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Long-Term Tillage and Poultry Litter Impacts Soil Carbon and Nitrogen Mineralization and Fertility

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Long-term tillage and manure application can alter a soil's ability to sequester nutrients and mineralize C and N. A laboratory incubation study (C and N mineralization) evaluated the long-term impact of poultry litter (PL) application (>10 yr) and tillage practice (>25 yr). Soil chemical properties (pH, total C, total N, and Mehlich-1 extractable P, K, Ca, and Mg) were also assessed. Soil was collected (0–5-, 5–10-, and 10–20-cm depths) from continuous soybean [*Glycine max* (L.) Merr.] and corn (*Zea mays* L.) systems managed under conventional tillage (CT) or no-till (NT) with either PL or inorganic fertilizer (IF) applications. The study was located in northeast Alabama on a Hartsells fine sandy loam (a fine-loamy, siliceous, subactive, thermic Typic Hapludult). Poultry litter and NT increased soil nutrients (N, P, K, Ca, and Mg), primarily at the 0- to 5-cm depth. No-till concentrated nutrients near the soil surface as opposed to the more even distribution seen under CT. The NT-PL treatment had higher soil C for corn and soybean (2.25 and 1.83 g kg^{-1} C, respectively), followed by NT-IF (1.73 and 1.11 g kg^{-1} C, respectively). Carbon and N mineralization was higher at the 0- to 5-cm depth for NT and CT compared with lower depths. Long-term PL application increased C and N mineralization more than IF. As depth increased, more C and N mineralization occurred under CT due to plow layer mixing. Results indicated that long-term tillage with PL application can increase soil C and N mineralization, nutrient retention, and organic matter.

Abbreviations: CEC, cation exchange capacity; CT, conventional tillage; IF, inorganic fertilizer; NT, no-till; PL, poultry litter; SOM soil organic matter.

Soils in the southeastern United States, where the climate is humid, are severely eroded from >200 yr of intense row crop agriculture. In this region, row crops have historically been conventionally tilled and supplemented with inorganic fertilizers. These agronomic practices have left the soil relatively infertile, highly eroded, low in organic matter, and easily compacted by rainfall and machine traffic (Carreker et al., 1977).

Research has shown that soil organic matter (SOM) is the central indicator of soil quality and health (Soil and Water Conservation Society, 1995). Soil organic matter affects soil fertility and the C and N mineralization capacities of the soil, which determines the availability of plant nutrients (Stevenson, 1994). Thus, soil productivity decreases as SOM content declines (Bauer and Black, 1994).

Adoption of conservation tillage systems has increased during the last two decades. The Conservation Technology Information Center (2009) estimated that 41.5% of U.S. cropland was managed with some form of conservation tillage in 2008. These practices can increase surface organic matter (Edwards et al., 1988), which increases the level of macronutrients (Ca, P, K, and Mg) and micronutrients (Mn, Zn, and Cu) (Edwards et al., 1992).

While it may take 3 to 5 yr to reap benefits from transitioning to conservation tillage, the fully functional system will have the long-term benefit of improved soil properties (Triplett and Dick, 2008). For instance, Hunt et al. (1996) showed that 9

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yr of NT significantly increased SOM in the top few centimeters compared with CT. After 12 yr, Campbell et al. (1999) showed that soil C storage increased in the 0- to 15-cm depth under a NT practice; most differences occurred in the 0- to 7.5-cm depth.

Manure utilization has also been shown to increase SOM. In the United States, the poultry industry produces approximately 8.9 billion broilers (National Agricultural Statistics Service, 2007, p. 1) and about 11.4 million Mg of broiler litter (a mixture of manure, feed, and organic bedding material such as peanut hulls or sawdust) each year (1.5 kg litter per broiler). At approximately 59% of the nation's output, the Southeast (Arkansas, Georgia, Alabama, Mississippi, and North Carolina) leads the nation in broiler production (Reddy et al., 2008). This broiler litter can serve as a relatively inexpensive source of nutrients for row crop production (Nyakatawa and Reddy, 2002).

