VARIABILITY OF CARBON SEQUESTRATION IN THE TIDEWATER REGION OF THE SOUTHEASTERN US

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ABSTRACT

In the humid, tropical southeastern U. S., the dynamics of total soil organic carbon (SOC), particulate organic matter (POM), CEC and bulk density (D_b) in the 0-5, 5-10, and 10-18 cm depths in cotton production systems with or without cover crops is unknown. The objective of this research was to examine the impact of cotton production systems either with or without winter cover crops on these soil properties. Two sites in the coastal plain region of North Carolina with different soil series were selected for this analysis. At each site cotton was grown with and without tillage. Significant depth and temporal interactions were found in D_b, POM and CEC while significant tillage effects were found in total C. Results on D_b found spatial variability with depth but not with season. Total C decreased with depth but was independent spatially and temporally. POM declined with time regardless of depth implying a priming effect. As for CEC, there was no consistent trend. Additionally, CEC exhibited a moderate correlation to POM but not to total C. Total C, total N and D_b did not differ by tillage system indicating more effort is needed to define and/or develop cropping systems that will provide the soil organic matter inputs necessary to maintain and build soil carbon. Lack of difference between the two soils represented in this study indicated that the key element in the variability in soil carbon in the coastal plain is the presence of organic soils found in the Carolina Bays which are a unique geographic feature of the southeastern US.

Keywords: Total carbon, cropping systems, cover crops, nitrogen, bulk density, CEC

INTRODUCTION

The use of conservation tillage cropping systems in the southeastern United States has increased 94 percent in the past ten years to include 42.5 percent of all cropland (Regional Synopsis, 2002). This increase in the use of reduced tillage has been made possible as a result of farm bill requirements, herbicide resistant crops and an understanding of the benefits of soil organic carbon (SOC). As shown by the literature, it is possible to enhance many of the soil properties that improve production with additions of plant dry matter to the soil in conjunction with long-term conservation tillage (Arshad et. al., 1999; da Silva et. al., 2001; Franzluebbers and Hans, 1996; Soon and Arshad, 2004;

Hunt et. al., 1996; Bruce et. al., 1995). Additionally, the residue that is returned to the soil surface is considered to be vitally important for biological diversity, as an energy source, and in substrates that are necessary for many soil functions (Franzluebbers, 2002a; Wagger and Denton, 1992; Soon and Arshad, 2004; Franzluebbers et. al., 1994b). Since there is a correlation between residue inputs, reduced tillage and benefits to soil carbon and other soil properties the key question is what impact do cotton cropping practices using either no-till or conventional tillage have on SOC and other soil properties in the warm, humid climate of the Southeastern US.

Although past research has indicated that soil organic matter (SOM) is the central indicator of soil productivity (Reeves, 1997), the level of SOM is not an absolute measure of a soil's level of productivity. Crop production can be limited in a soil that has high surface SOC and a high subsurface bulk density (D_b) that limits root penetration. Kay and VandenBygaart (2002) have also observed increases in D_b and a corresponding decrease of porosity in the plow layer with the conversion to no-tillage. Additionally, the interrelationship between the two properties is poorly documented (Kay and VandenBygaart, 2002).

Total SOC as a measure of past and current dry matter inputs, combined with particulate organic matter (POM), appear to be the best measures of organic C correlations with crop productivity. Contrary to total SOC, particulate organic matter consists of partially decomposed plant and animal residues and is the first step in the decay process between crop residues and stable humified organic matter (Gregorich and Janzen, 1996). Cambardella and Elliot (1992) define POM as the stabilized fraction of organic matter composed of root fragments in various stages of decomposition. This root fragment fraction appears to be a more important contributor to SOC than the surface dry matter fraction. Wander and Bollero (1999) suggest POM to be important due to its sensitivity as an indicator of soil quality.

In cold, dry environments (i.e. temperate climates), the relatively slow rate of decomposition of newly added crop residues in a no-tillage system has been proven to create large stocks of SOM and to improve soil quality (Arshad et. al., 1999; Franzluebbers, 2002a). However, in the humid, subtropical environment of the southeastern United States, the more rapid rate of decomposition generated by the greater moisture and temperature levels make it difficult to maintain SOC levels, unless at least 12 Mg/ha/yr (5 t/ac/yr) of total dry matter (i.e. crop residues plus cover crop residues) are returned to the soil surface each year (Bruce et. al., 1995)). Therefore, a reasonable amount of dry matter must be returned to the soil surface to decompose and become part of the SOC pool. As indicated by the literature additions of SOC will increase fertility, water holding capacity, structure and porosity of the soil when compared to a conventional tillage system (Bruce et. al., 1995; Hendrix et. al., 1998; Langdale et. al., 1990; Hunt et. al., 1996). Additionally, Franzluebbers (2002a) indicated that conservation tillage systems in areas with low native SOM (i.e. humid, subtropical environments) might show the greatest improvement compared with conventional tillage.

