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Carbon Dynamics under Long-Term Conservation and Disk Tillage Management in a Norfolk Loamy Sand

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Soil organic carbon (SOC) sequestration is an important process to mitigate CO_2 emissions. Our objectives were to determine the rates of C sequestration and to determine if the SOC pool was at or approaching equilibrium in plots under long-term (24-yr) conservation (CT) and disk tillage (DT) management. The plots were Norfolk loamy sand (fine-loamy, kaolinitic, thermic, Typic Kandiudult) and were under a row crop rotation. All plots received annual subsoiling, while only plots under DT were surface disked. Soil cores were collected to 90 cm deep. After 24 yr, the only significant increase in SOC occurred in CT plots at a 0- to 5-cm depth. The SOC pool in plots under DT was at a near-steady state, while the SOC pool under CT was not at equilibrium. This supports the conclusion that CT is an effective countermeasure to offset atmospheric CO_2 emissions.

Abbreviations: CT, conservation tillage; DT, disk tillage; SOC, soil organic carbon.

The SOC pool in surface soil is sensitive to changes in land use and crop and soil management practices. Loss of SOC often occurs under tillage practices that mix in surface residue, thereby raising turnover rates (Reicosky and Lindstrom, 1993; Prior et al., 2000; Balesdent et al., 2000; Bauer et al., 2006). Increases in SOC contents in surface soils have been achieved through CT management practices (Lal et al., 1998; Friebauer et al., 2004; Goh, 2004; King et al., 2004; Wang et al., 2004). Tilling soils using CT practices, where surface residue is minimally incorporated, can increase SOC concentrations by minimizing residue oxidation (Lal et al., 1998; Bauer et al., 2006).

A soil under CT management will eventually reach a maximum C sequestration capacity because a C input and output steady-state relationship will occur (Sauerbeck, 2001; Swift, 2001). These studies have reported that soil C sequestration rates under CT management can be very rapid in the first 5 to 10 yr, but after 15 to 20 yr can be followed by little change (Friebauer et al., 2004). Some soils under CT may take 50 yr to approach a steady-state C phase, depending on soil pedogenic properties, climatic conditions, and crop management (Lal et al., 1998).

A soil's C sequestration capacity is known to be controlled by its inherent physiochemical characteristics (Six et al., 2002). Various soil physical (e.g., silt + clay content, microaggregates) and chemical (e.g., formation of recalcitrant organic compounds) properties are known to be involved in protecting and reducing organic residue decomposition (Hassink, 1997; Six et al., 2002). Six et al. (2002) reported that a soil will reach its upper level of C storage when surfaces of the silt + clay fraction are C saturated and formation of aggregates that occlude humic substances is at a maximum. A soil at its maximum C sequestration capacity has been referred to as *C saturated* (Hassink, 1997; Watson et al., 2000; Six et al., 2002; Goh, 2004).

A tillage experiment that was established in the late 1970s (Hunt et al., 2004) was used to evaluate SOC concentration changes in a Norfolk loamy sand after 24 yr of CT and DT management. We hypothesized that SOC enrichment under CT after 24 yr should follow a saturation curve and approach a steady-state phase of equilibrium. The objectives of this study were (i) to determine the rates of C sequestration with time, and (ii) to ascertain if the SOC pool was at or approaching equilibrium in plots under long-term (24-yr) CT and DT management.

MATERIALS AND METHODS

Site Description, Crop and Tillage Management

Plots were established on a 2.8-ha tract of Norfolk loamy sand at the Clemson University Pee Dee Research and Education Center near Florence, SC (34°18′N, 79°44′W). In the mid-1970s, the site was mechanically cultivated and disk tilled for corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] production (Hunt et al., 1996). In the late 1970s, the site was set up with two similar sets of plots that were initially used for irrigated vs. unirrigated comparisons (until 1982), but since have been in different crop rotation phases. Five replicates of CT and DT practices have been maintained since the study was initiated in 1979. Crop rotations for the plots from 1979 to 2003 are presented in Table 1. In the first few years of the study, corn was the sole crop. In the mid-1980s, the 2-yr crop rotation was adopted. In the first year of this rotation, 10 plots (five plots under CT and five under DT) were planted with corn during one season, while the remaining 10 plots were double cropped with winter wheat (*Triticum aestivum* L.), followed by cotton (*Gossypium hirsutum* L.) or soybean. In the second year of this rotation, the plots that had previously been in corn were then doubled cropped with wheat followed by soybean. Corn was planted on the remaining plots during the second year of the rotation. Periodic drought episodes occasionally limited the crop rotation to fallow (Table 1). Wheat was removed from the rotation in the fall of 2003 and replaced with a rye (*Secale cereale* L.) cover crop to determine if its deep rooting system could increase SOC levels at deeper profile depths.

