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Soil carbon and nitrogen sequestration as affected by long-term tillage, cropping systems, and nitrogen fertilizer sources

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ABSTRACT

Disposal of poultry litter, a widely available organic manure in the southeastern USA because of a large-scale poultry industry, is a major concern because of its contamination in surface- and groundwater through N leaching and P runoff. Application of poultry litter in no-tilled intensive cropping system could increase soil C and N sequestration compared with the conventional-tilled system with inorganic N fertilization and reduce environmental contamination. We evaluated the 10-year effects of tillage, cropping systems, and N fertilizer sources on crop residue (stems + leaves) production and soil bulk density, organic C (SOC), and total N (STN) at the 0–20 cm depth in Decatur silt loam (clayey, kaolinitic, thermic, and Typic Paleudults) in northern AL, USA. Treatments were incomplete factorial combinations of three tillage practices [no-till (NT), mulch till (MT), and conventional till (CT)], two cropping systems [cotton (*Gossypium hirsutum* L.)–cotton–corn (*Zea mays* L.) and rye (*Secale cereale* L.)/cotton–rye/cotton–corn], and two N fertilization sources and rates (0 and 100 kg N ha^{-1} from NH_4NO_3, and 100 and 200 kg N ha^{-1} from poultry litter) in randomized complete block with three replications. Rye was grown as winter cover crop and corn as residual crop without tillage and fertilization. Mean crop residue returned to the soil from 1997 to 2005 was greater in rye/cotton–rye/cotton–corn than in cotton–cotton–corn and greater with NH_4NO_3 than with poultry litter at 100 kg N ha^{-1}. While SOC and STN concentrations at 10–20 cm after 10 years were not influenced by treatments, SOC and STN contents at 0–20 cm were greater with poultry litter than with NH_4NO_3 in NT and CT. These resulted in a C sequestration rate of 510 kg C ha^{-1} $year^{-1}$ and N sequestration rates of 41–49 kg N ha^{-1} $year^{-1}$ with poultry litter compared with −120 to 147 kg C ha^{-1} $year^{-1}$ and −23 to −3 kg N ha^{-1} $year^{-1}$, respectively, with NH_4NO_3. Cropping and fertilization sequestered C at 730 kg C ha^{-1} $year^{-1}$ and N at 67 kg N ha^{-1} $year^{-1}$ compared with fallow and no-fertilization in NT. Tillage and cropping system did not influence SOC and STN. Long-term poultry litter application or continuous cropping can sequester C and N in the soil compared with inorganic N fertilization or fallow, thereby increasing soil quality and productivity and reducing the potentials for N leaching and greenhouse gas emission.

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1. Introduction

Carbon sequestration using long-term novel soil and crop management practices is needed not only to increase soil C storage for C trading and mitigate greenhouse gas emission, such as CO_2, from the soil profile but also to improve soil quality and increase economic crop production. Similarly, N sequestration is needed to reduce the rate and cost of N fertilization, N leaching, and N_2O emission, another destructive greenhouse gas causing global warming. Soil organic matter (SOM), as indicated by soil C and N levels, can directly impact crop production. Bauer and Black (1994) reported that an increase in SOM content of 1 Mg ha^{-1} in the surface 3 cm of soil increased wheat grain yield by 15.6 kg ha^{-1}. Such an increase in crop production with increased SOM storage was a result of enhanced soil structure and improved soil water–nutrient–crop productivity relationships (Bauer and Black, 1994).

While conventional tillage without cover crop and N fertilization reduces SOM level by enhancing C and N mineralization and

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limiting C and N inputs (Dalal and Mayer, 1986; Balesdent et al., 1990; Cambardella and Elliott, 1993), conservation tillage with cover cropping and N fertilization can increase C and N storage in the surface soil (Jastrow, 1996; Allmaras et al., 2000; Sainju et al., 2002a, 2006). Studies suggest that conversion of conventional till (CT) to no-till (NT) can sequester atmospheric CO_2 by 0.1% ha^{-1} at the 0–5 cm soil depth every year, a total of 10 tons in 25–30 years (Lal and Kimble, 1997; Paustian et al., 1997). Sequestration of C in the soil by converting CT into NT can also conserve N, because soil organic C (SOC) and total N (STN) levels are highly related (Franzluebbers et al., 1995, 1999; Kuo et al., 1997b; Sainju et al., 2002b). However, SOC and STN levels below the 7.5-cm depth can be higher in tilled areas, depending on the soil texture, due to residue incorporation at greater depths (Jastrow, 1996; Clapp et al., 2000). Similarly, cover cropping and N fertilization can increase SOC and STN in tilled and non-tilled soils by increasing the amount of crop residue returned to the soil (Kuo et al., 1997a,b; Omay et al., 1997; Sainju et al., 2002a, 2006). The impact of tillage on SOC and STN can interact with cover cropping and N fertilization rate (Gregorich et al., 1996; Wanniarachchi et al., 1999; Sainju et al., 2002a), soil texture and sampling depth (Ellert and Bettany, 1995), and time since treatments were initiated (Liang et al., 1998).

Poultry litter, an inexpensive source of nutrients, is widely available in the southeastern USA because of a large-scale poultry industry (Kingery et al., 1994; Nyakatawa and Reddy, 2000; Nyakatawa et al., 2000). Disposal of large amount of poultry litter is causing an increasing environmental concern because of surface- and groundwater contamination of N and P from the litter through leaching and surface runoff. Application of poultry litter to crops, however, can increase SOM that can improve soil quality and productivity (Kingery et al., 1994). Studies have shown that manure application increased SOC and STN levels (Webster and Goulding, 1989; Collins et al., 1992; Rochette and Gregorich, 1998). Poultry litter application along with conservation tillage and cover cropping can provide an opportunity to increase C and N sequestration and soil quality and productivity in the humid southeastern USA where SOM level is lower than in northern regions due to a long history of cultivation and rapid rate of mineralization (Trimble, 1974; Doran, 1987; Langdale et al., 1992).

