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ARTICLE

Soil Tillage, Conservation, & Management

Loamy sand soil approaches organic carbon saturation after 37 years of conservation tillage

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Abstract

Conservation tillage is reported to increase soil organic carbon (SOC) and total nitrogen (TN) contents, but long-term (>30 yr) field results quantifying the responses in Coastal Plain Ultisols are sparse. The distribution, accumulation, and topsoil storage of SOC and TN after 37 yr of crop production using conventional (CvT) or conservation tillage (CnT) on a Norfolk loamy sand (fine-loamy, kaolinitic, thermic, Typic Kandiudults) were quantified. Soil samples were collected annually from the 0–5-, 5–10-, and 10–15-cm depth increments beneath corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], and cotton (*Gossypium hirsutum* L.) crops. Overall, SOC and TN accumulation in the 0–5-cm depth were highest for Norfolk soil under CnT. Focusing on total long-term changes for the 0–15-cm sampling depth beneath various corn crops shows that CnT and CvT sequestered 24.7 and 21.4 Mg C ha^{-1}, respectively. Between 1978 and 2016, there was a highly significant ($P < .0001$) exponential increase in SOC within the top 5-cm soil depth. However, the exponential curves began to plateau suggesting the Norfolk topsoil was approaching its organic carbon (OC) storage capacity. These field measurements strongly indicate that additional topsoil SOC increases with current tillage and crop management practices are limited.

Abbreviations: CnT, conservation tillage; CvT, conventional tillage; OC, organic carbon; SOC, soil organic carbon; TN, total nitrogen.

1 | INTRODUCTION

Core Ideas

- Soil organic carbon contents and total nitrogen were compared under conservation and conventional tillage.
- Conservation tillage increased soil organic carbon and total nitrogen contents.
- Soil organic carbon was highest under conservation tillage at the 0–5-cm topsoil depth.
- Surface soil organic carbon is approaching saturation under conservation and conventional tillage practices.
- Crop residue organic carbon input and soil organic carbon were not linearly correlated.

Sandy soils in the U.S. southeastern Coastal Plain have been cultivated for centuries (Gray, 1933; Trimble, 1974) generally using inversion tillage (i.e., disking, moldboard plowing, deep ripping, chisel plowing). Coupled with a warm, humid climate, tillage plus low-residue crops (e.g., cotton or soybean) have resulted in low SOC and TN concentrations due to increased soil aeration and physical accessibility of plant residues to microbial decomposition (Bauer, Frederick, Novak, & Hunt, 2006; Reicosky & Lindstrom, 1993). Decreased SOC has been shown to degrade soil tilth (quality/health) through loss of soil structure, increased soil crusting, and poor retention of nutrients and water (Lal, 2014; Six et al., 2002b; Wilhelm et al., 2010). Accelerated SOC loss has also contributed to a collateral reduction in TN because N is an integral component of plant residues and SOM (Lal, 2014).

The USDA-Agricultural Research Service (ARS) and Natural Resource Conservation Service (NRCS) have identified several soil and crop management practices that farmers and landowners are encouraged to adopt to rebuild SOC and TN contents. Conservation tillage (CnT) defined as "any tillage or planting system in which at least 30% of the soil surface is covered by plant residue after planting to reduce erosion by water; or where soil erosion by wind is the primary concern" (Wilson et al., 2008) is generally an integral component of these recommendations. With CnT, plant residues are allowed to accumulate (Diaz-Zorita & Grove, 2002; Franzluebbers, 2002; Zuber, Behnke, Nafziger, & Vilamil, 2015) due to minimal soil disturbance (Hunt, Bauer, Matheny, & Quisenberry, 1996; Novak, Bauer, & Hunt, 2007). One consequence of CnT is that SOC becomes vertically stratified (Lal, 2018; Nath & Lal, 2017; Zhao et al., 2015) because crop residues are not mechanically mixed throughout the Ap horizon. This may or may not be a problem since some have identified vertical SOC stratification as a soil quality benefit (Franzluebbers, 2002) because it can increase SOC and TN contents (Karlen et al., 1994; Nath & Lal, 2017; Zuber et al., 2015) and enhance soil aggregate formation (Mitchell et al., 2017; Nath & Lal, 2017; Zheng et al., 2018).

In addition to CnT, SOC and TN can be increased in Coastal plain soils by planting cover crops (Hubbard, Strickland, & Phatak, 2013; Mitchell et al., 2017; Nascente, Li, & Crusciol, 2013), and/or using crop rotations (e.g., corn, wheat (*Triticum avestivum* L.]), and soybean rather than continuous cotton. Both management strategies increase crop residue contributions of C and N which can ultimately increase SOC and TN pools (Havlin, Kissel, Maddux, Claassen, & Long, 1990; Wilhelm et al., 2010; Wilhelm, Johnson, Karlen, & Lightle, 2007).

