Rebuilding Organic Carbon Contents in Coastal Plain Soils Using Conservation Tillage Systems

J. M. Novak*
USDA-ARS
Coastal Plains Soil, Water, and Plant Res. Center
2611 West Lucas St.
Florence, SC 29501

J. R. Frederick
Clemson Univ.
Pee Dee Research and Education Ctr.
2200 Pocket Rd.
Florence, SC 29506

P. J. Bauer
D. W. Watts
USDA-ARS
Coastal Plains Soil, Water, and Plant Res. Ctr.
2611 West Lucas St.
Florence, SC 29501

Long-term disk tillage (DT) for cotton (*Gossypium hirsutum* L.) production in the southeastern U.S. Coastal Plain has resulted in soil organic C (SOC) content reductions. Conservation tillage (CT) management in some studies can rebuild SOC levels. A field study, with two adjacent 3.5-ha fields, both containing soil series formed in upland and depressional areas, was conducted using a 6-yr rotation of corn (*Zea mays* L.) and cotton to determine the CT and DT effects on SOC contents and residue characteristics returned to the soil. Annual soil samples were collected from 50 locations per field at 0- to 3- and 3- to 15-cm. After 6 yr under CT, residue accumulation promoted a significant SOC increase in the 0- to 3-cm depth in the upland soil series (about 0.7 Mg SOC ha^{-1}). The lack of residue mixing in the 3- to 15-cm depth in upland soils under CT, however, resulted in a significant SOC content decline at this depth (1.25–2.51 Mg SOC ha^{-1}). There was no significant SOC content change in soils under CT formed in depressional areas or in all soils under DT. During 6 yr, 14.8 Mg ha^{-1} of organic C from both corn and cotton residues was returned to soils under CT, but <4% was incorporated into the SOC pool. Levels of SOC in sandy upland soils can be increased at the surface after 6 yr of CT under a corn and cotton rotation, with the increase coming at the expense of an SOC decline at a deeper topsoil depth.

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

For more than 150 yr, sandy soils in the southeastern U.S. Coastal Plain region have been prepared for row crop production using some form of conventional tillage. This tillage operation inverts topsoil and mixes in crop residue, which hastens its microbial oxidation and leads to eventual losses from the SOC pool. The associated losses of SOC can result in poor soil physical conditions for plant growth (Busscher et al., 1987, 2001), and reduces the soil's ability to retain nutrients (Tisdale et al., 1993) and herbicides (Novak et al., 1996). In addition to conventional tillage, SOC loss in southeastern Coastal Plain soils has been exacerbated by cotton monoculture in which cotton returns low amounts of crop reside to the soil (Causarano et al., 2006). The SOC reduction leaves soils in this region more vulnerable to erosion losses, and thus increasing SOC is paramount for improving environmental quality.

Mention of a specific product or vendor does not constitute a guarantee or warranty of the product by the USDA or imply its approval to the exclusion of other products that may be suitable.

Soil Sci. Soc. Am. J. 73:622-629
doi:10.2136/sssaj2008.0193
Received 3 June 2008.
*Corresponding author (jeff.novak@ars.usda.gov).

Conservation tillage involves minimal surface tillage, leaving crop residues to accumulate at the soil surface. The unincorporated crop residues decompose more slowly than in soils under DT operations (Reicosky and Lindstrom, 1993; Lal and Kimble, 1997; Paustian et al., 2000; Bauer et al., 2006). Soil organic C accumulation under CT management is slow and depth specific, taking between 9 and 15 yr for significant SOC accumulation (Hunt et al., 1996; Lal et al., 2004). The SOC accumulation in CT usually is in the top few centimeters of soil (Hunt et al., 1996; Dolan et al., 2006; Novak et al., 2007; Blanco-Canqui and Lal, 2008). Conservation tillage management induces SOC stratification with depth, thus prompting many CT vs. SOC studies to limit sampling to shallow profile depths (Baker et al., 2007). A more complete evaluation of tillage management effects on SOC contents should involve collecting soil samples at deeper profile depths to separate tillage-induced OC stratification from real SOC changes (Staricka et al., 1991; Baker et al., 2007).

Reducing residue incorporation will promote lower SOC contents at deeper soil depths (Lal and Kimble, 1997; Wander et al., 1998; Deen and Kataki, 2003; Dolan et al., 2006; Blanco-Canqui and Lal, 2008). Dolan et al. (2006) reported that surface soils (0–20 cm deep) under no-till management in Minnesota had >30% more SOC than soils under moldboard or chisel plow tillage. Below a 20-cm depth, however, the trend was reversed. The results from these recent studies have caused researchers to suggest that CT practices may not always lead to net SOC accumulation in the whole soil profile (Dolan et al., 2006; Blanco-Canqui and Lal, 2008). In other words, the apparent SOC sequestration under minimum tillage management may simply be SOC stratification that implies sequestration due to the shallow sampling soil depths.

Modifying surface residue management by including row crops that return more residue mass and contain a higher C/N ratio (Burgess et al., 2002) than cotton are key components to rebuilding SOC contents. Significant SOC increases have been reported in the top 0- to 5- and 5- to 10-cm depths of a Norfolk loamy sand after 9 yr of CT under a cotton, wheat (*Triticum aestivum* L.), and soybean [*Glycine max* (L.) Merr.] rotation (Hunt et al., 1996). Below a 10-cm soil depth, however, there were no measurable SOC content changes.

Multiple soil series are commonly mapped across agricultural fields in the middle Coastal Plain region of South Carolina. These soil series can have diverse intrinsic properties (i.e., slope, drainage class, texture, etc.) that are known to influence SOC decomposition dynamics (Novak and Bertsch, 1991). Previous studies have shown that SOC concentrations in soils high in clay or silt may either change slowly or remain unaffected by conversion from conventional to reduced tillage systems (Yang and Wander, 1999; Puget and Lal, 2005). With respect to the southeastern U.S. Coastal Plain region, there is sparse information concerning the magnitude of SOC changes when converted from conventional to minimum tillage systems and how this process is affected by soils formed in different landscape positions. It was the intention of this investigation to determine if SOC contents in a paired field containing soils that formed in contrasting landscape positions can be modified using tillage and crop management systems. Specifically, the objectives were: (i) to evaluate differences in residue mass and chemical characteristics between cotton and corn under DT and CT; (ii) to compare DT and CT effects on annual changes in SOC levels on both a soil-series and a whole-field basis; and (iii) to examine the relationships between annual crop residue mass and its chemical characteristics with changes in SOC contents.