While SOC additions to the soil through decaying dry matter on the surface and root matter subsurface can make measurable improvements to a soil in the humid, subtropical southeastern U.S., the dynamics of total SOC, POM, CEC and D_b in the 0-5, 5-10, and 10-18 cm depths in a cotton production system that uses cover crops and/or additions of organic matter from mature cover crops (i.e. cover crops allowed to reach soft dough stage for cereals or early bloom for legumes) at rates >6 Mg/ha/yr (3 t/ac) are unknown. The objectives of this research were to determine what spatial and temporal effects cotton cropping systems using cover crops have on the following parameters: total SOC, POM, CEC, and D_b in conventional and no-till cropping systems and to use the information gained from this study to determine the causes for the extreme variability in soil C found in soils in the Southeastern US.

MATERIALS AND METHODS

Information About the Selected Locations

Two locations in the Coastal Plain region of North Carolina that are “coarse-loamy or fine-loamy” in the family particle size class and are “well drained” as defined by the USDA taxonomic soil survey system were selected. The coarse-loamy site was located at latitude/longitude: 35^o 2’ 0.5” N, 78^o 1’ 45.5” W while the fine-loamy site is located at latitude/longitude: 35^o 10’ 19.7” N, 78^o 9’ 25.5” W. The primary test site at location one, hereafter referred to as the coarse-loamy, has a soil series name of Butters (coarse-loamy, siliceous, semiactive, thermic Typic Paleudults); while the primary test site at location two, hereafter referred to as the fine-loamy site, has a soil series name of Thursa (fine-loamy, kaolinitic, thermic Typic Kandiudults).

At each location nine test sites were identified based on topography, slight differences in soil texture, soil color, and landscape position. These sites were selected to represent the key differences in the field. At two key test sites a USDA-NRCS soil scientist conducted a soils description using the bucket auger observation method to define the soils at each site. Particle size analysis was conducted at depth intervals 0-5, 5-10 and 10-18 cm in addition to the bucker auger observation method at both sites. Samples were collected from a test site near the center of each field and mailed to Waters Agricultural Laboratories, Inc, in Camilla, GA. for detailed soil texture analysis.

Site Cropping System Management

The coarse-loamy site was managed under a no-till system from before 2004 through 2008. In years 2004 through 2007, the cropping system was continuous cotton; while for 2008, the crop was switched to full season soybeans. For each year and crop, the N rate, N application month and N source are found in Table 1.

Table 1. N rate, N application month, and N source per crop and year at the coarse-loamy site.

Crop	Year	N rate[1]	N application month	N source
Cotton	2004-2007	10-17/74 (9-15/66.5)	April and June	$(NH_4)_2SO_4$
Soybeans	2008	N/A	N/A	N/A

[1] Planting/Layby N rate in kg/ha (lbs/ac)

The fine-loamy site was also managed under using conventional tillage from before 2004 through 2008. Continuous cotton was grown in crop years 2004 through 2007, while in 2008 corn was grown. Each winter, a rye cover crop was seeded after harvest of the cotton crop at a rate of ~1.7 kg/ha (1.5 bu/ac). The cover crop was allowed to reach a Feekes' growth stage of ~ 9.0 before termination. In 2004, the fine-loamy site was ripped using a DMI no-till ripper with berm tuckers. Table 2 contains the N rate, N application month and N source for each year and crop.

Table 2. N rate, N application month, and N source per crop and year at the fine-loamy site.

Crop	Year	N rate[1]	N application month	N source
Cotton	2004-2007	28/73 (25/65)	April and June	$(NH_4)_2SO_4$
Corn	2008	28/140 (25/125)	April and June	$(NH_4)_2SO_4$

[1] Planting/Layby N rate in kg/ha (lbs/ac)

Sampling Procedures

Prior to seeding the 2006 fall cover crop, a pre-cover crop set of soil cores was collected from row middles on all nine sites at both locations as a reference point for changes in the selected assays. Following the collection of the reference set of soil cores, four additional sets of soil cores were taken over a two-year period. Each year, two sets of cores were collected from all nine sites at both locations during the spring prior to planting of the cash crop and at planting of the cover crop in the fall. Soil cores were collected from depth intervals of 0-5, 5-10, 10-18 cm (0-2, 2-4, 4-7 in) within all plots at all sites.

For each plot and collection depth, three cores were collected. An undisturbed 7.6 cm (3 in) diameter soil core from a Uhland sampler (Blake, 1965) and two 9 cm (3.5 in) diameter soil cores were taken from each depth. All soil cores were carefully extracted using a small masonry trowel and/or shovel depending on depth. The undisturbed soil core was placed into a sampling tin while the other two soil cores were extracted, independently placed into a small plastic bucket, hand mixed, and placed into a cardboard soil sampling box or a 1 L (1 qt) Ziploc freezer bag, respectively. All samples were taken within a two-week period for a given site.