The effects of tillage, cropping systems, cover crops, and N fertilization on SOC and STN had been known (Kuo et al., 1997a,b; Sainju et al., 2002a, 2006). Limited information, however, is available about the long-term (≥10 years) combined effects of tillage, cropping systems, poultry litter, and inorganic N fertilization or the comparison of poultry litter vs. inorganic N fertilization on soil C and N sequestration in the southeastern USA. We hypothesized that conservation tillage with poultry litter application and intensive cropping that includes cover crop would increase SOC and STN levels compared with conventional tillage with or without inorganic N fertilization and cropping system without cover crop. Our objectives were to: (1) examine the effects of long-term (10 years) tillage, cropping system, poultry litter application, and inorganic N fertilization on mean crop biomass residue returned to the soil and soil bulk density, SOC, and STN levels in the southeastern USA and (2) quantify their effects on soil C and N sequestration rates.

2. Materials and methods

2.1. Experimental site and treatments

A long-term field experiment was conducted from 1996 to 2005 in the upland cotton production site at the Alabama Agricultural Experimental Station in Belle Mina, Alabama (34° 41′N, 86° 52′W), southeastern USA. The soil is a Decatur silt loam (clayey, kaolinitic, thermic, and Typic Paleudults) (FAO classification: Acrisols). Before the initiation of the experiment, soil samples collected randomly from 24 cores (5 cm inside diameter) within the experimental plots in 1996 had an average pH of 6.2, sand concentration 150 g kg^{-1}, silt concentration 580 g kg^{-1}, clay concentration 270 g kg^{-1}, SOC content 38.6 Mg C ha^{-1}, STN content 3.7 Mg N ha^{-1}, and bulk density 1.60 Mg m^{-3} at the 0–20-cm depth. The site had been used for growing cotton continuously for the last 5 years before the experiment was started in 1996. Details of the experiment and crop management practices were presented elsewhere (Nyakatawa and Reddy, 2000; Nyakatawa et al., 2000; Reddy et al., 2004).

Treatments consisted of an incomplete factorial combinations of three tillage practices [no-till, mulch till (MT), and conventional till], two cropping systems [cotton (*Gossypium hirsutum* L.)–cotton–corn (*Zea mays* L.), and rye (*Secale cereale* L.)/cotton–rye/cotton–corn], and two N fertilization sources and rates (NH_4NO_3 and poultry litter at 0 and 100 kg N ha^{-1}) (Table 1). In addition, poultry litter at 200 kg N ha^{-1} in rye/cotton–rye/cotton–corn and a fallow treatment without cropping and fertilization in NT were also included for comparing treatments with or without cropping and fertilization on SOC and STN. Treatments were arranged in a randomized complete block design with four replications. For this study, only three replications with uniform crop residue productions were selected. The individual plot size was 8 m × 9 m. Treatments were continued in the same plot every year to determine their long-term influence on SOC and STN.

The CT included moldboard plowing to a depth of 15–20 cm in November after autumn crop harvest and disking and leveling with a field cultivator (Lely USA Inc., Naples, FL, USA) in April of the following year before summer crop planting. The MT included tillage to a depth of 5–7 cm with a rotary field cultivator (Lely USA Inc., Naples, FL, USA) before planting that shallowly incorporated crop residues. The NT included planting in undisturbed soil using a no-till planter (Glascock Equipment and Sales, Veedersburg, IN, USA). The rye/cotton–rye/cotton–corn cropping system included 2 years of rye as winter cover crop and cotton as summer cash crop, followed by 1 year of residual corn crop. Similarly, cotton–cotton–corn cropping system contained 2 years of continuous cotton without rye cover crop, followed by 1 year of residual corn crop. Thus, each cropping system completed three cycles of crop rotation from 1997 to 2005. Fertilizers were applied only to cotton, not to rye and corn. While rye was grown as a winter cover crop, corn was grown as a residual crop without tillage and fertilization to remove residual nutrients left in the soil after cotton harvest every 3 years.

Rye [cv. Oklon (Pioneer Hi-Bred International Inc., Hunstville, AL, USA)] cover crop was planted in November and December at 60 kg ha^{-1} with a no-till driller (Glascock Equipment and Sales,

Table 1
Description of treatments used in the experiment

Treatment no.	Tillage[a]	Cropping system	N source	N rate (kg N ha^{-1})
1	CT	Rye/cotton–rye/cotton–corn	None	0
2	CT	Cotton–cotton–corn	NH_4NO_3	100
3	NT	Cotton–cotton–corn	NH_4NO_3	100
4	CT	Rye/cotton–rye/cotton–corn	NH_4NO_3	100
5	CT	Rye/cotton–rye/cotton–corn	Poultry litter	100
6	MT	Rye/cotton–rye/cotton–corn	NH_4NO_3	100
7	MT	Rye/cotton–rye/cotton–corn	Poultry litter	100
8	NT	Rye/cotton–rye/cotton–corn	NH_4NO_3	100
9	NT	Rye/cotton–rye/cotton–corn	Poultry litter	100
10	NT	Cotton–cotton–corn	None	0
11	NT	Rye/cotton–rye/cotton–corn	Poultry litter	200
12	NT	Fallow	None	0

[a] Tillage is CT, conventional till; MT, mulch till; NT, no-till.