All three of these management practices (CnT, cover crops, and rotations) are beneficial and should be incorporated into conservation programs, but soils will not indefinitely accumulate OC. At some site-specific point defined by soil resource and climate, a maximum SOC concentration will be reached at which point, annual OC inputs will establish an equilibrium with OC losses (Johnson et al., 2009; Sauerbeck, 2001; Swift, 2001). Soil science literature generally shows that SOC accumulates rapidly during the first 5−10 yr of CnT, but after 15−20 yr, the accumulation rate slows to where annual changes are minimal (Friebauer, Rounsevell, Smith, & Verhagen, 2004). However, generalizations can be tenuous as shown by Minasny et al. (2017) who reported in a recent global meta-analysis that with SOC enhancement practices (i.e., cover cropping, and CnT) SOC sequestration can continue for 30–40 yr before a new equilibrium is reached.

When a soil reaches its maximum SOC capacity, known as OC saturation (Hassink, 1997; Watson et al., 2000), additional C inputs from crop residue, animal manure, or municipal wastes will not enlarge the SOC pool (Goh, 2004; Six, Conant, Paul, & Paustian, 2002a; Stewart, Paustian, Conant, Plante, & Six, 2007). Rather, they will simply be lost through transformation reactions including microbial mineralization to CO_2 or solubilization and leaching as dissolved OC compounds.

Measured results quantifying SOC and TN responses to long-term (>30 yr) tillage and crop management practices are sparse for several reasons including inconsistent funding, slow responses to management changes, differences in research priorities, and changes in research personnel. Undeterred by those limitations, scientists from the USDA-ARS-Coastal Plains Soil, Water and Plant Research Center established a long-term crop and tillage management experiment in 1979 and have maintained replicated core tillage treatments (conventional vs. conservation) for nearly 40 yr. The initial objectives were to quantify soil fertility and physical responses with and without supplemental irrigation to harvesting different amounts of crop residue as a potential feedstock for bioenergy production (Karlen, Hunt, & Campbell, 1984). Conservation tillage included in-row subsoiling to facilitate root penetration through an eluviated (E) horizon with limited surface disturbance. Conventional tillage utilized multiple disking operations to incorporate winter weeds and crop residues as well as in-row subsoiling during the planting operation. Effects of crop residue removal, supplemental irrigation, and tillage on corn grain and stover yields (Karlen et al., 1984) and soil fertility changes (Karlen & Berti, 1989) were previously reported. Crop residue removal and the supplemental irrigation split were terminated as experimental variables in the mid-1980s, and project objectives were redirected to quantify tillage and crop rotation effects on yield (Busscher, Karlen, Sojka, & Burnham, 1988; Hunt, Bauer, Matheny, & Busscher, 2004), and SOC contents 14 (Hunt et al., 2004), or 24 (Novak et al., 2007) yr after initiating the field study. Anticipated SOC 44 yr after establishment were also projected using simulation modeling (Nash et al., 2018). An additional 13 yr have elapsed since field measurements were reported, thus providing a substantial amount of new data to coalesce with historic information. Having a 37-yr dataset that includes surface OC and TN content as well as the quantity of C inputs from crop residue now provides sufficient data to quantify long-term tillage and crop residue management effects on the accumulation, storage and profile distribution of both parameters. Our objectives for this study were to quantify changes in topsoil (0–15-cm) SOC and TN content, distribution and accumulation, and to determine if the Norfolk loamy sand topsoil has reached its OC saturation point after growing row-, small grain- and cover-crops using either CvT or CnT management practices for 37 yr.

2 | MATERIALS AND METHODS

2.1 | Site descriptions

The study site is located on a 2.8 ha field at the Clemson University Pee Dee Research and Education Center (PDREC) near Florence, SC (34°17′18.5 N, 79°44′16.3 W). The predominant soil series is a Norfolk loamy sand–which is characterized as a well-drained Ultisol, formed in highly weathered-loamy marine sediments, with a characteristic profile consisting of a shallow Ap (0–20 cm), poorly structured E (20–40 cm), and a clay-enriched Bt argillic horizon (40–180 cm). For at least the past 40 yr, the field has been used for row crop and tillage studies by Clemson University (http://www.Clemson.edu/public/experimentstation/history.html).

Initial soil fertility characteristics, crop rotation, supplemental irrigation, and tillage operations have been previously reported (Busscher et al., 1988; Hunt et al., 2004; Karlen et al., 1984; Novak et al., 2007). For this study, 20 (0.14 ha) plots were used with 10 planted to corn (five CnT and five CvT) and 10 used for a double-crop winter wheat followed by soybean system (Table S1). The plot replicates were number as one through five. The crop rotation blocks were rotated annually, with periodic transitions of the wheat–soybean system to a cereal rye (*Secale cereale* L.) cover crop–cotton system. No grain from the rye cover crop was harvested.