In all plots, some form of tillage operation was performed annually. In plots under DT, the soil surface was disrupted by disking to a depth of 15 cm followed by smoothing using an S-tined harrow equipped with a rolling basket (Table 1). In the 1970s and 1980s

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Table 1. Tillage practices and crop rotations used on the study site (1979–2003).

Time period	Tillage practice: Disk	Tillage practice: Conservation	Crop rotation†
1979–1982	disk, in-row subsoil‡	in-row subsoil‡	C
1983–1986	disk, in-row subsoil‡	in-row subsoil‡	C + W + SB
1987	disk, in-row subsoil§	in-row subsoil§	F
1988	disk, in-row subsoil§	in-row subsoil§	C
1989–1996	disk, in-row subsoil§	in-row subsoil§	C + W + CT
1996–2003	disk, paratill¶	paratill¶	C + W + SB

† C = corn, CT = cotton, F = fallow, SB = soybean, and W = wheat.

‡ Brown Harden superseeder.

§ Kelly Manufacturing Co. in-row subsoiler.

¶ Tye paratill.

when corn, wheat, and soybean were grown, a one-pass subsoiling and planting operation was performed initially with a Brown-Harden Superseeder. In the mid-1980s, this equipment was replaced with a Kelly Manufacturing Co. (Tifton, GA) in-row subsoiler and a Case-IH Model 800 planter (Case-IH Corp., Racine, WI). Between 1996 and 2003, the in-row subsoiling operation was replaced with paratilling to 42 cm using a Tye ParaTill (AGCO Corp., Duluth, GA) with shanks spaced 66 cm apart. Plots under CT were in-row subsoiled only and planted in one pass.

Soil Core Collection, Soil Organic Carbon, and Bulk Density Measurements

Soil core samples (0–90-cm depth) were collected annually after corn harvest from three locations within each of the five plots per tillage treatment. Cores were sectioned by depth and a composite sample was obtained to represent the 0- to 5-, 5- to 10-, 10- to 15-, 15- to 30-, 30- to 45-, 45- to 60-, and 60- to 90-cm soil profile depths. The SOC contents were measured by dry combustion using a LECO-2000 CNS analyzer (LECO Corp., Chicago, IL) and the results were expressed as grams per kilogram to compare with previous data (Hunt et al., 1996). The Norfolk loamy sand is an acidic soil (profile pH values <6.0), so the total C pool was assumed to be organic C. Soil cores were not collected in 1984, 1985, 1987, 1993, and 1999.

The soil sampling procedures in 2002 were modified to include bulk density (D_B) determinations to provide quantitative information on SOC contents calculated on an equivalent soil mass basis (Ellert et al., 2001). The equivalent mass method involved normalizing the mass of C per unit area for differences in soil mass by adding C from a subsoil depth (Ellert et al., 2001). Soil D_B samples were collected from three of the five plots per tillage treatment before soybean planting using the core method at 0- to 5-, 5- to 10-, and 10- to 15-cm depths (Grossman and Reinsch, 2002). This was done to minimize the disruptive nature of excavating shallow pits when collecting cores, which was an important consideration in the CT plots to assure minimal soil inversion and crop residue mixing into the topsoil. When analyzed for particle size (Miller and Miller, 1987), the surface 0- to 5-cm layer under DT consisted of 750, 240, and 10 g kg^{-1} of sand, silt, and clay, respectively; whereas values under CT were 670, 270, and 60 g kg^{-1}, respectively.

Statistics

Changes in SOC contents were statistically examined by calculating an average SOC content (as g kg^{-1}) for the 0- to 5-cm soil depth by pooling values across years for periods between 1980 and 1992 and 1994 to 2003. These values were then compared with initial SOC contents (1979) using a one-way ANOVA. Only SOC contents in the 0- to 5-cm soil depth are presented because no significant changes occurred with deeper profile depths. Carbon sequestration rates for both tillage treatments from 1979 to 1992 and 1994 to 2003 were then obtained by subtraction and dividing by the appropriate number of years.

The annual SOC contents averaged across tillage treatment in the 0- to 5-cm soil depth were examined using an exponential rise to a maximum model:

$$y = y_0 + a[1 - \exp(-bx)] \qquad [1]$$

where y = SOC (g kg^{-1}), x = year of study, and y_0, a, and b are equation parameters. This model provided a better statistical fit than a hyperbolic or a linear model (data not shown) and would permit calculations of future amounts of C sequestered.