Veedersburg, IN, USA) without fertilization. In April, 7 days after flowering, rye biomass yield was determined by harvesting biomass from a 1 m × 1 m area, after which it was killed either by applying glyphosate [isopropylamine salt of *N*-(phosphonomethyl) glycine] in NT and MT or by incorporating the residue into the soil by a field cultivator in CT. Inorganic N fertilizer (NH_4NO_3) and poultry litter were broadcast to cotton 1 day before planting in May. Both inorganic N fertilizer and poultry litter were incorporated to a depth of 5–8 cm in CT and MT using field cultivator and surface-applied in NT. No adverse effect of poultry litter on germination of cotton was detected; rather cotton seedling counts were 17–50% greater with poultry litter than with NH_4NO_3 during the first 4 days of emergence (Nyakatawa and Reddy, 2000). The poultry litter applied in each year from 1997 to 2005 contained total C at 337 ± 22 g C kg^{-1} and total N at 33 ± 4 g N kg^{-1}. A 60% N availability factor was used to calculate the amount of poultry litter required to supply 100 and 200 kg N ha^{-1} in each year (Keeling et al., 1995). In order to nullify the effects of P and K from poultry litter, inorganic N fertilized plots were applied with 67 kg P ha^{-1} [from triple superphosphate, $Ca(H_2PO_4)_2$)] and 67 kg K ha^{-1} (from muriate of potash, KCl) in each year.

After 4 weeks of cover crop kill, cotton [cv. Deltapine NuCotn 33B (Delta Pine Land Co., Hartsville, SC, USA)] was planted at 16 kg ha^{-1} in May of 1997, 1998, 2000, 2001, 2003, and 2004. In 1999, 2002, and 2005, corn [cv. Dekalb 687 (Pioneer Hi-Bred International Inc., Hunstville, AL, USA)] was planted at 78,000 seeds ha^{-1}. Both cotton and corn were applied with appropriate herbicides and pesticides during their growth to control weeds and pests. Cotton was also applied with appropriate growth regulator [Pix (1.1-dimethyl-piperidinium chloride) at 0.8 kg ha^{-1}] to control its vegetative growth. Irrigation was applied to cotton and corn ranging in amounts from 23 to 47 mm at a time (or a total of 560–571 mm from May to November) depending on soil water content to prevent moisture stress. Aboveground cotton and corn biomass (stems + leaves) yields were determined 2 weeks before lint and grain harvest in October–November by measuring plant samples in two 0.5 m^2 quadrants outside the yield rows in each plot after separating lint, seeds, and cobs. Yields of cotton lint and corn grain were determined by mechanically harvesting the central four rows (4 m × 9 m) with a combine harvester (Glascock Equipment and Sales, Veedersburg, IN, USA) in November of each year. After sampling, cotton lint and corn were removed from the rest of the plots with a combine harvester and crop residue (stems + leaves) were returned to the soil.

2.2. Soil sampling and analysis

In February 2006, soil samples were collected with a hand probe (10 cm inside diameter) from the 0 to 20 cm depth from five places in the central rows of the plot after removing the crop residue from the soil surface. These were separated into 0–10 cm and 10–20 cm depths, composited within a depth, air-dried, ground, and sieved to 2 mm for determining SOC and STN. At the same time, a separate undisturbed soil core (10 cm inside diameter) was taken from 0 to 10 cm and 10–20 cm depths from each plot to determine bulk density by dividing the mass of the oven-dried sample at 105 °C by the volume of the probe.

Total C concentration (g kg^{-1}) in the soil was determined by the dry combustion method using a C and N analyzer (Model no. 661-900-800, LECO Corp., St. Joseph, MI, USA) and was considered as SOC concentration, since the pH of the soil was <7.0 (Nelson and Sommers, 1996). Similarly, STN concentration was determined with the C and N analyzer as above at the same time as SOC was analyzed. The contents (Mg C or N ha^{-1}) of SOC and STN at 0–10 cm and 10–20 cm depths were calculated by multiplying their concentrations (g kg^{-1}) by bulk density for each treatment and depth (as discussed below) and thickness of the soil layer. The total contents at the 0–20 cm depth were determined by summing the contents at 0–10 cm and 10–20 cm.

2.3. Data analysis

Data for SOC, STN, and bulk density among and within soil depths were analyzed using the MIXED procedure of SAS (Littell et al., 1996). Treatment was considered as the main factor and fixed effect, soil depth as the repetitive measure factor and another fixed effect, and replication and treatment × replication as random effects. Since the treatments were laid out in an incomplete factorial arrangement, Treatments 2–4 and 8 (Table 1) containing complete combinations of tillage and cropping systems were used to determine the effect of tillage × cropping system interaction on SOC, STN, and bulk density. Similarly, Treatments 4–9 containing complete combinations of tillage and N sources were used to determine the effect of tillage × N source interaction on SOC, STN, and bulk density. For crop biomass yields, data were analyzed exactly as above by replacing soil depth by year after considering year as a repetitive measure factor. Means were separated by using the least square means test when treatments and interactions were significant. A least significant difference value [LSD (0.05)] was shown in the tables for comparing large number of treatments while treatment means were separated by letters for comparing small number of treatments. For comparing the effect of cropping and fertilization vs. fallow and no-fertilization in NT on SOC and STN, orthogonal contrasts were used to compare the mean of Treatments 3 and 8–11 vs. Treatment 12. Statistical significance was evaluated at $P \leq 0.05$, unless otherwise stated.

3. Results and discussion

3.1. Crop residue production

Crop biomass residue (stems + leaves) returned to the soil after autumn crop harvest forms an important source of C and N inputs to the soil and can influence SOC and STN. Mean annual crop residue returned to the soil from 1997 to 2005 was greater in NT with rye/cotton–rye/cotton–corn and poultry litter application at 200 kg N ha^{-1} (Treatment 11) than in other treatments, except in NT with rye/cotton–rye/cotton–corn and NH_4NO_3 at 100 kg N ha^{-1} (Treatment 8) (Table 2). Residue production was also greater with NH_4NO_3 than with poultry litter at 100 kg N ha^{-1} in the intensive cropping system (Treatment 8 vs. Treatments 5, 7, and 9). Without N fertilization, residue production was severely reduced (Treatments 1 and 10). Because of the absence of crops in fallow, there was no residue production in Treatment 12.