Crop varieties, planting rates, row width, and harvest dates varied over the decades due to varietal changes, experimental objectives, and equipment. Generally, Dekalb cultivars DK687 or DK69-72 (an AF2, Roundup-Ready (RR2) hybrid) corn was planted at 54,000–68,000 seeds ha^{-1}. Prichard Roundup-Ready (RR) soybean was planted at 13 seeds m^{-1}; Coker cultivar 9227 or Pioneer cultivar 2684 winter wheat was planted at 115 kg ha^{-1}; and DPL cultivar 458 Bt RR cotton was planted at 10 seeds m^{-1}. Row width varied between 0.76- and 0.97 m for row crops, and between 0.2–0.36 m for wheat. The cereal rye cover crop was planted between 2003 and 2007 at 105 kg seed ha^{-1} using a seed drill with 10-cm row spacing. From late 2008 through 2010, rye was removed from the rotation and the plots were managed in a simple corn and soybean rotation. Finally, from 2011 through 2016, full-season cotton was grown instead of soybean.

For all row-crops, either CvT or CnT, in-row subsoiling to a depth of ≈40 cm or a para-till operation was used annually to disrupt the compacted hardpan that forms within the E horizon (Supplemental Table S1). For the CvT treatment, multiple off-set diskings at a depth of 15 cm were used to incorporate crop residue prior to planting. The CnT treatments received no surface tillage (Supplemental Table S1), which thus maintained most crop residue on the soil surface.

2.2 | Rainfall totals

Annual total as well as monthly minimum and maximum rainfall data for the Pee Dee Weather Station (Site no. 2037) located at coordinates 34°18′ N and 79°44′ W in Darlington County, South Carolina, were obtained from the USDA-NRCS National Water and Climate Center website (https://wcc.sc.egov/nwcc/site?sitenum=2037&state=SC) for 2002 through 2013. Daily results for late 2014 to early 2015 were missing due to hurricane disruption, so data from an alternate weather station located at the PDREC and from Clemson University (https://www.Clemson.edu/cafla/research/peedee/weather.html) were used for 2014–2016 (Supplemental Table S2).

2.3 | Topsoil and bulk density collections

Composite soil samples from corn plots were collected annually from the 0–5-, 5–10-, and 10–15-cm depth increments during March or April of 2003 through 2013 for soil fertility analyses. Simultaneously, bulk density samples were collected from shallow excavation pits within three of the five replications for each tillage treatment as outlined by Grossman and Reinsch (2002). We did not collect bulk density samples from rep 2 plots because their slopes were >1% that would introduce differences in their soil drainage classes and hence potential variances in soil OC and TN decomposition dynamics. Additionally, no bulk density samples were collected from soils in plot 5 because soil in this area formed in a closed depression called a Carolina Bay (Daniels, Buol, Kleiss, & Ditzler, 1999). These soils are naturally enriched in SOC due to their poor internal drainage (Novak et al., 2007). Furthermore, samples were not collected from plots following soybean crop in 2003 and 2004 because of insufficient labor resources.

Soil fertility, bulk density, and crop residue samples were not collected in 2014 and 2015 because of a crop rotation shift designed to increase cotton production (Supplemental Table S1). In 2016, composite soil samples (n = 6–8) from the 0–5-cm depth increment were collected from three corn plots to provide SOC data for subsequent modeling of C and N dynamics for CnT and CvT treatments (Nash et al., 2018). After air-drying and passing through a 2-mm sieve, SOC contents were measured using a LECO 2000 CNS analyzer (LECO Corp.). Since bulk density was not measured in 2016, SOC concentrations were expressed on a g kg^{-1} basis.

2.4 | Crop yields and residue collection

Row crop grain and cotton lint yields were determined annually for reps 1, 3, and 4 of the CnT and CvT treatments. Aboveground crop biomass samples were collected by hand a few days after crop harvest by sampling from three randomly selected 1 m^2 areas within each plot. Rye cover crop biomass was collected in early May by hand-cutting aboveground plant material within a quarter-m^2 area at a stubble height of ≈2.5 cm. All biomass samples were oven dried at 60 °C, composited by tillage treatment, and ground to pass a 0.5-mm screen and analyzed using dry combustion to determine C content.

