, probably due to small sample size and low variations in topography among the sampled locations. With respect to long term trend in soil C storage, at conventional chisel plowed management, total C was found to decline by about 10 percent C from that baseline C value (1986-2007).Within conventional tillage system, C losses were found to be greater at unfertilized compared to fertilized treatments. As comparing management practices at present, soil C under no-till management and under organic management with cover crops tends to be higher than that of the conventional management, however, it has not changed as compared to 1988. That is, the conservational management practices appeared to have prevented total C loss as compared to conventional management but they did not lead to gains in absolute amount. Likewise, the total C of the never tilled grassland soil has decreased by about one third from the baseline C of 1986. In summary, none of the studied treatment showed increase in C content from the baseline values. With the projected increase in global temperature, at practical standpoint, at least adoption of NT or inclusion of cover crops in the crop rotation may be one of prerequisites to sustain the present C levels at soils in temperate region.

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Chapter V

SUMMARY AND CONCLUSIONS

As expected, management practices substantially influenced the spatial variability pattern in soil C distribution. Total C, N content and overall variance observed at 15 year old poplar from the surface depth (0-5 cm) was found to be closely similar to that of NT followed by CT-cover and substantially different from that of CT. With spatial variability characteristics, variogram values near the origin, variogram values at 1.5 m distance to sill ratios at poplar was greater compared to other agronomic treatments, which show that C is highly variable at very shorter distance at poplar, compared to agronomic treatments. Variability characteristics of the total C, N in the studied plots were strongly affected by topographical gradients at CT-cover and NT and least at poplar system. Overall the results indicated that poplar system did not differ substantially with no-till system in terms of soil C, N content and in overall C and N variability pattern in a landscape.

Comparing the spatial variability pattern between surface (0-5 cm) and below plowing (20-30 cm) depth, at CT, spatial correlation range, nugget and sill values at surface depth is substantially greater compared to below plow depth indicating greater variability in surface depth compared to below plowing depth. However at CT-cover, variability in C distribution pattern was found to be greater at even at subsurface depth. Topographical features have major effect controlling the spatial variability pattern at CT-cover compared to CT at both the studied depth. Inclusion of spatial variability information substantially improved the precision of the treatment estimates in this study.

Relationship between topography and soil C, N was found to vary with different tillage and management practices. Management practices significantly interacted with topographical features as represented by WI with both C and N. Topography had a stronger effect on soil C and N with the organic based chisel-plow system (CT-cover) compared to the chemical input based no-till (NT) and chisel plow (CT) systems. Greater regression slopes was observed between WI and C in CT-cover than CT; and greater differences in C content between CT-cover and CT in valleys than uphill. Among the landform elements, C and N content was found to be greater at valley areas compared to upperslope position in all the studied treatments. At 0-30 cm depth, CT-cover and NT was found to accumulate 2.2 and 1.81 Mg more C per acre than CT at uphill position and 3.7 and 6.2 Mg per acre more C than CT in the depressions. In overall, CT-cover was found to be equally efficient in maintaining C and N content as compared to NT treatments. Largest C and N benefits of CT-cover in the landscape were observed in valleys as compared to uphill position in the landscape. The results demonstrate that organic management has greater potential for C sequestration at lower landscape positions.

With respect to long term trend in soil C storage during the past 15-20 years at Michigan, soil C at conventional chisel-plow management has decreased by 0.9 to 1.15 g kg $^{-1}$ of soil and the never tilled grassland soil has decreased on 7.4 g kg $^{-1}$ of soil since 1986 levels. Within conventional tillage system, C loss was found to be greater in unfertilized compared to fertilized treatments. Soil C under no-till and organic based chisel plow system tends to show no change in C content from the baseline C values. No-till and organic tillage system might have prevented soil C loss as compared to conventional management system due to lesser soil disturbance at NT and additional C inputs in CT-cover but they did not lead to absolute gain in C. Baseline C was found to have negative relationship with changes in C content, and C loss was found to increase with increase in baseline values. Increase in silt and clay content leads to bring positive changes (gain in C) in C content in no-till system. Rising winter temperature might be one of the major factors that cause soil C loss at Michigan. In summary, none of the studied treatment showed increase in C content from the baseline values. With the increasing global warming potential, adoption of NT or inclusion of cover crops in the crop rotation may be one of the prerequisite to sustain the present C content in the soils of the temperate regions.