Sampling from row middles that were part of the field's normal traffic pattern was avoided. Field equipment widths and noticeable patterns were noted to define the trafficked middles and to determine the initial row middle for sampling. Once the initial row middle had been determined, subsequent sampling sites within each plot progressed down the same row middle for each plot.

The soil cores that were placed into the 1 L (1qt) Ziploc freezer bags were further subdivided for future analysis. Approximately one 78 ml sub-sample was pulled from each bag and placed into an individual sampling tin while the remainder of each sample was stored in a cooler at 5°C until prepared for further analysis.

Soil Properties Analyzed

Bulk density was determined on all undisturbed soil cores by oven drying the samples plus sampling tin at 105°C for a minimum of 24 hrs. The oven dry samples plus sampling tin were then weighted and recorded. A random set of sampling tins were previously weighed while empty and averaged together to quantify the sampling tin mass. The difference between the oven dry sample plus tin and the averaged sampling tin mass was used to determine the mass of oven dry soil. This mass of oven dry soil was then divided by the known volume for each soil core at each respective depth for the final D_b value. During each sampling interval, random sets of samples were dried for an additional 24 hrs under the same procedures as a quality control check.

Total SOC was determined by the dry combustion method as described by Nelson and Sommers (1982) through the use of a Perkin-Elmer 2400 CHN Elemental Analyzer. This instrument automatically measures C and N using the principles employed in the traditional Pregl and Dumas procedures. The 78 ml sub-samples pulled from the 1 L (1 qt) Ziploc bags were used for this analysis. The samples were first oven dried at 105°C for 24 hr. Once dry, the samples were hand ground using a mortise and pestle, and sieved with a 100-mesh U.S. Standard Series Sieve. The soil material that passed the 100-mesh sieve was returned to the sampling tin, capped and delivered to the North Carolina State University Analytical Services Lab where the dry combustion method was conducted.

Waters Agricultural Laboratories, Inc, in Camilla, GA conducted POM analysis on the remaining soil in each of the 1 L (1 qt) Ziploc freezer bags. The POM assay isolated POM from 20 g samples of air-dried soils by dispersion in 20 mL of 5% Na-hexametaphosphate. Liberated POM was collected on and dried in 53 µm opening polycarbonate mesh (Wander and Bollero 1999) to define the percent of POM material plus fine mineral matter. The dried POM plus fines (mineral soil particles) mass was then ignited at 360° C for 2 hrs to determine the loss on ignition percentage. The POM quantity was calculated from the mass of soil per depth unit times the percent of POM material plus fine mineral matter less percent solids remaining after ignition [%POM=(%POM+fines)-%fines after ignition].

CEC was determined using a summation of Ca, Mg, K and exchangeable acidity (Ac) as described by the NCDA&CS Soil Test laboratory. The Ca, Mg and K were extracted using a Mehlich 3 extractant (NCDA&CS). The Ac was determined by a Mehlich-buffer method at pH 6.6 resulting in the Ac component being determined at a pH between the soil and the buffer pH (NCDA&CS). This CEC methodology incorporates the measurement of non-exchangeable acidity related to pH dependent charges.

Statistical Analysis

After collection and analysis, statistical analysis was conducted on the selected soil properties using a randomized complete block split plot design model (RCBSPD):

$$Y_{ijkx} = \mu_{ijx} + R_x + (SR)_{ikx} + E_{ijkx}$$

where i denotes the sites at which cores were collected, j denotes levels of season, k denotes levels of depth, x denotes block, $R_x \sim N(0, \sigma_r^2)$ and $(SR)_{ikx} \sim N(0, \sigma_{sr}^2)$. Also, all random errors are mutually independent. The preceding model was tested through the PROC GLIMMIX procedure in SAS (SAS, 2003). Pearson's correlation coefficients (r_{xy}) were determined on selected assay results using PROC CORR while regression was determined using PROC REG procedures in SAS (SAS, 2003).

RESULTS AND DISCUSSION

Particle Size Analysis

Soil textures for the three depths at each field location were rated a loamy sand and sandy loam for the coarse-loamy and fine-loamy sites, respectively (Table 3). Particle size analysis from the fine-loamy site showed its percentage to be quite similar to a loamy sand texture. Therefore, the surface textures at both locations were essentially the same.

Bulk Density

The fixed effect depth*sampling time interaction on D_b was significant for both the coarse-loamy (*p=0.015*) and fine-loamy (*p=0.0003*) sites. The depth*sampling time interaction is further supported by the highly significant fixed main effects of depth and sampling time for D_b at both sites (*p<0.0001*). These significant interaction and main effects support D_b for the two soil texture \ family groups both being strongly temporally and spatially dependent. Cassel (1983) found a similar highly significant temporal and spatial interaction and main effect on a geographically similar fine-loamy soil in North Carolina.