MATERIALS AND METHODS

Site and Soil Description

A 7-ha field at the Clemson University Pee Dee Research and Education Center, near Florence, SC, was used for this study. This field is composed of well-drained soils in upland positions and poorly drained soils in depressional areas. The slope across the paired fields ranges from nearly level to between 1 and 3%. The field contains soil series that possess pedogenic properties typical for the region (Novak and Bertsch, 1991; Daniels et al., 1999). Represented well-drained soil series in upland locations include the Bonneau, Noboco, and Norfolk (Table 1). These soils series have topsoil layers dominated by sand, with mildly acidic pH values. The field also had one somewhat poorly drained soil series (Ocilla) and two poorly drained series (Coxville and Rains). These soils formed inside or along the rim of depressional areas. These depressional areas frequently pond water and receive fine-size eroded sediments (silt and clay) causing the topsoil to have lower sand contents than the upland soils (Table 1).

Cropping, Tillage, and Fertilizer Management Descriptions

This field had a prior history of DT and typical row crop production consisting of corn, cotton, soybean and winter wheat. In 1997, the 7-ha field was divided into two 3.5-ha sections, with one side under CT management and DT on the other half (Fig. 1). The DT management system centered on traditional production practices such as disking the soil, wider row spacing, in-row subsoiling, and one rate of fertilizer application across the entire field (Table 2). The CT management system featured more innovative production practices such as deep tillage only, narrow row spacing for corn, and precision application of P fertilizer (Table 2). In the year before the study (1997–1998), both sides of the field were planted with a double crop of winter wheat followed by soybean, crops that are common in rotations of the southeastern United States. The winter wheat residue on the DT tillage side was burned to remove it, while the residue on the CT side remained on the soil surface. After these practices were completed, the field and soil properties were regarded as reflecting initial experimental conditions. During the next 6 yr, the annual crop rotation was corn and cotton. Corn was planted in early April and was harvested in August. Cotton was planted in May and usually harvested in October. After fall harvesting, the residual stalks on the both fields were mowed and the field then left fallow until planting the following year. A description of crop cultivars, row spacing, and plant populations is provided in Table 2.

The CT side of the field was deep tilled to a depth of 40 cm using a six-shanked paratill (Tye Paratill) before corn and cotton planting. Shanks on the paratill were spaced 66 cm apart and a roller was mounted on the back of the unit to firm and smooth the soil surface as it traversed across the field. This deep-tillage implement lifts the soil and shatters hard pans while the roller does very minimal incorporation of surface residue. No other tillage operation was performed on the CT side of the field. The other side of the paired field was prepared using DT that consisted of at least two passes across the field using a traditional disk unit to incorporate residue to at least 15 cm deep. Following disking for corn, the field was in-row subsoiled to a depth of 40 cm

Table 1. Taxonomic classification and physical and chemical properties of the soil series.

Series	Taxonomic classification	Depth	Sand	Silt	Clay	Texture	pH
		cm	—— g kg^{-1} ——				
Bonneau	loamy, siliceous, subactive, thermic Arenic Paleudult	0–3	87	11	2	sand	6.0
		3–15	87	11	2	sand	5.7
Coxville	fine, kaolinitic, thermic Typic Paleaquult	0–3	44	46	11	loam	6.5
		3–15	45	44	11	loam	5.3
Noboco	fine-loamy, siliceous, subactive, thermic Oxyaquic Paleudult	0–3	79	18	3	loamy sand	6.4
		3–15	81	17	2	loamy sand	6.3
Norfolk	fine-loamy, kaolinitic, thermic Typic Kandiudult	0–3	83	15	2	loamy sand	6.4
		3–15	82	16	2	loamy sand	6.5
Ocilla	loamy, siliceous, semiactive, thermic Aquic Arenic Paleudult	0–3	83	14	3	loamy sand	6.1
		3–15	82	15	3	loamy sand	5.5
Rains	fine-loamy, siliceous, semiactive, thermic Typic Paleaquult	0–3	62	32	6	loamy sand	5.9
		3–15	58	34	8	loamy sand	5.3

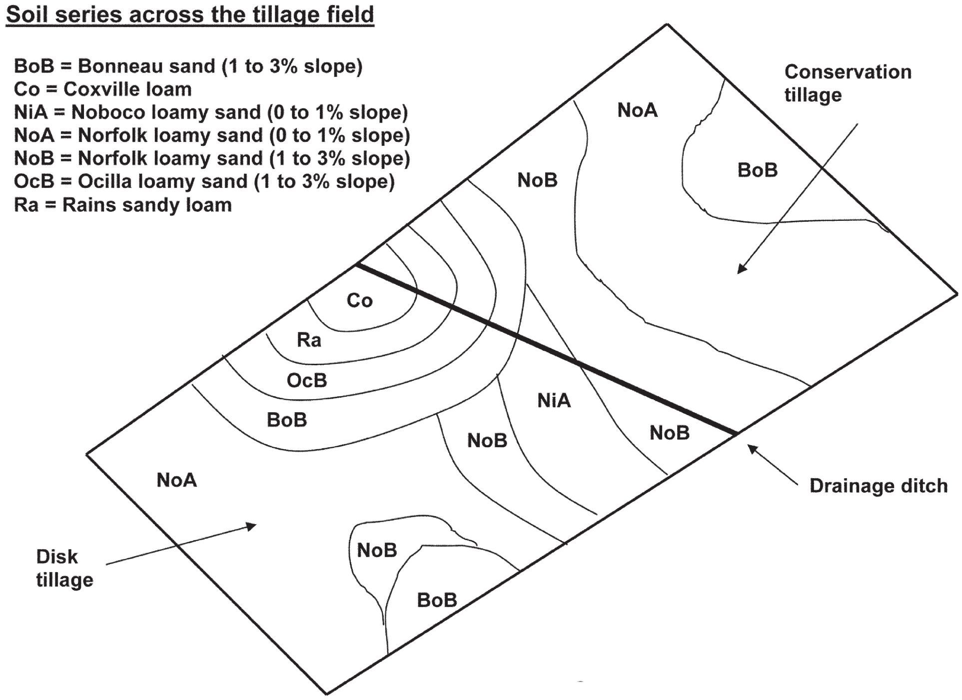

Fig. 1. Soil series and map units across the tillage fields at the Clemson University Pee Dee Research and Education Center.

using a straight-shanked subsoiler (Kelly Manufacturing Co.) to break up hard pans. For cotton, a straight-shanked subsoiler with row bedders was used to form rows, which were later leveled before planting.