2.5 | Statistics

Mean SOC and TN values in Mg ha^{-1} were calculated using annual values for 2002 through 2013 after sorting by crop rotation, tillage, and depth increments. Values from 2002 were included to meld with results and analyses reported by Novak et al. (2007). Significant changes in topsoil SOC and TN accumulation and stratification were identified using a two-way ANOVA to compare means from the 0–5-, 5–10- and 10–15-cm increments by depth, tillage, and the depth x tillage interaction. Mean SOC and TN contents for the entire 0–15-cm increment were calculated and tested for tillage and crop rotation effects using a one-way ANOVA. Similar to analyses conducted by Novak et al. (2007), annual mean SOC values for the 0–5-cm depth from 2002 through 2013 (including samples collected in 2016) were fitted using an exponential rise to a maximum model:

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

where, y = SOC (g kg^{-1}), x = year of study, and y_0, a, and b are equation parameters. This allows for results from the additional 15 yr of experimentation to be associated with data collected prior to 2002.

For plots where corn was grown, a Pearson Product Moment test was used to determine if topsoil OC content (in 0–5 cm increments) under each tillage operation was linearly dependent on total C input from crop residue during the study period. This was not done for plots involving soybean and cotton because residue input results were missing for 2 yr. All statistical analyses were performed at a P = .05 level of confidence using Sigma Stat version 3.5 software (SYSTAT Inc.).

3 | RESULTS AND DISCUSSION

3.1 | Crop grain yields and residue production

Mean CvT and CnT crop yields from 2002 through 2011 are presented in Table 1. Wheat yields under both tillage systems ranged between 1.6–2.1 Mg ha^{-1} and were similar to those reported (Karlen & Gooden, 1987) for no-till and disk-tillage (1.87 and 2.33 Mg ha^{-1}, respectively) on Norfolk soil. Corn grain yields for CvT and CnT varied tremendously from 0.28 to 7.90 Mg ha^{-1} between 2002 to 2011 because of annual rainfall amount and distribution. Mean soybean yield under CvT and CnT were also highly variable, ranging from 0.224 to 4.06 Mg ha^{-1}. Cotton yields for CvT and CnT were quite similar (0.551 Mg ha^{-1} or about 10% relative difference) at this site.

As noted above corn grain and soybean yield variations were primarily the result of periodic drought, especially during critical growth periods (e.g., pollination, seed filling, etc.; Heckman & Kamprath, 1992; Davis, Walker, Parker, & Mullinix, 1996). Corn in the SC Coastal Plain is usually planted in late March/early April, with pollination occurring in late June/early July. In 2002, rainfall during April and June, totaled only 16 and 22 mm, respectively, whereas in 2004, 26 and 125 mm

TABLE 1 Mean crop grain yields in plots under conventional (CvT) and conservation (CnT) tillage management (oven dry wt; $n = 3$)[a]

Year	Yields under CvT				Yields under CnT			
	Wheat	Corn	Soybean	Cotton	Wheat	Corn	Soybean	Cotton
	Mg ha^{-1}							
2002	1.934	0.323	*	*	1.601	0.277	*	*
2003	2.131	7.432	2.063	*	1.690	7.161	1.967	*
2004	*	5.868	4.058	*	*	5.445	3.281	*
2005	*	6.495	0.968	*	*	6.309	0.843	*
2006	*	3.996	2.282	*	*	5.28	2.381	*
2007	*	6.436	0.470	*	*	7.108	0.435	*
2008	*	1.150	2.302	*	*	1.263	2.483	*
2009	*	7.636	1.338	*	*	7.531	1.836	*
2010	*	7.902	0.239	*	*	7.264	0.224	*
2011	*	1.551	*	0.551	*	1.864	*	0.499
2012	*	*	*	*	*	*	*	*
2013	*	*	*	*	*	*	*	*

[a] Where * indicates data not available.

of rainfall were received during those 2 mo. Therefore, although annual mean rainfall for Eastern SC (1182 mm) is relatively high, (https://www.usclimatedata.com/climate/darlington/south-carolina/united-states/ussc0084), the distribution can be limited during critical growth periods. Furthermore, the sandy texture and low water holding capacity of most Coastal Plain soils [as little as 80 mm of water retention per meter of depth (Beale, Peele, & Lesesne, 1966)] can severely exacerbate plant water stress. If there is no rainfall for a 2-wk period when evapotransporation is high, crop yields can be significantly decreased (Sheridan, Knisel, Woodyand, & Asmussen, 1979; Sadler & Camp, 1986).

The calculated amount of crop residue (aboveground biomass minus grain) returned to both tillage treatments are reported in (Table 2). Corn generally returned the largest amount of residue followed by soybeans and wheat which were approximately equal, and cotton which was more variable (Table 2). This was consistent with previous studies (Novak, Frederick, Bauer, & Watts, 2008) showing that in the southeastern Coastal Plain, corn generally returns more residue than cotton. As previously shown in Nebraska (Doran et al., 1984) and elsewhere, soybean also returned less biomass in our study.