Table 3. Soil texture and particle size per site and depth interval

Site	Depth	Texture	% Sand	% Clay	% Silt
Coarse-loamy	0-5 cm	Loamy Sand	84.0	2.4	13.6
	5-10 cm	Loamy Sand	83.6	4.4	12.0
	10-18 cm	Loamy Sand	85.6	2.4	12.0
Fine-loamy	0-5 cm	Sandy Loam	77.2	8.4	14.4
	5-10 cm	Sandy Loam	78.8	8.4	12.8
	10-18 cm	Sandy Loam	80.8	6.4	12.8

Simple depth*sampling time interaction pairwise comparison of D_b estimates show the interaction effect at the coarse-loamy site to be dependant on the 5-10 cm depth while the fine-loamy site expressed its dependence in both the 0-5 and 5-10 cm depth (Table 4). No significant differences were observed between mean D_b values at depth 0-5 cm and 10-18 cm at the coarse-loamy site and depth 10-18 cm at the fine-loamy site.

Table 4. Estimated simple effect means for depth*sampling time interaction on D_b ($Mg\ m^{-3}$) at the key test sites for both the coarse-loamy and fine-loamy sites.

Sampling time[1]	Coarse-loamy			Fine-loamy		
	0-5 cm	5-10 cm	10-18 cm	0-5 cm	5-10 cm	10-18 cm
Fall 2006	1.4512 a	1.5452 a	1.6190 a	1.5407 b	1.6088 b	1.6821 a
Spring 2007	1.3457 a	1.4138 b	1.6258 a	1.5637 ab	1.6198 ab	1.6746 a
Fall 2007	1.3526 a	1.4225 b	1.6194 a	1.5912 a	1.6360 ab	1.6963 a
Spring 2008	1.4339 a	1.5789 a	1.6129 a	1.5624 ab	1.6505 a	1.6956 a
Fall 2008	1.4307 a	1.5786 a	1.6099 a	1.5336 b	1.6470 a	1.6995 a

[1] Means with the same letter per site and depth are not significantly different at $P \leq 0.05$ using the Tukey pairwise comparison method.

The significantly lower D_b values observed for the 2007 samples at the coarse-loamy site (Table 5) may be the result of limited rainfall during the year and cover crop water uptake (Wagger and Denton, 1989). Palmer "Z" index data (i.e. moisture anomaly index) for the coastal plain of NC shows below average precipitation from January 2006 through February 2008 which coincides with the low D_b values for 2007. This theory is somewhat supported by the small variations seen at the fine-loamy site since its soil moisture status would be greater with all other variables being equal when compared to the coarse-loamy site. At the coarse-loamy site, the main sampling time effect does not support Wagger and Denton (1989) while the fine-loamy site trended up with the drought of 2007 (Table 5). For the fine-loamy site, variability expressed between sampling times were quite small as can be seen by the HSD.

Mean main depth effect on D_b increased with each progressive depth interval at each site. This was apparent from the interaction effect but is highly significant when examined using pairwise analysis (Table 6). At both sites, the 0-5 cm depth was significantly lower than the 5-10 cm depth that was significantly less than the 10-18 cm depth. The variation of D_b with depth is most likely related to decreasing C contents within each depth interval (Table 9) and lack of clay (Table 3).

Table 5. Mean main sampling time effect on D_b ($Mg\ m^{-3}$) at each key test site.

Sampling time[1]	Coarse-loamy	Fine-loamy
Fall 2006	1.5385 a	1.6105 c
Spring 2007	1.4618 a	1.6194 bc
Fall 2007	1.4649 a	1.6412 a
Spring 2008	1.5419 a	1.6362 ab
Fall 2008	1.5397 a	1.6267 abc

[1] Means with the same letter at the same site are not significantly different at $P \leq 0.05$ using the Tukey pairwise comparison method.

Table 6. Mean main depth effect on D_b ($Mg\ m^{-3}$) for each key test site.

Depth[1]	Coarse-loamy	Fine-loamy
0-5 cm	1.4028 a	1.5583 a
5-10 cm	1.5078 b	1.6324 b
10-18 cm	1.6174 c	1.6896 c

[1] Means with the same letter at the same site are not significantly different at $P \leq 0.05$ using the Tukey pair wise comparison method.

Overall, the coarse-loamy site and the fine-loamy site exhibited a strong spatial and temporal interaction, however, there were no sampling time trends. Conversely, the depth effect did show an increasing trend with depth implying the depth factor in the depth*sampling time interaction as the dominate effect for the interaction on D_b in the soils in this study. Given the high percent sand content in each depth interval (Table 3) and the decreasing C contents with depth (Table 9), the D_b spatial variability was correlated with C (Table 10). However, the correlation between D_b and total C is weakly moderate, at a minimum, on the sandy textured soils under a residue management system in this study. Additionally, the lowest estimated means for the main effect of sampling time at the fine-loamy site, depth 10-18 cm coarse-loamy site for the interaction effect, and depths 5-10 and 10-18 cm fine-loamy site for the interaction effect were all above 1.6 Mg m^{-3} which has been described as root limiting (Naderman et al., 2006).