Fertilizer and lime were applied based on soil fertility recommendations from samples collected at 0- to 15-cm deep. Fertilizer P and K were broadcast applied at rates shown in Table 2. Potassium was applied uniformly and rates were based on a composite sample collected uniformly across each field. Fertilizer P application patterns and rates varied with tillage. It was uniformly applied across the DT field based on composite samples, whereas P was precision applied on the field under CT based on a 15-m grid sample pattern across the field. Lime was applied at 1120 kg ha^{-1} to the DT side of the field in 2002 and to the CT side in 2003.

Daily precipitation results were recorded at the Darlington County, South Carolina weather station (34°16′ N, 80°5′ W; Southeast Regional Climate Center, 2008). Annual precipitation totals during this 6-yr study ranged from 907 to 1260 mm; individual year totals are available from Southeast Regional Climate Center (2008).

Residue and Soil Collection

In 1998, global positioning system (GPS) technology was used to determine the location coordinates for 50 sampling points on each side of the paired field. Sampling sites were chosen to be well within a soil map unit and at least 5 m from any map unit boundary. From these locations, annual samples of soil, bulk density, and crop residues were collected. The number of sampling locations within individual soil series was based on the area of each series relative to the total field area. The three upland soil series (Bonneau, Noboco, and Norfolk) comprised almost 75% of the surface area in each field (Fig. 1), therefore more sampling locations (39 and 43 locations, respectively, under CT and DT) among the 50 sites were selected. A smaller number of sampling locations (7 and 11 locations in CT and DT, respectively) among the 50 sites were located in the depressional areas that contained three soil series (Coxville, Ocilla, and Rains). The individual number of sampling locations for each soil series is shown in Table 3. In the CT field, only one sampling point occurred in the Coxville and Noboco series because of each map unit's minimal area (<0.015 ha). The results from these two sites were only included in computations for an average result for the whole CT field. On the DT side, two locations were sampled in the Coxville series, which were only incorporated into an average for the whole DT field. Using GPS technology allowed repeated annual sampling within 0.5-m radius of the initial (1998) sampling points.

Aboveground crop residue samples from the corn and cotton crop were collected at 10 GPS locations across each field. At least one sampling location for residue harvest occurred in each soil series. The samples were collected approximately 2 wk after harvest from a 1-m^2 area. Crop residue samples consisted of a heterogeneous mixture of leaves, stems, husks, and any unharvested cotton lint.

In mid to late February of each year, annual soil samples were collected from the 0- to 3- and 3- to 15-cm soil depths at the 50 locations across each field using a 2.5-cm (i.d.) soil probe. Sampling in February was arbitrarily chosen to allow between 3 and 4 mo for residue decomposition and OC release into the soil organic matter pool. At the same time, annual soil bulk density samples were collected at eight sites across each field. At least one site for soil bulk density determination occurred in each soil series. Procedures from Grossman

Table 2. Tillage, crop, and fertilizer management practices for fields under disk and conservation tillage management.

Practice	Disk tillage		Conservation tillage	
	Corn	Cotton	Corn	Cotton
Tillage	2× disk, in-row subsoil†	Duall and bedding	No surface tillage, Paratill‡	No surface tillage, Paratill‡
Crops	1999, 2001 and 2003: Dekalb 687, 0.76-m row width, 55,000 seeds ha^{-1}	2000, 2002, 2004 and 2005: DPL 5415, 0.97-m row width, 12 seeds m^{-1}	1999, 2001 and 2003: Dekalb 687, 0.38-m row width, 63,500 seeds ha^{-1}	2000, 2002, 2004 and 2005: DPL 458 Bt RR, 0.97-m row width, 10 seeds m^{-1}
Fertilizer§	134 kg N, 56 kg P, 90 kg K ha^{-1}	90 kg N, 67–112 kg K and P ha^{-1}	157 N kg, 67 kg P, 112 kg K ha^{-1}	90 kg N, 67–112 kg K and P ha^{-1}
	Lime applied in 2002 at 1120 kg ha^{-1}		Lime applied in 2003 at 1120 kg ha^{-1}	

† Kelly Manufacturing Co. (Tifton, GA) in-row subsoiler.

‡ Tye Paratill (Bigham Brothers, Lubbock, TX).

§ Phosphorus application on conservation tillage field was precision applied to localized areas.

and Reinsch (2002) were used to collect soil bulk density samples from the 0- to 3- and 3- to 10-cm soil depths.

Table 3. Mean residue mass and its chemical characteristics (standard deviations shown in parentheses).

Tillage	Crop	Residue Mass	Residue OC	Residue N	Residue C/N ratio
		Mg ha^{-1}			
Conservation	corn	8.35 (0.44) a†	3.51 (0.28) a	0.06 (0.02) a	66 (35) a
	cotton	2.87 (1.05) b	1.21 (0.43) b	0.03 (0.02) a	40 (13) b
Disk	corn	7.76 (1.86) a	3.32 (0.93) a	0.05 (0.01) a	71 (31) a
	cotton	3.75 (0.36) b	1.61 (0.16) b	0.04 (0.01) a	42 (14) b

† Values compared between corn and cotton within a tillage treatment followed by a different letter are significantly different ($P < 0.05$).