Analysis of the interaction of tillage with cropping system and N source (using complete combination of treatments) indicated that tillage did not influence crop residue production (Table 2). Mean annual residue production, averaged across tillage and N sources, was greater with rye/cotton–rye/cotton–corn than with cotton–cotton–corn. Similarly, residue production, averaged across tillage and cropping systems, was greater with NH_4NO_3 than with poultry litter. While increased cropping intensity could have increased residue production in rye/cotton–rye/cotton–corn compared with cotton–cotton–corn, reduced soil N availability as a result of slow N mineralization probably decreased residue production with poultry litter compared with NH_4NO_3 when both of them were applied at 100 kg N ha^{-1}. When poultry litter was applied at 200 kg N ha^{-1}, residue production was not different between poultry litter applied at this N rate and NH_4NO_3 applied at 100 kg N ha^{-1}. This indicates that N release from poultry litter is

Table 2
Effects of tillage, cropping systems, and N sources on mean biomass (stems + leaves) residues of rye, cotton, and corn returned to the soil from 1997 to 2005

Treatment no.[a]	Mean crop biomass ($Mg\ ha^{-1}\ year^{-1}$)
1	6.1
2	11.5
3	13.0
4	14.0
5	12.2
6	14.0
7	11.7
8	16.4
9	13.3
10	10.7
11	16.8
12	–
LSD (0.05)[b]	2.7
CV (%)[c]	21.5
Cropping system (comparison of Treatments 2–4 and 8)[a]	
Rye/cotton–rye/cotton–corn	15.2 a[d]
Cotton–cotton–corn	12.2 b
N source ($100\ kg\ N\ ha^{-1}$) (comparison of Treatments 4–9)[a]	
NH_4NO_3	14.8 a
Poultry litter	12.4 b

[a] See Table 1 for treatment description.
[b] Least significant differences between treatments at $P = 0.05$.
[c] Coefficient of variation.
[d] Numbers followed by different letter within a column in a set are significantly different at $P \leq 0.05$ by the least square means test.

Table 3
Effects of tillage, cropping systems, and N sources on soil bulk density at the 0–10 cm and 10–20 cm depths in 2006

Treatment no.[a]	Bulk density	
	0–10 cm ($Mg\ m^{-3}$)	10–20 cm ($Mg\ m^{-3}$)
1	1.59	1.57
2	1.51	1.61
3	1.57	1.60
4	1.58	1.64
5	1.65	1.56
6	1.56	1.60
7	1.62	1.62
8	1.52	1.53
9	1.68	1.60
10	1.62	1.68
11	1.56	1.52
12	1.65	1.67
LSD (0.05)[b]	0.10	0.10
CV (%)[c]	4.5	4.6
N source ($100\ kg\ N\ ha^{-1}$) (comparison of Treatments 4–9)[a]		
NH_4NO_3	1.55 b[d]	1.59 a
Poultry litter	1.65 a	1.59 a
Contrast[e] (mean of Treatments 3 and 8–11 vs. Treatment 12)[a]		
Cropping and fertilization vs. fallow and no-fertilization in no-till	−0.06	−0.08*

Significant at $^*P \leq 0.05$.
[a] See Table 1 for treatment description.
[b] Least significant differences between treatments at $P = 0.05$.
[c] Coefficient of variation.
[d] Numbers followed by different letter within a column in a set are significantly different at $P \leq 0.05$ by the least square means test.
[e] Contrast values are the difference between treatment means.

crucial for crop production and that the amount of poultry litter application needs to be adjusted according to its N content and availability within a growing season for sustainable crop production.

3.2. Soil bulk density

Soil bulk density varied with treatments. At 0–10 cm, bulk density was greater in Treatment 9 than in Treatments 2, 3, 6, and 8, but at 10–20 cm, it was greater in Treatment 10 than in Treatments 1, 5, 8, and 11 (Table 3). This indicates that poultry litter application probably influenced bulk density more at the surface than at the subsurface soil. Bulk density at 0–10 cm was significantly influenced by N source but the effects of tillage, cropping system, and their interaction were not significant. At 0–10 cm, bulk density, averaged across tillage and cropping systems, was greater with poultry litter than with NH_4NO_3 at $100\ kg\ N\ ha^{-1}$. At 10–20 cm, cropping and fertilization reduced bulk density compared with fallow and no-fertilization in NT. Bulk density was not influenced by soil depth.

The lack of significant differences in bulk density among tillage and cropping systems suggest that tillage operation and crop type or cropping sequence probably had less influence on soil compaction and therefore on bulk density. One of the possible reasons could be that soils in the experimental site had higher SOC concentration (9.5–15.9 $g\ kg^{-1}$) than normally found in other soils (6.0–10.0 $g\ kg^{-1}$) in the southeastern USA (Sainju et al., 2002a,b, 2006). It was not known if bulk density of soils with higher SOC was less influenced by tillage and cropping systems than soils with lower SOC. Similarly, the reasons for higher bulk density with poultry litter than with inorganic N fertilizer were not known. Since bulk density can influence the conversion of SOC and STN from mass to volume basis, both mass ($g\ kg^{-1}$) basis as influenced by depth and volume ($Mg\ ha^{-1}$) basis of SOC and STN were discussed.