Continuous application of manure or litter can increase the levels of N, P, K, C, Ca, and Mg in the soil (Mugwira, 1979; Wallingford et al., 1975; Wood et al., 1996; Ginting et al., 2003), thus creating a reservoir of soil nutrients for several years after application. This is because only a portion of the N and other nutrients are made available to plants by soil microbes in the first year following application (Motavalli et al., 1989; Eghball et al., 2002, 2004). For instance, 55% of the N in poultry litter becomes available to plants in the year of application, indicating that 45% of the N is available in succeeding years (Eghball et al., 2002).

Few studies have investigated manure or litter application under conservation tillage on increasing SOM in the southeastern United States. For example, in Alabama the application of manure or poultry litter to conservation tillage systems (typically in 2–5-yr studies) has shown large variability in the amount of SOM generated (Wood et al., 1996; Nyakatawa et al., 2001; Balkcom et al., 2005; Tewolde et al., 2008). Further research is needed to validate short-term findings and to understand how long-term conservation practices impact soil sustainability. The objectives were to determine the impact of long-term tillage (>25 yr) and poultry litter application (>10 yr) on soil C and N mineralization and fertility status.

MATERIALS AND METHODS

Site Description

The field experiment was conducted at the Sand Mountain Research and Extension Center in the Appalachian Plateau region of northeast Alabama. The soil was a Hartsells fine sandy loam (a fine-loamy, siliceous, subactive, thermic Typic Hapludult). Climate in this region is subtropical with no dry season; the mean annual rainfall is 1325 mm and the mean annual temperature is 16°C (Shaw, 1982). Before initiation of the field study in 1980, the site had been under intensive row crop production for >50 yr.

Experimental Design and Treatments

The experiment was a split plot design with a randomized complete block arrangement of two tillage treatments (main plots initiated in 1980) and two fertilization treatments (split plots initiated in 1991) for which there were four blocks. The main plots (tillage) were 5.49 by 15.25 m and split plots (fertilization) were 5.49 by 7.62 m with a 1.82-m buffer separating the plots. The cropping systems were continuous corn and continuous soybean. Each plot consisted of four rows with 0.92-m spacings for corn and 0.76-m spacings for soybean. The two cropping systems (soybean and corn) were evaluated independently due to differences in management and fertilization practices. The tillage treatments consisted of CT (moldboard plow and disking followed by rototiller in the spring) and NT (planting into crop residue with a double disk-opener planter). The fertilization treatments consisted of PL and IF. Poultry litter was applied to soybean at 45 kg P ha^{-1} (based on P_2O_5) and to corn at 170 kg N ha^{-1} (based on total N). The average PL nutrients applied each year from 1991 to 2004 were 170 kg N ha^{-1}, 9.8 kg P ha^{-1}, 144 kg K ha^{-1}, 129 kg Ca ha^{-1}, and 30 kg Mg ha^{-1} for corn and 29 kg P ha^{-1}, 42 kg K ha^{-1}, 37 kg Ca ha^{-1}, and 9 kg Mg ha^{-1} for soybean. Inorganic fertilizer plots received commercial fertilizer to match the rate of N added from PL to the corn and soybean plots. Both PL and IF were surface broadcast. Dolomitic lime and KCl (0–0-60) were applied in the fall according to Auburn University soil test recommendations. Lime and K application rates varied across years, but all plots received the same amount when applied.

Soil Sampling

Soil samples were collected on 26 Feb. 2005, before fertilization. The soil was sampled at 0- to 5-, 5- to 10-, and 10- to 20-cm depth increments. Six soil cores (25-mm diam.) were collected per plot and composited by depth; surface plant residue was removed before sampling. After returning to the laboratory, the soil samples were passed through a 2-mm sieve to remove root material. The soil mass was recorded and moisture content was determined gravimetrically. Subsamples were stored at 4°C until use.