Cereal rye residue returned between 0.51–5.19 Mg ha^{-1} with the highest amount under the soybean + cotton rotation (Table 2). Higher amounts of cereal rye biomass were returned to soil when grown before soybean (May planting) than before corn (March or April planting). The 2-mo difference in cereal rye harvest provided a longer window for cereal rye growth that translated into higher biomass production.

3.2 | Accumulation, stratification, and storage of soil organic carbon and total nitrogen

3.2.1 | Soil organic carbon contents

Tillage intensity (CnT vs. CvT), sampling depth (0–5-, 5–10- and 10–15 cm), and tillage × depth interactions significantly affected mean SOC concentrations (Table 3; $P < .001$) between 2002 and 2013. Within the 0–5-cm depth increment SOC after either corn or soybean/cotton rotation was 1.8 times higher for CnT than CvT. This was consistent with other CnT studies (Deen & Katatki, 2003; Potter, Jones, Torbert, & Unger, 1997; Yang & Wander, 1999), which attributed near-surface SOC accumulation to the lack of mixing crop residues throughout the Ap horizon. Furthermore, mean CnT SOC contents decreased within the 5–10- and 10–15-cm depths increments compared to CvT. Although there was no detectable SOC benefit at the lower depth increments, the positive effect of CnT within the surface 5 cm was sufficient to influence mean 0–15-cm SOC values which were 1.55–1.49 Mg ha^{-1} higher than with CvT for both crop sequences (Table 3).

Plotting the annual mean SOC contents (with error bars) as a function of individual soil depth and tillage confirmed that OC had accumulated in the top 5 cm of soil (Figure 1). There were annual SOC fluctuations under CnT, especially in the top 5 cm, and none of the depth increments correlated with calculated C input associated with crop residues ($P > .5$; data not presented). Annual mean SOC contents under CvT showed no detectable changes (Figure 1) and there was also no linear response to C input from crop residue ($P > .2$).

TABLE 2 Mean crop residues masses returned to plots under conventional (CvT) and conservation tillage (CnT) management (oven dry wt; $n = 3$)[a]

	Residue under CvT				Residue under CvT			
Year	Wheat	Corn	Rye	Sum	Rye	Soybean	Cotton	Sum
	Mg ha^{-1}							
2002	7.831	7.111	*	14.942	*	*	*	*
2003	6.603	12.837	*	19.440	*	5.513	*	5.513
2004	*	11.888	0.507	12.395	6.603	8.089	*	14.692
2005	*	17.053	4.319	21.372	4.089	8.93	*	13.019
2006	*	16.639	1.004	17.643	4.221	6.601	*	10.822
2007	*	16.396	1.013	17.409	7.191	6.179	*	13.37
2008	*	15.107	1.369	16.476	10.569	9.323	*	19.892
2009	*	17.434	*	17.434	*	6.87	*	6.87
2010	*	17.393	*	17.393	*	8.932	*	8.932
2011	*	8.825	*	8.826	*	*	3.847	3.847
2012	*	13.717	*	13.717	*	*	6.650	6.650
2013	*	13.341	*	13.341	*	*	10.373	10.373
	Residue under CnT				Residue under CnT			
	Wheat	Corn	Rye	Sum	Rye	Soybean	Cotton	Sum
	Mg ha^{-1}							
2002	6.550	7.263	*	13.813	*	*	*	*
2003	6.505	12.623	*	19.173	*	6.020	*	6.02
2004	*	11.546	0.932	11.938	7.83	8.127	*	15.957
2005	*	17.400	5.193	22.593	5.076	8.842	*	13.918
2006	*	18.626	0.645	19.271	5.582	7.431	*	13.013
2007	*	17.591	1.214	18.805	6.000	6.796	*	12.796
2008	*	15.501	1.573	17.074	12.493	7.937	*	20.43
2009	*	16.890	*	16.890	*	8.167	*	8.167
2010	*	15.988	*	15.988	*	7.450	*	7.450
2011	*	10.525	*	10.525	*	*	4.300	4.300
2012	*	14.609	*	14.609	*	*	6.397	6.937
2013	*	14.192	*	14.192	*	*	9.325	9.325

[a] Where * indicates data not available.

3.2.2 | Soil organic carbon saturation

Calculations were also made to determine if 37 yr of tillage and crop management treatments on a Norfolk loamy sand had resulted in/or was approaching SOC saturation. We used (a) simulation modeling SOC content (g kg^{-1}) vs. years of study, and (b) computed mass balance using the sum of residue C inputs (Mg ha^{-1}) and change in topsoil SOC content (Mg ha^{-1}; within the 0–15-cm depth) from 2002 to 2013. Data from 1979 to 2001 (mg kg^{-1}; Novak et al., 2007) were combined with the more recent annual measurements (2002–2016) to assess the long-term effects. Because the research site had a variety of crop sequence treatments during the 37 yr, combining was done only for soil samples collected from wheat + corn + rye treatments between 2002 and 2016. Pairing those two data pools for CnT and CvT showed good overall model fits ($r^2 = .48–.71$) and the relationship was highly significant ($P < .0001$).