3.3. Soil organic carbon

The SOC concentration varied with treatments at 0–10 cm but was not influenced by them at 10–20 cm. At 0–10 cm, SOC concentration was greater in Treatments 6, 9, and 11 than in Treatments 1, 3, 8, 10, and 12 (Table 4). This suggests that poultry litter application increased SOC concentration at the surface soil compared with inorganic N fertilization at 0 or $100\ kg\ N\ ha^{-1}$. Similarly, at 0–20 cm, SOC content was greater in Treatments 5 and 9 than in Treatments 1, 8, 10, and 12, indicating that poultry litter application increased soil C storage compared with inorganic N fertilization or no N fertilization. When statistical analysis of complete treatments was conducted, tillage, cropping system, and N source did not influence SOC concentration, although they influenced crop residue production (Table 2). Nitrogen source and tillage × N source interaction were, however, significant for SOC content at 0–20 cm. The SOC content at 0–20 cm, averaged across cropping systems, was greater with poultry litter than with NH_4NO_3 at $100\ kg\ N\ ha^{-1}$ in NT and CT (Table 5). Cropping and fertilization increased SOC concentration and content compared with fallow in NT. Increasing the rate of poultry litter application to supply N from 100 to $200\ kg\ N\ ha^{-1}$, however, did not affect SOC in NT, because SOC concentrations and contents were not different between Treatments 9 and 11. The SOC concentration decreased with soil depth.

The decrease in SOC in the fallow treatment in NT after 10 years could be a result of limited C input due to reduction or absence of plant growth. Reduced amount of crop residue returned to the soil, followed by its increased decomposition due to fallow as a result of increased soil temperature and water content can reduce SOC (Halvorson et al., 2002). In contrast, increase in C inputs due to cropping and N fertilization as a result of increased crop residue

Table 4
Effects of tillage, cropping systems, and N sources on soil organic C (SOC) and total N (STN) at the 0–10 cm and 10–20 cm depths in 2006

Treatment no.[a]	SOC concentration		SOC content	STN concentration		STN content	C/N ratio	
	0–10 cm ($g C kg^{-1}$)	10–20 cm ($g C kg^{-1}$)	0–20 cm ($Mg C ha^{-1}$)	0–10 cm ($g N kg^{-1}$)	10–20 cm ($g N kg^{-1}$)	0–20 cm ($Mg N ha^{-1}$)	0–10 cm	10–20 cm
1	12.9	10.4	36.8	1.18	1.00	3.45	10.9	10.4
2	15.2	11.6	41.7	1.35	1.04	3.72	11.3	11.2
3	13.5	10.8	38.6	1.26	0.97	3.54	10.7	11.1
4	14.3	10.7	40.1	1.31	0.98	3.67	10.9	10.9
5	15.3	11.8	43.7	1.51	1.04	4.11	10.1	11.3
6	15.9	11.0	42.6	1.42	1.01	3.85	11.2	10.9
7	15.4	10.6	42.2	1.49	0.92	3.91	10.3	11.5
8	13.5	11.0	37.4	1.23	1.03	3.44	11.0	10.7
9	15.9	10.5	43.7	1.52	1.02	4.19	10.5	10.3
10	12.6	10.3	37.8	1.17	0.97	3.52	10.8	10.6
11	15.9	11.1	41.6	1.58	1.00	3.98	10.1	11.1
12	10.0	9.5	32.5	0.93	0.92	3.06	10.9	10.3
LSD (0.05)[b]	2.4	–	4.9	0.20	–	0.45	–	–
CV (%)[c]	14.5	8.2	10.2	15.4	9.0	10.4	9.8	7.5

[a] See Table 1 for treatment description.
[b] Least significant differences between treatments at $P = 0.05$.
[c] Coefficient of variation.

production (Table 2) probably increased SOC in other treatments. For this, it was assumed that increase in aboveground residue production also increases belowground (root) residue production. Sainju et al. (2005, 2006) reported that increased aboveground shoot production also increased belowground root production in cotton and rye. Increase in SOC due to increased cropping intensity (Sherrod et al., 2003; Sainju et al., 2006) and N fertilization (Liang and Mackenzie, 1992; Gregorich et al., 1996; Omay et al., 1997) as a result of increased crop residue returned to the soil had been known. Further increase in SOC due to poultry litter application compared with inorganic N fertilization in NT and CT suggests that increased C input from poultry litter could have contributed to increased SOC level. Poultry litter that supplied 100 $kg N ha^{-1} year^{-1}$ also contributed 1.7 $Mg C ha^{-1} year^{-1}$. As a result, part of C supplied by poultry litter could have converted to SOC. Several researchers (Collins et al., 1992; Rochette and Gregorich, 1998; Aoyama et al., 1999) have also reported greater SOC with manure application than without. Although crop residue returned to the soil was higher (Table 2), doubling the rate of poultry litter application to supply N at 200 $kg N ha^{-1}$, however, did not increase SOC compared with that applied at 100 $kg N ha^{-1}$ in NT, probably a result of increased C mineralization. The reasons for similar SOC levels between poultry litter and NH_4NO_3 in MT were not known.

Since the original (1996) level of SOC content at 0–20 cm was 36.8 $Mg C ha^{-1}$, the changes in SOC level from 1996 to 2006 as influenced by tillage and N sources ranged from −1.2 to 5.1 $Mg C ha^{-1}$ (Table 5). This resulted in estimated C sequestration rates of −120 to 510 $kg C ha^{-1} year^{-1}$, assuming that C sequestration is

Table 5
Effects of tillage, cropping systems, and N sources on soil C sequestration at 0–20 cm depth in 2006