Soil organic C contents from cores collected in 2002 were expressed on a megagram per hectare basis for the 0- to 5-, 5- to 10-, and 10- to 15-cm depths and were then compared between tillage treatments using Student's t-test at a $P < 0.05$ level of significance. This analysis also required that the SOC contents by depth and tillage be adjusted to account for differences in soil D_B values using the equivalent soil mass method (Ellert et al., 2001). All statistical analyses were performed using SigmaStat Version 3.00 software (SYSTAT Inc., Richmond, CA).

RESULTS AND DISCUSSION

Soil Organic Carbon Contents and Carbon Sequestration

Significant changes in SOC contents were limited to the 0- to 5-cm soil depth (deeper profile data not shown); consequently, attention was focused on comparing SOC contents in this soil layer. The mean SOC contents and standard error in the surface layer (0–5-cm depth) under DT and CT were 6.3 ± 0.8 and 5.3 ± 0.2 g kg^{-1}, respectively, before the experiment was initiated (Table 2). These low SOC contents in Norfolk loamy sand with a prior history of row crop production are not atypical for the Coastal Plain region (Hunt et al., 1996). During 1980 to 1992, there was a significant increase in the SOC content under CT. In fact, the value under CT averaged during 1980 to 1992 was almost twice the initial SOC content. The SOC contents in soil under CT continued to accumulate between 1994 and 2003 to reach a mean value of 15.9 g kg^{-1}. The accumulation of SOC at the surface in soil under CT is similar to results reported by Reicosky et al. (1995), Potter et al. (1997), Yang and Wander (1999), and

Table 2. Norfolk soil organic carbon (SOC) contents (0–5 cm deep) and estimated rates of C sequestered under different tillage systems.

Tillage	SOC 1979†	SOC 1980–1992	SOC 1994–2003	C sequestration 1980–1992	C sequestration 1994–2003
	g kg^{-1}			g kg^{-1} yr^{-1}	
disk	6.3a‡	7.8a	9.2a	0.12	0.13
conservation	5.3a	11.1b	15.9c	0.45	0.44

† Data from Hunt et al. (1996).

‡ Means followed by a different letter are significantly different at the $P < 0.05$ level.

Deen and Kataki (2003). Plant residue typically accumulates at the soil surface under CT because the residue is minimally mixed into the soil. Accumulation of residue at the soil surface causes the rate of plant residue oxidation to be slower under CT than under DT (Bauer et al., 2006).

During both periods of this study, there was a sizable difference in the rate of C sequestration under DT and CT (Table 2). The rate of C sequestration under CT was higher than the rate under DT. This condition is probably related to the residue having a slower rate of oxidation due to minimal incorporation into the soil. It was common to observe corn and cotton residue remaining on the soil surface in the CT plots for almost 2 yr after the harvest date. The low C sequestration rate in soil under DT is a consequence of mixing in the plant residue, where oxidation and decomposition proceeds rapidly (Wander et al., 1998; Yang and Wander, 1999; Bauer et al., 2006).

No significant increase in SOC contents during 14 yr under DT implies that the SOC pool in the 0- to 5-cm-deep soil layer was at a steady-state phase of equilibrium (Table 2). Similarly, the curve in the SOC content vs. year plot for DT reached a plateau starting at about the 14th year of the study (Fig. 1). This model predicts that the SOC content under DT after 30 yr of study was 9.29 g kg^{-1}, which is similar to the mean value shown in Table 2 after 24 yr of management. It appears that the maximum amount of C sequestered in the Norfolk soil 0- to 5-cm-deep layer under DT has been reached with this cropping system. This condition may be related to the dominance of sand (750 g kg^{-1}) and a low amount of clay particles (10 g kg^{-1}) in the Norfolk loamy sand. These characteristics are known to influence the C sequestration potential of soils (Balesdent et al., 2000).

The SOC pool under CT management was not at equilibrium after 14 yr but continued to increase in C even after 24 yr of management (Table 2). Regression of SOC by year shows that the slope was still a positive value in the later time period of this study (Fig. 2). A positive slope implies that the SOC content was still increasing after 24 yr under CT. Indeed, a predicted mean SOC value of 16.9 g kg^{-1} was obtained when 30 yr of study was used in the model. The implication was that the SOC pool was not at a steady state, but has the potential to accumulate more C under the current CT and crop management practices.