Curves from the exponential model projections show distinct changes in SOC trajectory as a function of tillage and year of study. For example, the CnT slope began to level off in 2016 which was the 37th yr of experimentation, whereas, the CvT slope was nearly level from 1998 to 2008 (the 20th–30th yr of study). As indicated by Hassink (1997) and Watson et al. (2000), a near level relationship exposed by a model between SOC content and time suggests that the soil is at or is approaching OC saturation. The shape of the exponential model for this site suggests that topsoil under

TABLE 3 Mean quantities of soil organic carbon (SOC) and total nitrogen (TN) contents from results pooled between 2002 and 2013 sorted by depth, tillage and crop rotation management (standard deviation in parentheses)

	SOC		TN	
Depth	**Conventional**[a]	**Conservation**	**Conventional**	**Conservation**
cm	Mg ha^{-1}			
Corn				
0–5	6.93 (1.17)a, a	12.38 (2.84)a, b	0.68 (0.25)a, a	1.03 (0.30)a, b
5–10	6.93 (1.08)a, a	7.54 (2.26)b, a	0.69 (0.22)a, a	0.79 (0.32) b, a
10–15	6.18 (1.41)a, a	4.76 (1.58)c, b	0.60 (0.26)a, a	0.49 (0.29) c, a
Mean[b]	6.68a	8.23 b	0.64a	0.75a
Soybean/cotton				
0–5	7.19 (1.09)a, a	12.91 (2.14)a, b	0.68 (0.22)a, a	1.06 (0.22)a, b
5–10	7.79 (1.39)a, a	7.82 (1.85)b, a	0.69 (0.24)a, a	0.71 (0.26)b, a
10–15	6.47 (1.19)b, a	5.18 (1.36)c, b	0.63 (0.27)a, a	0.52 (0.29)b, a
Mean	7.15a	8.64b	0.67a	0.76a
	***P*-value**		***P*-value**	
Effect	**Corn**	**Soybean/cotton**	**Corn**	**Soybean/cotton**
Tillage	<.001	<.001	.102	.127
Depth (cm)	<.001	<.001	<.001	<.001
Tillage x depth	<.001	<.001	.011	.006

[a] First letter indicates significant differences by depth within tillage treatment and second letter indicates differences between tillage determined using a two-way ANOVA.

[b] Overall topsoil mean (0–15-cm depth) tested for significant differences using a one-way ANOVA at $P < .05$.

CnT is slowly accumulating more SOC, whereas CvT soil is at or near C saturation (Figure 2).

A second approach used to determine if SOC saturation had been reached was to measure OC inputs from crop residues and compare the values with SOC change over time (Six et al., 2002a; Goh, 2004). When the SOC content no longer changes significantly after following crop residue additions, the soil is approaching OC saturation. Once again, this approach was only for soils under the wheat + corn + rye rotation since OC input from soybean in 2002 was unavailable due to severe drought. For CnT and CvT treatments this approach revealed a cumulative OC input of 88.6 and 86.0 Mg ha^{-1}, respectively, between 2002–2013, but mean SOC content for the top 15 cm was relatively unchanged (i.e., 2.5–12% relative variation in Figure 3). The small SOC variation after almost 90 Mg ha^{-1} of residue OC input supports the definition of SOC saturation as defined by Six et al. (2002a) and Goh (2004).

From a soil fertility management perspective, a soil's OC saturation limit is important because it defines the limit of OC storage from most organic sources (i.e., crop residue, manure, etc.) and the potential impact on nutrient and water retention (Hassink et al., 2002; Six et al., 2002a). Furthermore, the OC saturation point is unique for every soil and varies as a function of texture (Hassink, 1997), aggregation (Angers, 1998), and organic residue recalcitrance (Stewart, A, Paustian, Conant, & Six, 2008).

3.2.3 | Soil total nitrogen contents

Mean TN content in the 0–5-cm increment showed significant differences for CnT and CvT treatments (Table 3) with values being 1.6 times higher under CnT than with CvT. Differences in TN within the 5–10- and 10–15-cm depths were not significant (Table 3, $P = .102$ and .127). Statistical analysis also showed that mean TN content was depth dependent ($P < .001$), and the depth x tillage interactions were significant ($P = .011$ and .006). Despite the significant TN differences within the 0–5-cm increment, cumulative mean values for the entire 0–15-cm increment for both CnT and CvT were not significantly different.