Sample Preparation and Measurements

Each crop residue sample was dried at 60°C for 48 to 72 h, weighed, and later ground to 2 mm or less. Each soil sample was air dried and passed through a 2-mm sieve. Crop residue samples were analyzed for OC and total combustible N (TCN) contents, while OC only was measured in the soil samples using a LECO-2000CNS analyzer (LECO Corp., St. Joseph, MI) and results were expressed on a weight-per-hectare basis. For this study, the crop residue TCN content (all N minus NH_4–N) was assumed to represent the total N content of the residue. Additionally, the soils across both fields were fairly acidic (pH < 6.4; Table 1), so the total C pool was assumed to be solely OC. The residue C/N ratios were determined by division using their OC and TCN contents (wt ha^{-1} basis). The pH of soil was measured using a 2:1 deionized H_2O/soil ratio and the particle size analyses of select samples from each series was determined using the micropipette method of Miller and Miller (1987).

Statistics

The corn and cotton mean annual residue characteristics (mass, OC percentage, C/N ratios) were compared within tillage treatments using a Student's *t*-test. With respect to changes in SOC contents, tillage management effects after 6 yr were assessed both on individual soil series and by averaging annual field SOC contents by tillage treatment and depth. A Student's *t*-test was used to compare SOC for individual soil series. Preliminary analysis of SOC contents using a Kolmogorov–Smirnov test revealed that the values were not normally distributed. Data transformations using the logarithmic, square root, and arcsine methods (Zar, 1999) did not result in correction of the non-normal distribution. Therefore, a nonparametric Mann–Whitney rank sums test was used to test their median SOC values. The same test was used to compare the annual median SOC contents by individual depths and then combined depths when measured before the study (1998) with values measured after 6 yr of treatment (2004). Relative changes in SOC by depth and by tillage treatment were determined by difference between the final and initial years of the experiment. The amount of residue entering the SOC pool was determined by dividing the change in SOC (difference between 1998 and 2004) by the 6-yr sum of residue OC returned to soil.

The annual field mean residue mass and its C/N ratio by tillage treatment were used to determine if relationships existed with changes in the associated field mean annual SOC content. For this examination, only soil characteristics from the 0- to 3-cm depth under both tillage management systems were used because residue was not mixed into deeper depths under CT. In these examinations, significant relationships between these variables were identified using a Pearson product moment correlation. All statistical tests were performed using SigmaStat Version 3.5 (SPSS, Chicago, IL).

RESULTS AND DISCUSSION

Crop Residue Mass, Organic Carbon and Nitrogen Contents, and Carbon/Nitrogen Ratios

Under both tillage management systems, corn returned two to three times more residue mass and OC to the soil (Table 3). Corn residue (cobs, stems, leaves, and husks) under both tillage systems contained N amounts similar to the cotton residue.

Burgess et al. (2002) reported that corn residue consisting of cobs, stems, leaves, and husks had a C/N ratio of 67, similar to the results presented in Table 3. Under both tillage systems, corn had higher field mean C/N ratios than cotton (Table 3). The cotton residue had mean C/N ratios of 40 and 42 under CT and DT, respectively. These results are similar to Lachnicht et al. (2004), who reported a range of 30 to 40 for cotton.

Changes in Soil Organic Carbon Contents

The two upland soil series, Bonneau and Norfolk, had a significant SOC content change at the shallow depth after 6 yr of CT (Table 4). The mean SOC contents at the 0- to 3-cm depth of both soil series increased during the study by 0.7 Mg ha^{-1}. This SOC increase is equivalent to an average rate of 0.12 Mg ha^{-1} yr^{-1}. This OC rate increase was within the SOC sequestration range of 0.10 to 0.60 Mg C ha^{-1} yr^{-1} reported by Follett (2001).

The SOC accumulation in the top few centimeters of soil under CT was similar to other reports (Reicosky et al., 1995; Potter et al., 1997; Yang and Wander, 1999; Deen and Kataki, 2003; Novak et al., 2007). Crop residues typically accumulate at the soil surface under CT because the residue is minimally mixed into the soil, thereby slowing decomposition (Reicosky and Lindstrom, 1993; Lal and Kimble, 1997; Prior et al., 2000; Bauer et al., 2006).

Soil organic C contents declined at the 3- to 15-cm depth for the upland soils after 6 yr of CT, with quantities decreasing between 1.25 and 2.51 Mg ha^{-1}. This calculates to an annual SOC loss rate of 0.21 to 0.42 Mg ha^{-1} yr^{-1}. Soil organic C declines at deeper soil depths under no-till management is not unusual. Blanco-Canqui and Lal (2008) reported that in three of their 11 sites, no-till management had lower SOC contents below the 10-cm depth than soil under DT. Dolan et al. (2006) also reported an SOC decline at deeper profile depths (below 25 cm) under no-till than under moldboard and chisel plow treatments. Isolating crop residues to the soil surface under CT removes residue contributions to the soil organic matter pool, thus causing an SOC reduction with depth.

There are a few possible explanations for the SOC decline at deeper profile depths under minimum tillage. It may be related to not mixing crop residues to deeper profile depths (Franzluebbers, 2002; Blanco-Canqui and Lal, 2008), differences in crop rooting depths (Blanco-Canqui and Lal, 2008), improved aeration due to deep tilling (Doty et al., 1975; Campbell and Phene, 1977), and growing a single annual crop

Table 4. Annual means and standard deviations (in parentheses) for soil organic C (SOC) contents measured in 1998 and 2004 for each soil series by tillage and landscape position.