Total Carbon

Both the coarse-loamy and fine-loamy sites yielded significant fixed main effects for season and depth ($p<0.0001$) on total C. Fixed interaction effects of depth*sampling time for total C at both sites were not significant. This is consistent with the “within-plot variability” found by Bird et al. (2002) in a coarse-loamy soil in a semi-arid range but is contrary to the lack of significance between sampling events reported by Sainju et al. (2007) on a fine-loamy soil. In this study, sampling time represents within-plot variability. The significant main effects in the absence of an interaction effect indicate total C distribution variability is spatial and temporal independent.

Main sampling time pairwise comparisons were variable across season for the coarse-loamy site and essentially insignificant at the fine-loamy site (Table 7). At the coarse-loamy site, Fall 2006 had significantly larger carbon content than all other sampling periods. The explanation for the significantly larger Fall 2006 estimate is not known. Spring 2008 produced the next largest carbon content value that was larger than either 2007 sampling event and the Fall 2008 sampling time. The trend between sampling time at the coarse-loamy site was a decrease in the Fall carbon content from the preceding Spring. The variability in total C values for the coarse-loamy site may be due in part to greater oxidation rates caused by increased porosity (i.e. decreased D_b) during the same sampling time combined with increased quality substrates input each Spring enhancing the soil microbiological communities causing a rapid decomposition of C.

Correlations between total carbon and D_b found a week inverse relationship between the two factors that increased with depth (Table 8). The inverse relationship found in this study were similar to those found by Naderman (2006).

Table 7. Main sampling time effect total C (g/kg) means at each key test site.

Sampling time [1]	Coarse-loamy	Fine-loamy
Fall 2006	23.260 a	10.183 b

Spring 2007	15.416 c	10.556 b
Fall 2007	13.553 d	10.478 b
Spring 2008	19.769 b	11.215 a
Fall 2008	14.244 d	10.141 b

[1] Means with the same letter per site and depth are not significantly different at $P \leq 0.05$ using the Tukey pairwise comparison method.

Mean total C values between depths at each site decreased with each progressive depth interval (Table 9). At both sites, the 0-5 cm depth was significantly larger than the 5-10 cm depth that was significantly larger than the 10-18 cm depth. The decreasing C with depth effect is expected in a natural system where homogenization with depth is absent.

Table 8. Correlation between total C and D_b

Depths	# Samples	p-value	r	r^2	D_b
All	810	<0.0001	-0.3646	0.1329	1.70851-0.10108(C)
0-5 cm	270	0.0047	-0.1715	0.2940	1.58364-0.06142(C)
5-10 cm	270	0.0027	-0.1822	0.0332	1.64991-0.05883(C)
10-18 cm	270	<0.0001	-0.5442	0.2962	1.71465-0.05379(C)

Particulate Organic Matter

Particulate organic matter fixed effects means were significant for depth*sampling time interaction for both sites (coarse-loamy $p<0.0001$; fine-loamy $p=0.0047$). The main effects of season and depth were also significant at both sites ($p<0.0001$).

Table 9. Main depth effect total C (g/kg) at each key test site.

Depth[1]	Coarse-loamy	Fine-loamy
0-5 cm	19.147 a	14.356 a
5-10 cm	16.935 b	10.094 b
10-18 cm	15.664 c	7.093 c

[1] Means with the same letter at the same site are not significantly different at $P \leq 0.05$ using the Tukey pairwise comparison method.

Pairwise comparison of POM means for the depth*sampling time interaction for both the coarse-loamy and fine-loamy sites do not reveal any trend when all sampling times are included within each depth (Table 10). However when the Fall 2006 values are excluded, a decreasing trend with time is present for each depth at both sites. It is reasonable to exclude Fall 2006 POM since cover crop inputs were minimal before Spring 2007. Pairwise comparisons of POM for the main depth and sampling time effect further enhance the trending decline between increasing depth intervals and sampling times Spring 2007 and Fall 2008.

Table 10. Estimated POM (g/kg) simple effect means for depth*sampling time interaction for both the coarse-loamy and fine-loamy site.

	Coarse-loamy			Fine-loamy		
Sampling time[1]	0-5 cm	5-10 cm	10-18 cm	0-5 cm	5-10 cm	10-18 cm
Fall 2006	0.242 b	0.217 ab	0.196 ab	0.920 b	0.443 b	0.275 ab
Spring 2007	0.413 a	0.262 a	0.230 a	1.022 a	0.598 a	0.351 a
Fall 2007	0.261 b	0.183 bc	0.155 bc	0.671 cd	0.394 b	0.218 abc
Spring 2008	0.211 b	0.132 c	0.124 c	0.726 c	0.328 bc	0.195 bc
Fall 2008	0.259 b	0.128 c	0.116 c	0.555 d	0.220 c	0.130 c

[1] Means with the same letter per site and depth are not significantly different at $P \leq 0.05$ using the Tukey pairwise comparison method.