3.3 | Organic carbon storage potentials in sandy-textured soils

Parent material, climate, and texture have strong effects on SOC content and the ability of a specific soil to store OC (Troeh & Thompson, 2005). Sandy soils formed in Coastal marine sediments generally have a low potential to store OC because they are warmer, better aerated, and have higher OC mineralization rates than finer-textured soils (Jobbágy & Jackson, 2000). Furthermore, the bonding of OC substances to minerals is also recognized as an important factor influencing a soils OC mineralization potential and thus the longevity of OC storage (Six et al., 2002a). Sand

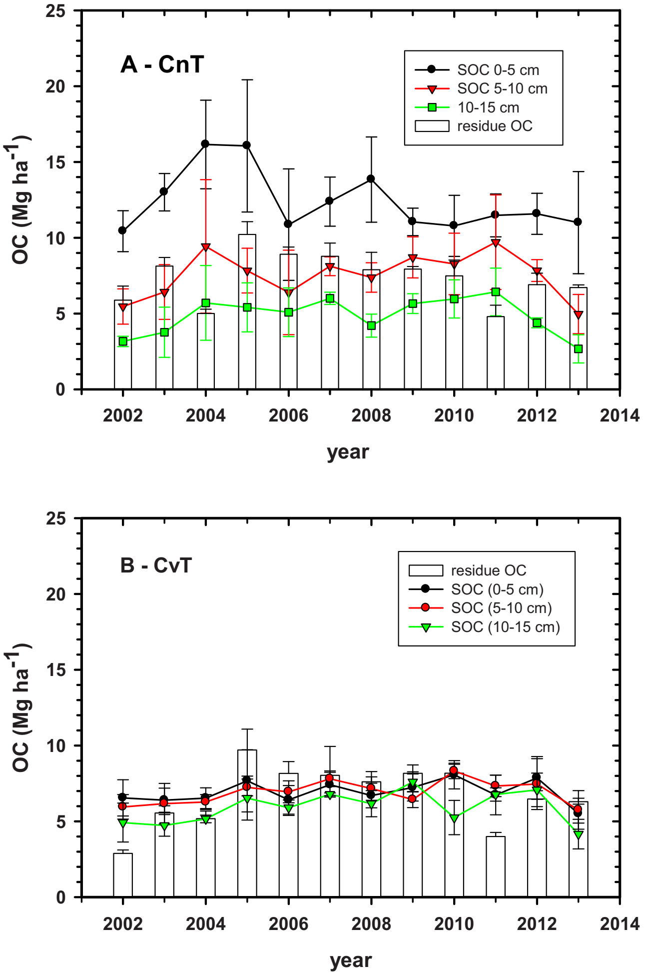

FIGURE 1 Comparison of mean topsoil soil organic carbon (SOC) contents and residue additions between 2002–2013 to soil under conservation (CvT) and conventional (CnT) management (corn ground only)

particles exhibit weak bonding affinities for OC substances because of the dominance of quartz particles (von Lutzow et al., 2007). Weak binding between quartz particles and OC substances decreases the protection of those compounds from soil microbes. Thus, when combined with higher mean annual temperatures and a humid climate such as in the southeastern Coastal Plain, the OC substances can be rapidly oxidized to CO_2 (Bond-Lamberty & Thomson, 2010).

In comparison, OC will accumulate in fine-textured soils because OC substances can bind with silt and clay surfaces through mechanisms such as ligand exchange and polyvalent cation bridges leading to the formation of clay–humic complexes (Stevenson, 1994). Those complexes will eventually coalesce into micro-aggregates (Six, Elliott, & Paustian, 1999; Tisdall & Oades, 1982), thus enabling both mechanisms to reduce microbial mineralization and enhance their accumulation (Blanco-Canqui & Lal, 2004).