Tillage	Series	Landscape position	Depth	Mean SOC contents		
				1998	2004	Δ†
			cm	Mg ha^{-1}		
Conservation	Bonneau	upland	0–3	2.31 (0.12)	2.98 (0.43)	0.68*
	n = 7		3 –15	11.7 (1.31)	9.19 (1.64)	−2.51*
	Norfolk	upland	0–3	1.95 (0.27)	2.65 (0.46)	0.70*
	n = 35		3–15	9.30 (1.45)	8.05 (1.67)	−1.25*
	Ocilla	depression	0–3	3.04 (0.94)	3.3 (0.20)	0.26
	n = 3		3–15	16.12 (4.44)	10.88 (1.04)	−5.25
	Rains	depression	0–3	5.43 (2.21)	4.61 (1.62)	−0.83
	n = 3		3–15	20.87 (4.55)	15.95 (4.07)	−4.92
Disk	Bonneau	upland	0–3	2.17 (0.55)	2.15 (0.78)	−0.02
	n = 11		3–15	8.84 (2.38)	9.49 (3.01)	0.65
	Noboco	upland	0–3	2.95 (0.20)	2.69 (0.15)	−0.26
	n = 4		3–15	13.49 (1.20)	12.61 (1.03)	−0.88
	Norfolk	upland	0–3	2.55 (0.78)	2.25 (0.65)	−0.30
	n = 24		3–15	10.13 (3.87)	10.51 (3.33)	0.38
	Ocilla	depression	0–3	3.75 (1.58)	3.35 (1.56)	−0.40
	n = 6		3–15	16.82 (5.60)	20.12 (7.34)	3.3
	Rains	depression	0–3	6.49 (0.95)	6.67 (1.77)	0.18
	n = 3		3–15	30.28 (5.61)	30.93 (6.54)	0.65

* Significantly different using a t-test at $P < 0.05$ probability level.

† Differences between mean SOC contents measured in 2004 and 1998.

(Sherrod et al., 2003; Sainju et al., 2006). The lack of residue incorporation under minimum tillage is well known to promote SOC accumulation at shallow soil depths (<10–20-cm depth; West and Post, 2002; Blanco-Canqui and Lal, 2008). Soil under no-till or minimum tillage may be unfavorable for deep root penetration by corn because of high soil bulk density with profile depth and favorable moisture conditions near the soil surface (Blanco-Canqui and Lal, 2008). Deep tillage to 38 cm was used to break up a hard subsoil layer in a sandy Coastal Plain soil, resulting in improved soil aeration compared with the control soil under moldboard plowing (Doty et al., 1975). In this study, soils under CT were deep tilled to 40 cm using a paratill, which probably improved soil aeration and resulted in SOC decomposition at deeper profile depths. More SOC can be sequestered in cropping systems that use a higher cropping intensity that returns more surface residue (Sherrod et al., 2003) and cover crops that add both above- and belowground organic residue (Franzluebbers, 2005). Moreover, Johnson et al. (2006) reported that C supplied from roots can account for as much as 65 to 75% of the residue-C conversion to SOC. In the studies of Hunt et al. (1996) and Novak et al. (2007), a double-crop rotation consisting of corn, wheat, and soybean was used. In this study, the lack of a double crop may have lowered the contribution of root biomass to the SOC pool.

At both depths under CT, the Ocilla and Rains soils did not experience a significant SOC content change. The Ocilla and Rains series had the highest initial SOC contents at the beginning of the experiment (Table 4), and consequently observing a statistical change was difficult. Additionally, their annual mean SOC values had relatively high standard deviations, which may have masked any changes. It is also possible that soils formed in depressional areas have a large buffer to changes induced by tillage and crop management practices. The fine-sized particles (silt and clay, Table 1) associated with these soils is well known to stabilize SOC because the sorbed OC is protected from microbial oxidation (Stevenson, 1994; Hassink, 1997; Six et al., 2002).

Disking in crop residues increases their rate of mineralization and contributes to a general decline in soil organic matter levels (Reicosky et al., 1995; Balesdent et al., 2000). Residue incorporation places the food source for the microbes in close association with water and other nutrients, thereby facilitating oxidation and SOC declines. Soil organic C contents, however, did not appreciably decline at either soil depth under DT regardless of landscape position (Table 4). The slight SOC change in all soils under DT suggests that the SOC turnover during the 6-yr period was equal to the amount of C returned through crop residues and root biomass. Soil organic matter levels usually change slowly following an alteration in crop or tillage management (Lal et al., 2004); therefore, if may take longer than 6 yr to detect significant SOC changes in the DT system.

The annual mean and median SOC contents sorted by depth and tillage across the whole field were calculated to determine the whole-field effects and then to estimate the amount of crop residue OC entering the SOC pool (Table 5). The SOC contents, when averaged across both fields, were found to be non-normally distributed, probably due to the large SD associated with soils in depressional areas. Data transformation did not correct the non-normal distribution.

A nonparametric test revealed that the field median SOC contents at 0 to 3 cm deep were significantly higher under CT than DT. This finding is similar to others (Reicosky et al., 1995; Potter et al., 1997; Yang and Wander, 1999; Deen and Kataki, 2003; Novak et al., 2007). When averaged across the CT field, the soil at the 0- to 3-cm depth had a significant increase in the median value (0.63 Mg ha^{-1}) compared with the initial site conditions. The SOC increase under CT required the cumulative input of almost 15 Mg ha^{-1} of OC as crop residue, but only about 4% of the residue OC entered the SOC pool (Table 5). This percentage is a low amount of OC that was returned to the SOC pool. A similar result was obtained by Kong et al. (2005) and Sainju et al. (2006), who reported a residue-C conversion to SOC content of between 4 and 8%.

Across the field, the median SOC content at 3 to 15 cm after 6 yr under CT had a decline of 2.39 Mg ha^{-1} (Table 5). Although the field under CT had an SOC loss at this deeper soil depth, the overall benefits of CT in reducing erosion and water runoff (Rhoton et al., 2002; Lal, 2005), lowering tractor fuel consumption (Karlen et al., 1991), and increasing herbicide sorption (Novak et al., 1996) are sufficient reasons to continue to promote its use.

The cumulative residue OC amounts returned to soils under DT (14.17 Mg OC ha^{-1}) were similar to residue amounts returned under CT (14.8 Mg OC ha^{-1}, Table 5). Whereas soil under CT, when averaged across the field, had a net increase in SOC at 0 to 3 cm, all soils under DT on a field basis did not experience an SOC content change at either depth. In fact, the values were for the most part relatively unchanged. This would suggest that residue OC inputs (both above- and belowground sources) under DT across the field were probably at a near equilibrium with OC outputs. Since changes in SOC contents in tillage comparison experiments are slow to be detected, this condition may also be due to the short duration (6 yr) of this experiment.