Comparison of Treatments 4–9[a]		SOC concentration		SOC content	Changes in SOC from 1996 to 2006	C sequestration rate
Tillage[b]	N source[c] (100 $kg N ha^{-1}$)	0–10 cm ($g C kg^{-1}$)	10–20 cm ($g C kg^{-1}$)	0–20 cm ($Mg C ha^{-1}$)	0–20 cm ($Mg C ha^{-1}$)	0–20 cm ($kg C ha^{-1} year^{-1}$)
NT	AN	13.5	11.0	40.1	1.47	147
	PL	15.9	10.5	43.7	5.10	510
MT	AN	15.9	11.0	42.6	3.97	397
	PL	15.4	10.6	42.2	3.63	363
CT	AN	14.3	10.7	37.4	−1.20	−120
	PL	15.3	11.8	43.7	5.10	510
LSD (0.05)[d]		–	–	3.1	3.1	310
CV (%)[e]		9.1	6.7	6.9	95.3	95.3
Means						
	AN	14.6 a[f]	10.9 a	40.0 b	1.41 b	141 b
	PL	15.6 a	11.0 a	43.2 a	4.61 a	461 a
Contrast[g] (mean of Treatments 3 and 8–11 vs. Treatment 12)[a]						
Cropping and fertilization vs. fallow and no-fertilization in no-till		4.3**	1.2*	7.3***	7.3***	730***

Significant at $^{*}P \leq 0.05$, $^{**}P \leq 0.01$, and $^{***}P \leq 0.001$.
[a] See Table 1 for treatment description.
[b] Tillage is CT, conventional till; MT, mulch till; NT, no-till.
[c] N source is AN, NH_4NO_3; PL, poultry litter.
[d] Least significant differences between treatments at $P = 0.05$.
[e] Coefficient of variation.
[f] Numbers followed by different letter within a column in a set are significantly different at $P \leq 0.05$ by the least square means test.
[g] Contrast values are the difference between treatment means.

linear from 1996 to 2006. This was based on the changes of SOC from 1996 to 2006, since data on SOC content as influenced by treatments from 1997 to 2005 were not available. Averaged across tillage and cropping systems, poultry litter sequestered C at an estimated rate of 461 kg C ha^{-1} $year^{-1}$ compared with 141 kg C ha^{-1} $year^{-1}$ with NH_4NO_3. Similarly, cropping and fertilization sequestered C at 730 kg C ha^{-1} $year^{-1}$ compared with fallow and no fertilization in NT. This shows that cropping and fertilization can increase C sequestration compared with no cropping and fertilization and that poultry litter application can further increase C sequestration compared with inorganic N fertilization, regardless of tillage.

3.4. Soil total nitrogen

Similar to SOC, STN concentration at 0–10 cm and content at 0–20 cm varied with treatments (Table 4). At 0–10 cm, STN concentration was greater in Treatment 11 than in other treatments, except in Treatments 5–7 and 9. At 0–20 cm, STN content was greater in Treatment 9 than in other treatments, except in Treatments 5–7 and 11. This shows that increased intensive cropping and poultry litter application likely increased soil N concentration and storage compared with less intensive cropping and inorganic N fertilization at 0 or 100 kg N ha^{-1}. As with SOC, poultry litter application at 200 kg N ha^{-1} did not increase STN concentration and content compared with the application at 100 kg N ha^{-1}. The STN concentration was not significant for tillage × cropping system and tillage × N source interactions at 0–10 cm and 10–20 cm. However, STN content at 0–20 cm, averaged across cropping systems, was greater in NT with poultry manure than in NT with NH_4NO_3, MT with poultry litter and NH_4NO_3, and CT with NH_4NO_3 (Table 6). Averaged across tillage and cropping systems, STN concentration at 0–10 cm and content at 0–20 cm were greater with poultry litter than with NH_4NO_3. Cropping and fertilization increased STN concentration at 0–10 cm and content at 0–20 cm compared with fallow and no-fertilization in NT.

Lack of cropping and N fertilization, followed by increased N mineralization likely decreased STN in the fallow treatment compared with other treatments containing crops, similar to SOC (Halvorson et al., 2002). In contrast, cropping and N fertilization could have increased STN in other treatments due to increased N cycling as a result of increased crop residue returned to the soil (Table 2). Since crop residue production was lower with poultry litter than with NH_4NO_3 at 100 kg N ha^{-1} (Table 2), increased STN with poultry litter compared with NH_4NO_3 (Table 6) could be a result of greater N contribution and turnover of poultry litter N into STN. Poultry litter contained 33 ± 4 g N kg^{-1} and a 60% N availability factor was used to supply 100–200 kg N ha^{-1} to crops in each year (Keeling et al., 1995). As a result, a portion of the non-available N (40%) in poultry litter could have converted to STN. Increased rate of poultry litter application to supply N at 200 kg N ha^{-1}, however, did not affect STN compared with the application at 100 kg N ha^{-1}, possibly a result of increased N mineralization.

The difference between original level of STN in 1996 (3.70 Mg N ha^{-1}) and final levels in 2006 allowed us to calculate changes in STN levels at 0–20 cm as influenced by tillage and N sources after 10 years, which ranged from −0.23 to 0.49 Mg N ha^{-1} (Table 6). Assuming that N sequestration is linear over time (since STN data from 1997 to 2005 were not available), these changes in STN levels led to N sequestration rates of −23 to 49 kg N ha^{-1} $year^{-1}$. No-till with poultry litter application sequestered the greatest amount of N compared with other tillage and N source treatments. Averaged across tillage and cropping systems, poultry litter sequestered N at 38 kg N ha^{-1} $year^{-1}$ compared with a loss of 4 kg N ha^{-1} $year^{-1}$ with NH_4NO_3. This suggests that almost all N supplied by inorganic N fertilizer is either taken by crops or lost through leaching and volatilization, leaving little or none to convert it into STN, regardless of tillage and cropping systems. Furthermore, the negative N sequestration rate with inorganic N fertilization indicates that N could have taken up by crops both from soil and fertilizer, thereby resulting in increased

Table 6
Effects of tillage, cropping systems, and N sources on soil N sequestration at the 0–20 cm depth in 2006