The SOC contents from soils collected in 2002 under DT and CT are shown in Fig. 2. In the 0- to 5-cm soil depth, the SOC content under CT was significantly higher (15.3) than under DT (6.8 Mg ha^{-1}). The CT and crop management strategies used in this study caused an additional 8.5 Mg C ha^{-1} to be sequestered in the 0- to 5-cm depth layer compared with soil under DT. Roberson (2006) also reported on a study in which SOC increased substantially (2.2 Mg ha^{-1}) in a CT vs. DT comparison across several soil types in North Carolina. Capturing this much more C in the soil should facilitate atmospheric CO_2 concentration reductions.

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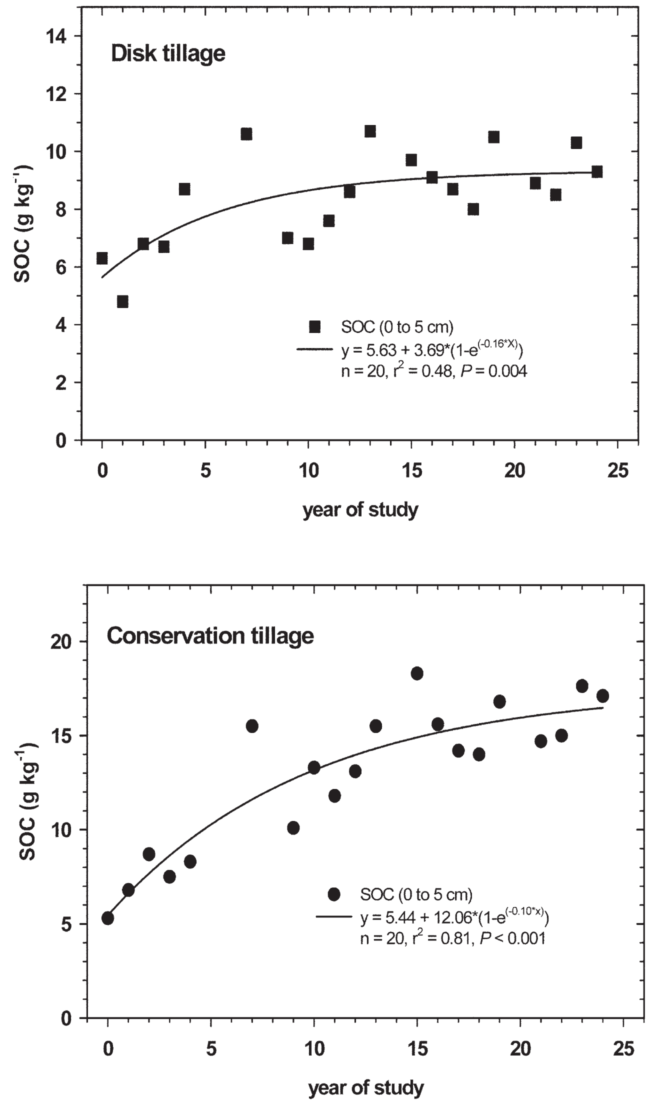

Fig. 1. Soil organic carbon (SOC) content of Norfolk loamy sand under disk and conservation tillage management (data from 1979–2003).

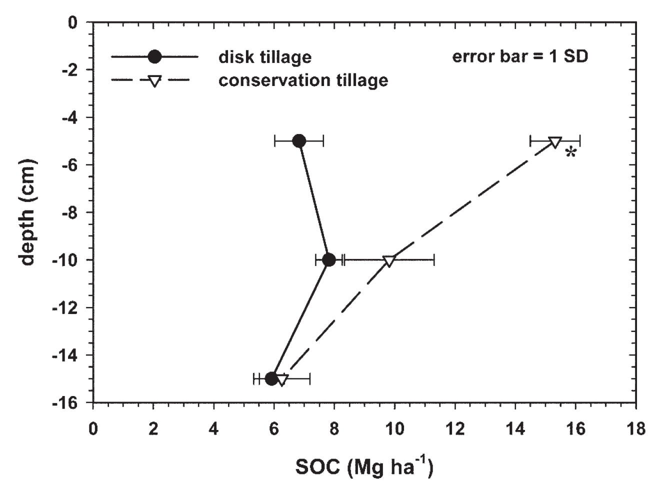

Fig. 2. Mean Norfolk soil organic carbon (SOC) contents under conservation and disk tillage (from soil samples and bulk density data collected in 2002 only). *Significant at $P < 0.05$.

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