Table 5. Changes in field mean and median soil organic C (SOC) contents before this study (1998) and after 6 yr (2004) of crop and tillage management, summation (Σ of organic C (OC) added as plant residue, and percentage of plant residue OC entering the SOC pool (SD = standard deviation).

Tillage	Depth	Statistic	SOC contents 1998	SOC contents 2004	SOC contents Change	Residue OC Σ (6 yr)	Residue OC as SOC pool
	cm		Mg ha^{-1}			Mg ha^{-1}	%
Conservation	0–3	mean	2.36	2.87	0.51	14.8	3.5
		SD	1.10	1.01			
		median	2.04 a†	2.67 b	0.63	14.8	4.3
	3–15	mean	11.99	9.73	−2.26	–	–
		SD	5.13	6.32			
		median	10.66 a	8.27 b	−2.39	–	–
Disk	0–3	mean	3.11	2.84	−0.27	14.17	–
		SD	1.67	1.59			
		median	2.44 a	2.16 a	−0.28	–	–
	3–15	mean	13.31	13.29	−0.22	–	–
		SD	7.78	7.70			
		median	10.25 a	10.51 a	0.26	–	–

† Median values followed by a different letter are significantly different using a Mann–Whitney rank sum test ($P = 0.05$).

There are numerous reports that CT causes SOC to accumulate at the soil surface, although on a whole-profile basis (to about 60 cm), more SOC is stored in the soil profile under DT systems (Deen and Kataki, 2003; Dolan et al., 2006; Blanco-Canqui and Lal, 2008). This finding has caused concern that minimum tillage farming is no better than DT for storing SOC in the whole profile. Blanco-Canqui and Lal (2008) reviewed the literature and reported that in 14 of 16 comparisons of tillage effects on SOC contents under numerous row crop and cereal rotations, there were no significant differences in profile SOC levels. In response to this concern, the field median SOC contents stored in the topsoil of CT and DT were compared (Table 6) to determine which management system had the highest SOC levels after 6 yr. In 1998, there was more SOC stored in soils under DT at the 0- to 3-cm depth, while similar SOC amounts were stored at 3 to 15 cm. Our measurements showed that the OC stored in both soil layers across the field under DT (12.7 Mg ha^{-1}), however, was similar to the OC stored under CT (12.69 Mg ha^{-1}). After 6 yr of tillage and crop system management, a shift occurred in profile SOC storage. More OC was stored in the 0- to 3-cm depth under CT, whereas OC stored at 3 to 15 cm declined relative to DT. Summing the OC accumulated at both depths revealed that in 2004 more OC was stored under DT than CT (12.67 vs. 11.03 Mg ha^{-1}, Table 6). This finding is similar to others (Deen and Kataki, 2003; Dolan et al., 2006; Blanco-Canqui and Lal, 2008). Higher amounts of OC stored in soil layers under DT suggest that root biomass amounts were higher under DT, or those C pathways into or out of the long-term C storage pools were different in soils under CT management. The benefits of using CT to maintain soil quality characteristics and reduce soil erosion and water runoff losses should not be overlooked; however, the principle that CT will sequester more SOC on a deep-soil basis than DT may need re-examination.

Residue Chemical Characteristics and Soil Organic Carbon Contents

Adding more OC through residue returned to the soil has shown mixed results with regard to increasing the SOC content. A few studies have reported a linear relationship between increasing residue OC inputs and greater SOC contents (Vanotti et al., 1997; Campbell et al., 2001; Mandal et al., 2007). Campbell et al. (1991), however, did not show a substantial SOC increase with increasing residue input. These contrary results should not be unexpected because the relationship between SOC content changes and residue inputs can differ among sites, management practices, and soil characteristics (West and Six, 2007).

Annual mean SOC changes (limited to the 0- to 3-cm depth) under each tillage management system were correlated with either annual mean total residue mass, OC as residue, or residue C/N ratios. A Pearson product moment correlation showed that there were no significant relationships ($P > 0.05$) under either tillage management system between annual SOC changes and residue mass input, mass of OC, or its C/N ratio. Under CT, this may be due to residue accumulation at the soil surface that did not enter the SOC pool within the 3- to 4-mo window past harvest when soil samples were collected. In fact, on the soil surface of the field under CT, it was common to observe the remains of crop residuee for >1 yr past harvest.

Table 6. Comparison of field median soil organic C (SOC) contents (*n* = 50) at both depths and their sum within the conservation tillage (CT) and disk tillage (DT) systems measured at initial and final periods of the study.

Year	Depth	Median SOC contents CT	Median SOC contents DT
	cm	Mg ha^{-1}	
1998	0–3	2.04 a†	2.44 b
	3–15	10.66 a	10.25 a
	Sum	12.7	12.69
2004	0–3	2.66 a	2.16 b
	3–15	8.37 a	10.51 b
	Sum	11.03	12.67

† Median values between tillage systems followed by a different letter are significantly different using a Mann–Whitney rank sum test at $P = 0.05$.

CONCLUSIONS

Long-term conventional tillage for row crop production has caused sandy soils in the southeastern U.S. Coastal Plain region to have relatively low topsoil OC contents. Soil OC contents can influence intrinsic characteristics such as aggregation, bulk density, water infiltration rate, nutrient storage capacity, herbicide retention, and the rooting environment. These are important characteristics for Coastal Plain soils with regard to harvesting high crop yields. This study evaluated the option of using CT and incorporating corn into a cotton rotation with the goal of rebuilding SOC levels. Additionally, this study examined if this practice was successful at increasing SOC contents in soils formed in different landscape positions (upland vs. depressional positions) and across a field containing pedogenically diverse soil series. The SOC contents in the surface 0- to 3-cm depth were significantly increased under CT in the two upland soil series as well as when averaged across the whole field. After 6 yr of CT, an SOC content increase of 0.7 Mg ha^{-1} occurred only in the Bonneau and Norfolk series, both of which are upland soils.

Soils in depressional areas under CT and all soils under DT did not have a significant SOC change. Soils under DT had more SOC stored in the topsoil (0- to 15-cm depth combined) compared with soil under CT, implying that DT management could have a more significant role in C sequestration than previously credited.