Comparison of Treatments 4–9[a]		STN concentration		STN content	Changes in STN from 1996 to 2006	N sequestration rate
Tillage[b]	N source[c] (100 kg N ha^{-1})	0–10 cm (g N kg^{-1})	10–20 cm (g N kg^{-1})	0–20 cm (Mg N ha^{-1})	0–20 cm (Mg N ha^{-1})	0–20 cm (kg N ha^{-1} $year^{-1}$)
NT	AN	1.23	1.03	3.44	−0.23	−23
	PL	1.52	1.02	4.19	0.49	49
MT	AN	1.42	1.01	3.84	0.15	15
	PL	1.49	0.92	3.91	0.21	21
CT	AN	1.31	0.98	3.67	−0.03	−3
	PL	1.51	1.04	4.11	0.41	41
LSD (0.05)[d]		–	–	0.24	0.24	24
CV (%)[e]		9.2	8.0	7.8	96.0	93.0
Means						
	AN	1.55 b[f]	1.59 a	3.65 b	−0.04 b	−4 b
	PL	1.65 a	1.59 a	4.07 a	0.38 a	38 a
Contrast[g] (mean of Treatments 3 and 8–11 vs. Treatment 12)[a]						
Cropping and fertilization vs. fallow and no-fertilization in no-till		0.42**	0.08	0.67***	0.67***	67***

Significant at $^{**}P \leq 0.01$, $^{***}P \leq 0.001$.
[a] See Table 1 for treatment description.
[b] Tillage is CT, conventional till; MT, mulch till; NT, no-till.
[c] N source is AN, NH_4NO_3; PL, poultry litter.
[d] Least significant differences between treatments at $P = 0.05$.
[e] Coefficient of variation.
[f] Numbers followed by different letter within a column in a set are significantly different at $P \leq 0.05$ by the least square means test.
[g] Contrast values are the difference between treatment means.

crop yields and residue production. In contrast, positive N sequestration rate with poultry litter could be a result of increased N turnover rate, as discussed above.

The C/N ratio of the soil was not influenced by tillage, cropping systems, and N sources even after 10 years (Table 4). This suggests that both soil organic C and N probably change at the same rates in the humid subtropical southeastern USA, regardless of management practices. Several researchers have reported that SOC and STN are highly related and sequestration of C also leads to sequestration of N (Franzluebbers et al., 1995, 1999; Kuo et al., 1997b; Sainju et al., 2002b).

4. Conclusions

Results of this study showed that long-term (10 years) cropping and fertilization increased soil C and N sequestration compared with no cropping and fertilization in the fallow treatment in NT. Poultry litter application to cotton further increased C and N sequestration compared with inorganic N fertilization, although inorganic N fertilization increased the amount of crop residue returned to the soil, regardless of tillage and cropping systems. Increased crop residue with increased cropping intensity as a result of inclusion of rye cover crop also did not influence soil C and N levels. Continuous cropping can increase C and N sequestration compared with fallow due to increased C and N cycling, which can help to offset greenhouse gas emission, such as CO_2 and N_2O. Similarly, poultry litter, instead of disposing it as a waste material that can contaminate surface- and groundwater through N leaching and P runoff, can be used to sequester C and N, which can increase soil quality and productivity and mitigate greenhouse gas emissions. Increasing the rate of poultry litter application to supply N from 100 to 200 kg N ha^{-1} in NT, however, did not increase soil C and N sequestration.

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References

Allmaras, R.R., Schomberg, H.H., Douglas Jr., C.J., Dao, T.H., 2000. Soil organic carbon sequestration potential of adopting conservation tillage in U.S. croplands. J. Soil Water Conserv. 55, 365–373.

Aoyama, M., Angers, D.A., N'Dayegamiye, A., Bissonnette, N., 1999. Protected organic matter in water-stable aggregates as affected by mineral fertilizer and manure applications. Can. J. Soil Sci. 79, 419–425.

Balesdent, J., Mariotti, A., Boisgontier, D., 1990. Effect of tillage on soil organic carbon mineralization estimated from ^{13}C abundance in maize fields. J. Soil Sci. 41, 587–596.

Bauer, A., Black, A.L., 1994. Quantification of the effect of soil organic matter content on soil productivity. Soil Sci. Soc. Am. J. 58, 185–193.

Cambardella, C.A., Elliott, E.T., 1993. Carbon and nitrogen distribution in aggregates from cultivated and native grassland soils. Soil Sci. Soc. Am. J. 57, 1071–1076.

Clapp, C.E., Allmaras, R.R., Layese, M.F., Linden, D.R., Dowdy, R.H., 2000. Soil organic carbon and ^{13}C abundance as related to tillage, crop residue, and nitrogen fertilizer under continuous corn management in Minnesota. Soil Tillage Res. 55, 127–142.

Collins, H.P., Rasmussen, P.E., Douglass, C.L., 1992. Crop rotation and residue management effects on soil carbon and microbial dynamics. Soil Sci. Soc. Am. J. 56, 783–788.

Dalal, R.C., Mayer, R.J., 1986. Long-term trends in fertility of soils under continuous cultivation and cereal cropping in southern Queensland. II. Total organic carbon and its rate of loss from soil profile. Aust. J. Soil Res. 24, 281–292.

Doran, J.W., 1987. Microbial biomass and mineralizable nitrogen distributions in no-tillage and plowed soils. Biol. Fertil. Soils 5, 68–75.

Ellert, B.H., Bettany, J.R., 1995. Calculation of organic matter and nutrients stored in soil under contrasting management regimes. Can. J. Soil Sci. 75, 529–538.

Franzluebbers, A.J., Hons, F.M., Zuberer, D.A., 1995. Soil organic carbon, microbial biomass, and mineralizable carbon and nitrogen in sorghum. Soil Sci. Soc. Am. J. 59, 460–466.

Franzluebbers, A.J., Langdale, G.W., Schomberg, H.H., 1999. Soil carbon, nitrogen, and aggregation in response to type and frequency of tillage. Soil Sci. Soc. Am. J. 63, 349–355.