Laboratory Analysis

Laboratory analysis was performed by the Auburn University Soil Testing Laboratory as described by Hue and Evans (1986). Specifically, total C and N for the soil and PL were determined by dry combustion using a CN LECO 2000 analyzer (LECO Corp., St. Joseph, MI). Soil pH was determined on 1:1 soil/water suspensions with a glass electrode pH meter. Concentrations of P, K, Mg, and Ca were determined using a Mehlich 1 (double acid) extracting solution (Olsen and Sommers, 1982) for soil and with the dry ash procedure for PL (Donohue, 1983); both were measured by inductively coupled Ar plasma emission spectrometry (Soltanpour et al., 1982) using the ICAP 9000 (Thermo Jarrell Ash, Franklin, MA).

Carbon and Nitrogen Mineralization

Methods of incubation followed the procedures described by Torbert et al. (1999). Twenty-five grams of moist, sieved (2-mm) soil (oven-dried weight basis) were placed in 118-mL (4-oz) plastic containers. Deionized water was added to bring the soil moisture to approximately −20 kPa at a bulk density of 1.3 Mg m^{-3}. Each plastic container was placed in a separate quart jar and 10 mL of water was added to the bottom of each jar (not sample) for humidity control.

Soil C mineralization was measured by placing a 10-mL CO_2 trap (vial containing 1 mol L^{-1} NaOH) in the sealed jar with the soil. The jars were incubated in the dark at 25°C and removed to evaluate the amount of CO_2 evolved on Days 7, 30, 60, and 90; the vials were removed and replaced on each sampling date except Day 90 to prevent oversaturation of the CO_2 trap. After removal, 1 mL of saturated $BaCl_2$ solution ($\sim$1 mol L^{-1}) was added to each trap to stop CO_2 absorption. The NaOH was then backtitrated with 1 mol L^{-1} HCl, using phenolthalein as an indicator, to determine the amount of CO_2 released from the soil samples. Potential C mineralization was the difference between the blanks (sealed jar without soil) and the CO_2–C captured in the CO_2 traps. The concentrations of CO_2 determined on 7, 30, 60, and 90 d after incubation were added together to determine the total amount of C mineralized for the 90-d incubation period, as described by Anderson (1982). Carbon mineralization was divided by total C to calculate C turnover.

Soil N mineralization was determined as the difference between the final (Day 90) and initial (day of initiation) soil inorganic N content. The concentrations of NH_4 and NO_2 + NO_3 were determined by extraction, using 2 mol L^{-1} KCl as described by Keeney and Nelson (1982), and measured colorimetrically using a Bran+Luebbe Auto Analyzer 3 (Bran+Luebbe, Norderstedt, Germany).

Statistics

The experimental design was a split plot with four replications. For each cropping system, tillage treatments were the main plots, with fertilization as the split plots. Corn and soybean analyses were performed separately using the Mixed procedure of SAS (Littell et al., 1996). A significance level of P < 0.05 was established.

Table 1. Effect of poultry litter vs. inorganic fertilization and no-till (NT) vs. conventional tillage (CT) on soil pH, cation exchange capacity (CEC), total C, total N, and C/N ratio at the 0- to 5-, 5- to 10-, and 10- to 20-cm depths for the soybean and corn cropping systems.