On a field average under CT, there was a significant pooled median SOC increase in the 0- to 3-cm depth of 0.63 Mg SOC ha^{-1}. This SOC increase was connected to residue accumulation at the soil surface and was not statistically linked to crop residue mass, its OC content, or its C/N ratio. The SOC significantly declined at the 3- to 15-cm depth by 2.39 Mg SOC ha^{-1}. Soils that formed in depressional landscape positions did not have significant SOC content changes regardless of tillage practice.

To increase topsoil SOC levels in upland soils, a large mass of OC as residue was needed. During 6 yr, 14.8 Mg ha^{-1} of OC from both corn and cotton residues was collectively returned to the soil under CT; <4% was incorporated into the SOC pool. We concluded that SOC levels near the surface in sandy upland soils under CT can be increased after 6 yr under an annual corn and cotton rotation. This increase, however, was limited to a shallow topsoil depth and was achieved at the expense of an SOC decline at a deeper topsoil depth.

ACKNOWLEDGMENTS

Sincere gratitude is expressed to the Clemson University Pee Dee Research and Education Center farm crew and to Sue Griggs, Ernie Strickland, and Warren Busscher for assistance with this project. This research was partially funded by CSREES Project no. 6657-12000-004-00D entitled “Improving soils and their management for more efficient water use in environmentally sustainable agriculture.”

REFERENCES

Baker, J.M., T.E. Ochsner, R.T. Venterea, and T.J. Griffis. 2007. Tillage and soil carbon sequestration: What do we really know? Agric. Ecosyst. Environ. 118:1–5.

Balesdent, J., C. Chenu, and M. Balabane. 2000. Relationships of soil organic matter dynamics to physical protection and tillage. Soil Tillage Res. 53:215–230.

Bauer, P.J., J.R. Frederick, J.M. Novak, and P.G. Hunt. 2006. Soil CO_2 flux from a Norfolk loamy sand after 25 years of conventional and conservation tillage. Soil Tillage Res. 90:205–211.

Blanco-Canqui, H., and R. Lal. 2008. No-tillage and soil profile carbon sequestration: An on-farm assessment. Soil Sci. Soc. Am. J. 72:693–701.

Burgess, M.S., G.R. Mehuys, and C.A. Madramootoo. 2002. Nitrogen dynamics of decomposing corn residue components under three tillage systems. Soil Sci. Soc. Am. J. 66:1350–1358.

Busscher, W.J., J.R. Frederick, and P.J. Bauer. 2001. Effect of penetration resistance and timing of rain on grain yield of narrow-row corn in a Coastal Plain loamy sand. Soil Tillage Res. 63:15–24.

Busscher, W.J., L.D. Spivey, and R.B. Campbell. 1987. Estimation of soil strength properties for critical rooting conditions. Soil Tillage Res. 9:377–386.

Campbell, C.A., K.E. Brown, M. Schnitzer, R.P. Zentner, and L. Townley-Smith. 1991. Effect of crop rotation and fertilization on soil organic matter and some biochemical properties of a thick Black Chernozem. Can. J. Soil Sci. 71:377–387.

Campbell, C.A., F. Selles, G.P. Lafond, and R.P. Zentner. 2001. Adopting zero tillage management: Impact on soil C and N under long-term crop rotations in a thin Black Chernozem. Can. J. Soil Sci. 81:139–148.

Campbell, R.B., and C.J. Phene. 1977. Tillage, matric potential, oxygen and millet yield relations in a layered soil. Trans. ASAE 20:271–275.

Causarano, H.J., A.J. Franzluebbers, D.W. Reeves, and J.N. Shaw. 2006. Soil organic carbon sequestration in cotton production systems of the southeastern United States: A review. J. Environ. Qual. 35:1374–1383.

Daniels, R.B., S.W. Buol, H.J. Kleiss, and C.A. Ditzler. 1999. Soil systems in North Carolina. Tech. Bull. 314. North Carolina State Univ., Raleigh.

Deen, W., and P.K. Kataki. 2003. Carbon sequestration in a long-term conventional versus conservation tillage experiment. Soil Tillage Res. 74:143–150.

Dolan, M.S., C.E. Clapp, R.R. Allmaras, J.T. Baker, and J.A. Molina. 2006. Soil organic carbon and nitrogen in a Minnesota soil as related to tillage, residue and nitrogen management. Soil Tillage Res. 89:221–231.

Doty, C.W., R.B. Campbell, and D.C. Reicosky. 1975. Crop response to chiseling and irrigation in soils with a compact A2 horizon. Trans. ASAE 18:668–672.

Follett, R.F. 2001. Soil management concepts and carbon sequestration in cropland soils. Soil Tillage Res. 89:221–231.

Franzluebbers, A.J. 2002. Soil organic matter stratification ratio as an indicator of soil quality. Soil Tillage Res. 66:95–106.

Franzluebbers, A.J. 2005. Soil organic carbon sequestration and agricultural greenhouse gas emissions in the southeastern USA. Soil Tillage Res. 83:120–147.

Grossman, R.B., and T.G. Reinsch. 2002. Bulk density and linear extensibility. p. 201–228. *In* J.H. Dane and G.C. Topp (ed.) Methods of soil analysis. Part 4. SSSA Book Ser. 5. SSSA, Madison, WI.

Hassink, J. 1997. The capacity of soils to preserve organic C and N by their association with clay and silt particles. Plant Soil 191:77–87.

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 Water Conserv. 51:255–258.

Johnson, J.M., R.R. Allmaras, and D.C. Reicosky. 2006. Estimating source carbon from crop residues, roots, and rhizodeposits using the national grain-yield database. Agron. J. 98:622–636.

Karlen, D.L., W.J. Busscher, S.A. Hale, R.B. Dodd, E.E. Strickland, and T.H. Garner. 1991. Drought condition energy requirements and subsoiling effectiveness for selected deep tillage implements. Trans. ASAE 34:1967–1972.