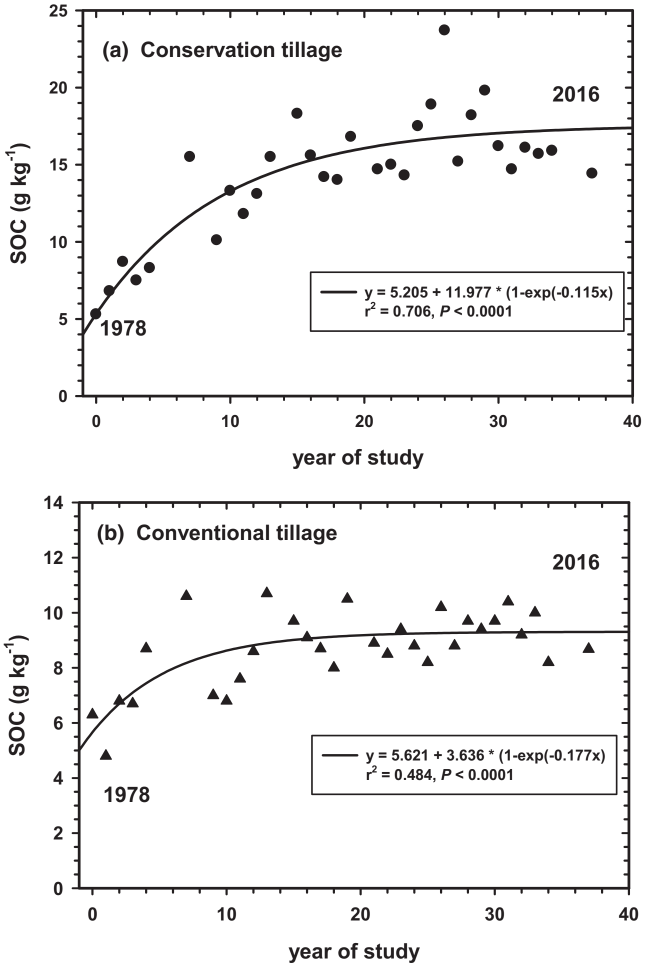

FIGURE 2 Mean soil organic carbon (SOC) contents vs. year of study under (a) conservation and (b) conventional tillage. (Curve is an exponential model depicting the predicted SOC content as a function of year of study)

Our results show that under the current tillage, crop management, and residue input scenarios, the Norfolk topsoil is nearing its capacity to store OC. That does not preclude, however, any more OC storage in the Norfolk topsoil (0–15-cm deep). In fact, recently Nash et al. (2018) reported that topsoil SOC increases were projected to occur when our results (2002–2013) were ran through the CQESTR model. The model projected SOC gains of 0.28 Mg C ha^{-1} upon longer use of CnT, along with corn and cover crops that produce high crop residue returns and belowground OC contributions. Similarly, these authors also report that the Norfolk soil profile will eventually reach OC saturation, although it was projected to be several years away (by 2030; Nash et al., 2018). Thus, our suggestion that the Norfolk topsoil is approaching OC saturation corroborates the model projection by Nash et al. (2018), but the timescale for this occurrence is several years different.

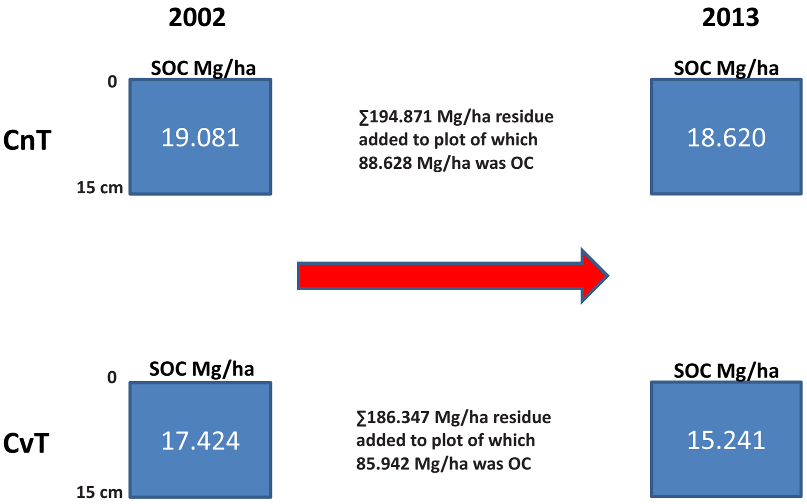

FIGURE 3 Mass balance of organic carbon (OC) additions as residue with changes in topsoil soil organic carbon (SOC) contents (0–15 cm) for plots under a wheat + corn + cereal rye rotation

4 | CONCLUSION

Sandy soils in the SE USA Coastal Plain region have low SOC content, decreased nutrient and water retention, and structural deficiencies because SOC and TN have been depleted by nearly two centuries of crop production using various forms of inversion tillage. To mitigate these losses, CnT and cover crop management are being recommended to rebuild these two important soil health parameters. Results following 37 yr of known management confirm that long-term CnT can significantly increase SOC and TN content in the surface 5 cm compared to CvT. We also showed that CnT resulted in significant vertical stratification of SOC and TN which did not occur under CvT.

This evaluation also showed that the Norfolk topsoil under both CnT and CvT was approaching OC saturation. The projected number of years required to reach saturation varies based on tillage intensity, but overall our results confirm that using CnT under a wheat + corn + cereal rye cover crop can bolster C sequestration and TN contents within sandy Ultisols in the U.S. southeastern Coastal Plain.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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