Given the management system used for both sites plus the additions of cover crop residues, the results presented here are contrary to the expectation of a soil maintained under soil C building practices (Wander, 2004). With the addition of cover crops, the expectation was to increase or maintain steady state POM concentrations; this was not achieved. Instead the opposite effect happened. In a temperate environment, added organic residues decompose quickly resulting in approximately one-third of the original C persisting after one year (Wander, 2004). This study was conducted in a sub-tropical environment implying a much higher decomposition rate. The low C:N ratios indicate the potential for a rapid decomposition rate. It is believed the decline in POM values at both sites is the result of the priming effect.

CEC

The fixed effect depth*sampling time interaction for CEC was significant for both the coarse-loamy ($p=0.0021$) and fine-loamy ($p=0.039$) sites. Other significant fixed effects on CEC were the main effect of depth and season for both sites ($p<0.0001$). Analysis of pairwise comparisons for the depth*sampling time interaction are shown in Table 11.

Table 11. Estimated CEC (meq/100 cm^3) simple effect means for depth*sampling time interaction for both the coarse-loamy and fine-loamy sites.

	Coarse-loamy			Fine-loamy		
Sampling time [1]	0-5 cm	5-10 cm	10-18 cm	0-5 cm	5-10 cm	10-18 cm
Fall 2006	3.7 b	3.1 a	2.8 b	5.9 a	3.5 a	3.0 a
Spring 2007	3.7 b	3.2 a	2.9 ab	5.7 ab	3.5 a	2.8 ab
Fall 2007	4.3 a	3.3 a	2.9 ab	5.5 b	3.3 a	2.7 ab
Spring 2008	4.3 a	3.3 a	2.9 ab	6.0 a	3.4 a	2.8 ab
Fall 2008	4.4 a	3.3 a	3.3 a	5.0 c	2.9 b	2.5 b

[1] Means with the same letter per site and depth are not significantly different at $p \leq 0.05$ using the Tukey pairwise comparison method.

For the coarse-loamy site, there was a small trend of increasing CEC with time for depths 0-5 and 10-18 cm. At the fine-loamy site, the trend is decreasing CEC with time for all three depths. Pairwise comparison analysis of the main effect of depth or sampling time on CEC variability at both sites further support the interaction effect and the spatial and temporal dependence of CEC measurement (Table 12 and 13). Specifically for the main depth effect on CEC, the means decreased progressively with each depth interval. Likewise for the main sampling time effect on CEC, the trends as discussed from the interaction effect for both sites were similar, however, their magnitudes were smaller. This indicates total C is not the influential factor in the CEC estimated means. The simple correlation between C and CEC for this study was $r_{xy} = 0.27$ overall which supports the total C not being the main factor in the CEC estimated means.

Table 12. Main depth effect CEC (meq/ 100 cm^{-3}) means at each site.

Depth[1]	Coarse-loamy	Fine-loamy
0-5 cm	4.1 a	5.6 a
5-10 cm	3.2 b	3.3 b
10-18 cm	2.9 c	2.8 c

[1] Means with the same letter at the same site are not significantly different at $p \leq 0.05$ using the Tukey pairwise comparison method.

Table 13. Main sampling time effect CEC (meq/ 100 cm^{-3}) means at each key test site.

Sampling time[1]	Coarse-loamy	Fine-loamy
Fall 2006	3.19 c	4.15 a
Spring 2007	3.26 c	3.99 abc
Fall 2007	3.52 a	3.82 c
Spring 2008	3.49 b	4.07 ab
Fall 2008	3.65 a	3.45 d

[1] Means with the same letter at the same site are not significantly different at $P \leq 0.05$ using the Tukey pair wise comparison method.

The correlation of greater significance is between POM and CEC (Table 14). Overall the correlation between POM and CEC was $r_{xy} = 0.69$. When partitioned by depth interval, a strong moderate correlation of $r_{xy} = 0.66$ for the 0-5 cm depth was maintained but decreased to the point of insignificance at the 10-18 cm depth (Table 20).

Differences in Total C among sampling sites within a field

There were no significant differences among the fixed effects (site, depth, and sampling time) on total carbon at the coarse-loamy site indicating a lack of spatial variability at this no-till site. However, at the conventionally tilled fine-loamy site, there was a weak but significant sampling site*depth*sampling time interaction (*p=0.0541*) and a significant sampling site*depth interaction (*p=0.0429*) (Table 15). All other fixed effects were not significant (e.g. sampling site*sampling time and sampling site). It appears that the changes in total C were not spatially nor temporally variable but did differ spatially by depth. This is probably due to differences in water movement into the soil profile caused by soil permeability or landscape position. This data stands in contrast to data collected on fields with wide variations in soil series ranging from a sandy loam to an organic soil.