Depth and tillage	Fertilization	pH	CEC	Total C	Total N	C/N ratio
cm			cmol kg^{-1}	——g kg^{-1}——		
			Soybean			
0–5						
NT	inorganic	6.5 a†	9.15 b	11.10 b	1.18 b	9.39 a
	litter	6.4 a	12.52 a	18.33 a	1.49 a	12.33 a
CT	inorganic	5.9 b	6.12 c	9.00 bc	0.80 c	11.27 a
	litter	6.2 ab	6.10 c	8.46 c	0.71 c	11.90 a
5–10						
NT	inorganic	6.0 a	5.42 a	7.25 a	0.73 a	9.95 a
	litter	6.0 a	6.55 a	8.48 a	0.66 a	12.81 a
CT	inorganic	6.2 a	5.39 a	7.37 a	0.70 a	10.56 a
	litter	6.3 a	5.68 a	7.41 a	0.62 a	11.87 a
10–20						
NT	inorganic	5.9 b	4.87 a	5.49 a	0.36 a	15.36 a
	litter	5.9 b	5.27 a	6.35 a	0.49 a	12.97 ab
CT	inorganic	6.3 a	5.07 a	5.24 a	0.53 a	9.88 b
	litter	6.4 a	4.78 a	4.88 a	0.49 a	9.89 b
LSD(0.05)‡		0.4	1.54	1.58	0.18	3.10
			Corn			
0–5						
NT	inorganic	6.5 a	9.53 b	17.32 b	1.28 b	13.48 a
	litter	6.5 a	13.79 a	22.47 a	1.82 a	12.33 a
CT	inorganic	6.0 b	5.23 d	8.30 d	0.77 c	10.80 a
	litter	6.4 a	7.54 c	11.67 c	0.94 c	12.46 a
5–10						
NT	inorganic	5.9 b	5.79 ab	8.47 b	0.73 a	11.55 a
	litter	6.0 ab	6.42 ab	10.36 a	0.76 a	13.59 a
CT	inorganic	6.3 a	5.00 b	7.58 b	0.63 a	11.97 a
	litter	6.3 a	6.72 a	9.33 ab	0.71 a	13.22 a
10–20						
NT	inorganic	5.6 b	4.30 a	5.89 a	0.45 a	13.00 a
	litter	5.7 b	5.14 a	6.94 a	0.58 a	11.91 a
CT	inorganic	6.2 a	4.35 a	5.26 a	0.47 a	12.24 a
	litter	6.1 a	5.09 a	5.99 a	0.47a	12.64 a
LSD(0.05)‡		0.4	1.87	2.26	0.19	4.43

† Means within a column followed by the same letter do not significantly differ for comparisons within a depth (0.05 level).

‡ Comparison of means among depth.

RESULTS AND DISCUSSION

In general, analyses of the soil chemical properties and C and N mineralization indicated that changes have resulted from management practices. Significant differences were mainly observed at the 0- to 5-cm depth. The following discussion is an in-depth look at how management practices impacted soil characteristics and nutrient dynamics.

Soil Cation Exchange Capacity

The cation exchange capacity (CEC) was greatly affected by tillage, fertilizer, and depth, as evidenced by a significant interaction of these factors for the soybean (P < 0.0242) and corn (P < 0.0294) cropping systems (Tables 1 and 2). Most CEC differences were observed at the 0- to 5-cm depth. The tillage effect on the CEC (averaged across all fertilizer treatments) was higher under NT at the 0- to 5-cm depth for the soybean (77%) and corn (83%) cropping systems. This agrees with the results of Tarkalson et al. (2006), who reported

Table 2. Analysis of variance results for soil pH, cation exchange capacity (CEC), total C, Total N and C/N ratio.

Source	$P > F$ (0.05)				
	pH	CEC	Total C	Total N	C/N ratio
			Soybean		
Depth	0.4805	<0.0001	<0.0001	<0.0001	0.6923
Litter	0.5521	0.0006	0.0004	0.4166	0.4623
Depth × litter	0.9603	0.0144	0.0353	0.1220	0.0473
Tillage	0.2956	<0.0001	<0.0001	<0.0001	0.0251
Depth × tillage	0.0032	<0.0001	<0.0001	<0.0001	0.0287
Litter × tillage	0.3389	0.0005	<0.0001	0.0106	0.6527
Depth × litter × tillage	0.6228	0.0242	0.0065	0.0912	0.9089
			Corn		
Depth	<0.0001	<0.0001	<0.0001	<0.0001	0.9080
Litter	0.0152	<0.0001	<0.0001	0.0001	0.7121
Depth × litter	0.4655	0.0001	<0.0001	0.0039	0.4275
Tillage	0.0099	<0.0001	<0.0001	<0.0001	0.6575
Depth × tillage	<0.0001	<0.0001	<0.0001	<0.0001	0.9298
Litter × tillage	0.8497	0.4728	0.1697	0.0439	0.7398
Depth × litter × tillage	0.1409	0.0294	0.0387	0.0826	0.6446

Table 3. Effect of poultry litter vs. inorganic fertilization and no-till (NT) vs. conventional tillage (CT) on soil extractable levels of K, Mg, Ca, P, at the 0- to 5-, 5- to 10-, and 10- to 20-cm depths for the soybean and corn cropping systems.