Kong, A.Y., J. Six, D.C. Bryant, R.F. Denison, and C. van Kessel. 2005. The relationship between carbon input, aggregation, soil organic carbon stabilization in sustainable cropping systems. Soil Sci. Soc. Am. J. 69:1078–1085.

Lachnicht, S.L., P.F. Hendrix, R.L. Potter, D.C. Coleman, and D.A. Crossley, Jr. 2004. Winter decomposition of transgenic cotton residue in conventional-till and no-till systems. Appl. Soil Ecol. 27:135–142.

Lal, R. 2005. Soil erosion and the global carbon cycle. Environ. Int. 29:437–450.

Lal, R., M. Griffin, J. Apt, L. Lave, and M. Morgan. 2004. Managing soil carbon. Science 204:393.

Lal, R., and J.M. Kimble. 1997. Conservation tillage for carbon sequestration. Nutr. Cycling Agroecosyst. 49:243–253.

Mandal, B., B. Majumder, P.K. Bandyopadhyay, G.C. Hazra, A. Gangopadhyay, R.N. Samantary, A.K. Mishra, J. Chaudhury, M.N. Saha, and S. Kundu.

2007. The potential of cropping systems and soil amendments for carbon sequestration in soils under long-term experiments in subtropical India. Global Change Biol. 13:357–369.

Miller, W.P., and D.M. Miller. 1987. A micro-pipette method for soil mechanical analysis. Commun. Soil Sci. Plant Anal. 18:1–15.

Novak, J.M., P.J. Bauer, and P.G. Hunt. 2007. Carbon dynamics under long-term conservation and disk tillage management in a Norfolk loamy sand. Soil Sci. Soc. Am. J. 71:453–456.

Novak, J.M., and P.B. Bertsch. 1991. The influence of topography on the nature of humic substances in soil organic matter at a site in the Atlantic Coastal Plain of South Carolina. Biogeochemistry 15:111–126.

Novak, J.M., D.W. Watts, and P.G. Hunt. 1996. Long-term tillage effects on atrazine and fluometuron sorption in Coastal Plain soils. Agric. Ecosyst. Environ. 60:165–173.

Paustian, K., J. Six, E.T. Elliott, and H.W. Hunt. 2000. Management options for reducing CO_2 emissions from agricultural soils. Biogeochemistry 48:147–163.

Potter, K.N., O.R. Jones, H.A. Torbert, and P.W. Unger. 1997. Crop rotation and tillage effects on organic carbon sequestration in the semiarid southern Great Plains. Soil Sci. 162:140–147.

Prior, S.A., D.W. Reicosky, D.W. Reeves, G.B. Runion, and R.L. Raper. 2000. Residue and tillage effects on planting implements induced short-term CO_2 and water loss from a loamy sand soil in Alabama. Soil Tillage Res. 54:197–199.

Puget, P., and R. Lal. 2005. Soil organic carbon and nitrogen in a Mollisol in central Ohio as affected by tillage and land use. Soil Tillage Res. 80:201–213.

Reicosky, D.C., W.D. Kemper, G.W. Langdale, C.L. Douglas, Jr., and P.E. Rasmussen. 1995. Soil organic matter changes resulting from tillage and biomass production. J. Soil Water Conserv. 50:253–261.

Reicosky, D.C., and M.J. Lindstrom. 1993. Effects of fall tillage method on short-term carbon dioxide flux from soil. Agron. J. 85:1237–1243.

Rhoton, F.E., M.J. Shipitalo, and D.L. Lindbo. 2002. Runoff and soil loss from midwestern and southeastern US silt loam soils as affected by tillage practice and soil organic matter content. Soil Tillage Res. 66:1–11.

Sainju, U.M., B.P. Singh, W.F. Whitehead, and S. Wang. 2006. Carbon supply and storage in tilled and no tilled fields as influenced by cover crops and nitrogen fertilization. J. Environ. Qual. 35:1507–1517.

Sherrod, L.A., G.A. Peterson, D.G. Westfall, and L.R. Ahuja. 2003. Cropping intensity enhances soil organic carbon and nitrogen in a no-till agroecosystems. Soil Sci. Soc. Am. J. 67:1533–1543.

Six, J., R.T. Conant, E.A. Paul, and K. Paustian. 2002. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. Plant Soil 241:155–176.

Southeast Regional Climate Center. 2008. Climate database (CLIMOD). Available at www.sercc.com (verified 18 Dec. 2008). SERCC, Univ. of North Carolina, Chapel Hill.

Staricka, J., R.R. Allmaras, and W.W. Nelson. 1991. Spatial variation of crop residue incorporation by tillage. Soil Sci. Soc. Am. J. 55:1668–1674.

Stevenson, F.J. 1994. Humus chemistry. 2nd ed. John Wiley & Sons, New York.

Tisdale, S.L., W.L. Nelson, J.D. Beaton, and J.L. Havlin. 1993. Soil fertility and fertilizers. 5th ed. Macmillan Publ. Co., New York.

Vanotti, M.B., L.G. Bundy, and A.E. Peterson. 1997. Nitrogen fertilizer and legume–cereal rotation effects on soil productivity and organic matter dynamics in Wisconsin. p. 106–119. *In* E.A. Paul et al. (ed.) Soil organic matter in temperate agroecosystems. CRC Press, Boca Raton, FL.

Wander, M.M., M.G. Bidart, and S. Aref. 1998. Tillage impacts on depth distribution of total and particulate organic matter in three Illinois soils. Soil Sci. Soc. Am. J. 62:1704–1711.

West, T.O., and W.M. Post. 2002. Soil organic carbon sequestration rates by tillage and crop rotation: A global data analysis. Soil Sci. Soc. Am. J. 66:1939–1946.

West, T.O., and J. Six. 2007. Considering the influence of sequestration duration and carbon saturation on estimates of soil carbon capacity. Clim. Change 80:25–41.

Yang, X.M., and M.M. Wander. 1999. Tillage effects on soil organic carbon distribution and storage in a silt loam soil in Illinois. Soil Tillage Res. 52:1–9.

Zar, J.H. 1999. Biostatistical analysis. 4th ed. Prentice Hall, Upper Saddle River, NJ.