Table 14. Correlation between POM and CEC

Depths	# Samples	p-value	r	r^2	CEC
All	810	<0.0001	0.6933	0.4806	2.68259+28.86925(POM)
0-5 cm	270	<0.0001	0.6633	0.4399	3.73349+21.29398(POM)
5-10 cm	270	<0.0001	0.3390	0.1149	3.03629+8.44691(POM)
10-18 cm	270	0.3472	0.0574	0.0033	2.79062+2.74265(POM)

Table 15. Estimated total carbon (g/kg) simple effect means for the sample site*depth interaction at the fine-loamy site.

Sample Site within Field[1]	Fine-loamy 0-5 cm	Fine-loamy 5-10 cm	Fine-loamy 10-18 cm
1	14.073 a	9.973 a	6.320 a
2	14.100 a	10.200 a	7.153 a
3	14.267 a	10.900 a	7.867 a
4	15.580 a	10.947 a	7.453 a
5	15.007 a	10.327 a	7.100 a
6	15.147 a	9.833 a	7.673 a
7	13.493 a	10.307 a	7.333 a
8	13.727 a	8.967 a	6.367 a
9	13.813 a	9.393 a	6.567 a

[1] Means with the same letter per site and depth are not significantly different at $P \leq 0.05$ using the Tukey pairwise comparison method.

CONCLUSIONS

Spatial (sampling depth) and temporal variability for each assay at the key test sites exhibited either a significant interactive effect (i.e. D_b, POM, and CEC) or significant main effects (i.e. total C). Bulk density at the coarse-loamy site exhibited essentially no trend at depth across sampling times. At the fine-loamy site a similar insignificant trend of depth across sampling time as displayed at the coarse-loamy site was seen. However, there was a trend of increasing D_b with depth at both sites and an overall trend of increasing D_b across sampling time for the fine-loamy site. The increasing trend with depth is the result of decreasing C with depth combined with increasing % sand content. Correlation of D_b with total C having an inverse relationship supports the observation of increasing D_b with depth and a decreasing total C with depth. This conclusion indicates that over the duration of this study, the use of deep rooted cover crops and/or additions of biomass to the soils in this test failed to improve D_b at any depth given the tillage system and the environmental conditions.

As alluded to in the correlation between D_b and total C, total C declined independently with depth at both sites. Also, total C declined with sampling time at the coarse-loamy site but not at the fine-loamy site. These declines in total C at the coarse-loamy site with depth and over sampling time display the importance of discovering improved C management strategies on soils with high oxidation rates in a subtropical environment. Similar to the coarse-loamy site, soils at the fine-loamy site can benefit from discovering improved C management strategies with depth, however, these soil were more consistent at maintaining total C levels across sampling times. Between the two sites, the inherent soil differences are displayed which ultimate effect the obtainable levels of a measured assay.

POM effects were spatially and temporally dependent. For POM, the general trend was to decline with time in all depths except for the surface depth at the coarse-loamy site. Overall, the apparent decline of both PMN and POM is the result of a moderate correlation between the two measures where POM was negatively influenced by a priming effect on the biomass inputs in a sub-tropical environment. This unexpected declining trend for POM in a no-till system seen for both the coarse-loamy and fine-loamy sites indicates the need for further study on ways to increase the POM levels.

For CEC, the overall trend was to increase temporally at each depth at the coarse-loamy site while at the fine-loamy site the temporal trend was to decline at each depth. For both sites, the bulk of the temporal interactive trend variability was in the 0-5 cm depth. This is consistent with CEC measurement association with organic matter fluxes near the soil surface in a no-till system. Consequently, POM and CEC were significantly correlated overall with the correlation strength decreasing with depth.

Overall for both the coarse-loamy and fine-loamy soil families with a loamy sand/sandy loam surface texture in subtropical environment under either a conventional or no-till system, there is a need to increase total C and POM inputs to both the surface and internal depths of a soil profile in order to maintain and then build the soil quality. Increases in these two measures are necessary to positively influence the level of the D_b, total N, and CEC. Achieving a positive influence in these soils without quality organic matter inputs, that is organic matter that is more resistant to decomposition, is difficult. This may point to the need for application of organic matter inputs that have a greater recalcitrant potential; however, this will require additional study. Additionally, adopting other management systems may be necessary for quality improvement.

Data collected spatially across the field did not indicate any significant differences in total C when averaged over sampling depth among sampling sites on these coarse or fine loamy sands. The lack of variability indicates that total soil C is uniformly low in these soils. The only spatial difference among sites lies in the depth at where most of the soil C is found. This is most likely due to slight differences in soil permeability and in landscape positions offering the opportunity for better water infiltration into the soil profile. These sandy locations could be managed using uniform practices to improve total soil C.

REFERENCES

Arshad, M.A., A.J. Franzluebbers, and R.H. Azooz. 1999. Components of surface soil structure under conventional and no-tillage in northwestern Canada. Soil & Tillage Research. 53: 41-47.

Bird, S.B., J.E. Herrick, M.M. Wander and S.F. Wright. 2002. Spatial heterogeneity of aggregate stability and soil carbon in semi-arid rangeland. Environmental Pollution. 116:445-455.