Gregorich, E.G., Ellert, B.H., Drury, C.F., Liang, B.C., 1996. Fertilization effects on soil organic matter turnover and corn residue carbon storage. Soil Sci. Soc. Am. J. 60, 472–476.

Halvorson, A.D., Wienhold, B.J., Black, A.L., 2002. Tillage, nitrogen, and cropping system effects on soil carbon sequestration. Soil Sci. Soc. Am. J. 66, 906–912.

Jastrow, J.D., 1996. Soil aggregate formation and the accrual of particulate and mineral associated organic matter. Soil Biol. Biochem. 28, 665–676.

Keeling, K.A., Hero, D., Rylant, K.E., 1995. Effectiveness of composted manure for supplying nutrients. In: Fertilizer, Ag-lime and Pest Management Conference, January 17–18, 1995, Madison, WI. University of Wisconsin, Madison, WI, USA, pp. 77–81.

Kingery, W.L., Wood, C.W., Delaney, D.P., Williams, J.C., Mullins, G.I., 1994. Impact of long-term land application of broiler litter on environmentally related soil properties. J. Environ. Qual. 23, 139–147.

Kuo, S., Sainju, U.M., Jellum, E.J., 1997a. Winter cover crop effects on soil organic carbon and carbohydrate. Soil Sci. Soc. Am. J. 61, 145–152.

Kuo, S., Sainju, U.M., Jellum, E.J., 1997b. Winter cover cropping influence on nitrogen in soil. Soil Sci. Soc. Am. J. 61, 1392–1399.

Lal, R., Kimble, J.M., 1997. Conservation tillage for carbon sequestration. Nutr. Cycl. Agroecosys. 49, 243–253.

Langdale, G.W., West, L.T., Bruce, R.R., Miller, W.P., Thomas, A.W., 1992. Restoration of eroded soil with conservation tillage. Soil Technol. 5, 81–90.

Liang, B.C., Gregorich, E.G., Mackenzie, A.F., Schnitzer, M., Voroney, R.P., Monreal, C.M., Beyaert, R.P., 1998. Retention and turnover of corn residue carbon in some eastern Canadian soils. Soil Sci. Soc. Am. J. 62, 1361–1366.

Liang, B.C., Mackenzie, A.F., 1992. Changes in soil organic carbon and nitrogen after six years of corn production. Soil Sci. 153, 307–313.

Littell, R.C., Milliken, G.A., Stroup, W.W., Wolfinger, R.D., 1996. SAS System for Mixed Models. SAS Inst. Inc., Cary, NC, USA.

Nelson, D.W., Sommers, L.E., 1996. Total carbon, organic carbon, and organic matte. In: Sparks, D.L., et al. (Eds.), Methods of Soil Analysis. Part 3. Chemical Methods. SSSA Book Series 5. Soil Science Society of America, Madison, WI, USA, pp. 961–1010.

Nyakatawa, E.Z., Reddy, K.C., 2000. Tillage, cover cropping, and poultry litter effects on cotton. I. Germination and seedling growth. Agron. J. 92, 992–999.

Nyakatawa, E.Z., Reddy, K.C., Mays, D.A., 2000. Tillage, cover cropping, and poultry litter effects on cotton. II. Growth and yield parameters. Agron. J. 92, 1000–1007.

Omay, A.B., Rice, C.W., Maddux, L.D., Gordon, W.B., 1997. Changes in soil microbial and chemical properties under long-term crop rotation and fertilization. Soil Sci. Soc. Am. J. 61, 1672–1678.

Paustian, K., Andren, O., Janzen, H.H., Lal, R., Smith, P., Tian, G., Tiessen, H., Van Noordwjik, M., Woomer, P.L., 1997. Agricultural soils as a sink to mitigate CO_2 emissions. Soil Use Manage. 13, 230–244.

Reddy, K.C., Nyakatawa, E.Z., Reeves, D.W., 2004. Tillage and poultry litter application effects on cotton growth and yield. Agron. J. 96, 1641–1650.

Rochette, P., Gregorich, E.G., 1998. Dynamics of soil microbial biomass C, soluble organic C, and CO_2 evolution after three years of manure application. Can. J. Soil Sci. 78, 283–290.

Sainju, U.M., Singh, B.P., Whitehead, W.F., 2002a. Long-term effects of tillage, cover crops, and nitrogen fertilization on organic carbon and nitrogen concentrations in sandy loam soils in Georgia, USA. Soil Tillage Res. 63, 167–179.

Sainju, U.M., Singh, B.P., Yaffa, S., 2002b. Soil organic matter and tomato yield following tillage, cover cropping, and nitrogen fertilization. Agron. J. 94, 594–602.

Sainju, U.M., Singh, B.P., Whitehead, W.F., 2005. Tillage, cover crop, and nitrogen fertilization effects on cotton and sorghum root biomass, carbon, and nitrogen. Agron. J. 97, 1279–1290.

Sainju, U.M., Singh, B.P., Whitehead, W.F., Wang, S., 2006. Carbon supply and storage in tilled and non-tilled soils as influenced by cover crops and nitrogen fertilization. J. Environ. Qual. 35, 1507–1517.

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

Trimble, S.W., 1974. Man-induced Soil Erosion on the Southern Piedmont 1700–1970. Soil and Water Conservation Society, Ankeny, IA, USA.

Wanniarachchi, S.D., Voroney, R.P., Vyn, T.J., Beyaert, R.P., Mackenzie, A.F., 1999. Tillage effects on the dynamics of total and corn residue-derived soil organic matter in two southern Ontario soils. Can. J. Soil Sci. 79, 473–480.

Webster, C.P., Goulding, K.W.T., 1989. Influence of soil carbon content on denitrification from fallow land during autumn. J. Sci. Food Agric. 49, 131–142.