Blake, G.R. 1965. Bulk density. In C.A. Black et al. (ed.) Methods of soil analysis, part 1. Agronomy 9:374-390. Am. Soc. Of Agron., Madison, WI.

Bruce, R.R., G.W. Langdale, L.T. West, and W.P. Miller. 1995. Surface soil degradation and soil productivity restoration and maintenance. Soil. Soil Sci. Soc. Am. J. 59: 654-660.

Cambardella, C.A. and E.T. Elliott. 1992. Particulate soil organic matter changes across a grassland cultivation sequence. Soil. Soil Sci. Soc. Am. J. 56: 777-783.

Cassel, D.K. 1983. Spatial and temporal variability of soil physical properties following tillage of Norfolk loamy sand. Soil Sci. Soc. Am. J. 47:196-201.

da Silva, Alvaro Pires, A. Nadler, and B.D. Kay. 2001. Factors contributing to temporal stability in spatial patterns of water content in the tillage zone. Soil & Tillage Research. 58: 207-218.

Franzluebbers, A.J. 2002a. Soil organic matter stratification ratio as an indicator of soil quality. Soil & Tillage Research. 66: 95-106.

Franzluebbers, A.J., F.M. Hons and D.A. Zuberer. 1994b. Seasonal changes in soil microbial biomass and mineralizable C and N in wheat management systems. Soil Biol. Biochem. 26:1469-1475.

Franzluebbers, A.J. and F.M. Hons. 1996. Soil-profile distribution of primary and secondary plant-available nutrients under conventional and no tillage. Soil & Tillage Research. 39: 229-239.

Gregorich, E.G. and H.H. Janzen. 1996. Storage of soil carbon in the light fraction and macroogranic matter. p. 167-190. In M.R. Carter and B.A. Stewart (ed.). Structure and organic matter storage in soils. Lewis Publ., CRC Press, Boca Raton, Fla.

Hendrix, P.F., A.J. Franzluebbers, and D.V. McCracken. 1998. Management effects of C accumulation and loss in soils of the southern Appalachian Piedmont of Georgia. Soil & Tillage Research. 47: 245-251.

Hunt, P.G., D.L. Karlen, T.A. Matheny, and V.L. Quisenberry. 1996. Changes in carbon content of a Norfolk loamy sand after 14 years of conservation or conventional tillage. J. Soil and Water Cons. 51: 255-258.

Kay, B.D. and A.J. VandenBygaart. 2002. Conservation tillage and depth stratification of porosity and soil organic matter. Soil & Tillage Research. 66: 107-118.

Langdale, G.W., R.L. Wilson, Jr., and R.R. Bruce. 1990. Cropping frequencies to sustain long-term conservation tillage systems. Soil. Soil Sci. Soc. Am. J. 54: 193-198.

Naderman, G., B.G. Brock, G.B. Reddy and C.W. Raczkowski. 2006. Long term no-tillage effects on soil carbon and soil density within the prime crop root zone. Project Report.

Nelson, D.W. and L.E. Sommers. 1982. Total carbon, organic carbon, and organic matter. P. 539-579. In A.L. Page et. al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Momogr. 9. ASA and SSSA, Madison, WI.

Reeves, D.W. 1997. The role of soil organic matter in maintaining soil quality in continuous cropping systems. Soil & Tillage Research. 43: 131-167.

Regional Synopses. 2002. 2002 National Crop Residue Management Survey. Available from www.ctic.purdue.edu/Core4/CT/ctsurvey/2002/RegionalSynopsis.html. Accessed August 11, 2004.

Sainju, U.M., H.H. Schomberg, B.P. Singh, W.F. Whitehead, P.G. Tillman, and S.L. Lachnicht-Weyers. 2007. Cover crop effect on soil carbon fractions under conservation tillage cotton. Soil & Tillage Research, doi:10.1016/j.still.2007.06.006.

SAS Institute. 2003. SAS/STAT. Version 9.1. SAS Institute, Cary, NC.

Soon, Y.K. and M.A. Arshad. 2004. Tillage and liming effects on crop and labile soil nitrogen in an acid soil. Soil & Tillage Research. Available at www.sciencedirect.com.

Wander, M.M. 2004. Soil organic matter fractions and their relevance to soil function. In:Magdoff F. Weil R. (eds) Advances in agroecology. CRC pp. 67-102.

Wander, M.M. and G.A. Bollero. 1999. Soil quality assessment of tillage impacts in Illinois. Soil. Soil Sci. Soc. Am. J. 63: 961-971.

Wagger, M.G. and H.P. Denton. 1992. Crop and tillage rotations: Grain yield, residue cover, and soil water. Soil. Soil Sci. Soc. Am. J. 56: 1233-1237.

Wagger, M.G. and H.P. Denton. 1989. Influence of cover crop and wheel traffic on soil physical properties in continuous no-till corn. Soil Sci. Soc. Am. J. 53:1206-1210.