Depth and tillage	Fertilization	P	K	Ca	Mg
cm		mg kg^{-1}			
		Soybean			
0–5					
NT	inorganic	64.0 b†	78.6 b	1164.1 b	183.9 b
	litter	156.5 a	137.7 a	1643.3 a	249.5 a
CT	inorganic	65.1 b	102.5 b	629.9 c	108.1 c
	litter	74.4 b	107.3 b	692.9 c	115.1 c
5–10					
NT	inorganic	28.9 c	41.9 b	541.6 a	85.5 a
	litter	80.6 a	95.1 a	680.8 a	115.1 a
CT	inorganic	35.5 b	59.3 b	586.9 a	95.1 a
	litter	51.5 b	76.5 b	625.9 a	101.0 a
10–20					
NT	inorganic	24.0 a	32.0 b	408.3 a	78.4 a
	litter	45.3 a	76.6 a	460.0 a	86.6 a
CT	inorganic	23.8 a	37.9 b	476.6 a	83.4 a
	litter	30.5 a	47.9 ab	531.0 a	77.4 a
LSD(0.05)‡		21.86	35.26	240.44	49.18
		Corn			
0–5					
NT	inorganic	61.6 c	96.5 c	1221.1 b	195.9 b
	litter	179.9 a	187.3 a	1859.8 a	266.4 a
CT	inorganic	49.5 c	70.0 d	518.1 d	97.0 d
	litter	126.4 b	161.8 b	895.8 c	141.3 c
5–10					
NT	inorganic	25.0 b	48.9 b	529.9 a	88.8 a
	litter	81.5 a	136.9 a	653.1 a	110.1 a
CT	inorganic	20.8 b	38.5 b	529.9 a	94.6 a
	litter	71.6 a	120.1 a	739.1 a	118.6 a
10–20					
NT	inorganic	21.6 bc	35.8 b	335.5 a	69.4 a
	litter	49.5 a	103.8 a	397.5 a	77.9 a
CT	inorganic	12.3 c	25.5 b	414.5 a	79.1 a
	litter	34.0 ab	80.9 a	451.8 a	80.6 a
LSD(0.05)‡		19.1	30.3	286.5	49.6

† Means within a column followed by the same letter do not significantly differ for comparisons within a depth (0.05 level).

‡ Comparison of means among depth.

that soil under NT had a 20% higher CEC at the 0- to 5-cm depth compared with CT after 27 yr of tillage. Others have reported that increased CEC near the soil surface under NT systems (compared with CT) can result from more soil organic C (Jaiyeoba, 2003; Ciotta et al., 2003). No significant differences were observed below the 5-cm depth.

At the 0- to 5-cm depth, PL (averaged across all tillage treatments) increased the CEC in the soybean (22%) and corn (45%) cropping systems compared with the IF treatments (Table 3). Also, a significant increase in the CEC (21%) was observed at the 5- to 10-cm depth for the corn cropping system only. This was similar to the findings of Gao and Chang (1996), who reported an increased soil CEC after 18 yr of continuous manure application. Thus, the tillage × fertilizer × depth interaction was a result of litter that was added being restricted to the surface few centimeters of soil, thereby causing a stratification of basic cations observed under NT compared with mixing of the basic cations as observed under CT.

Extractable Soil Macronutrients

Phosphorus levels were higher at the 0- to 5-cm depth than the 5- to 10- and 10- to 20-cm depths under NT-PL, as evidenced by the significant tillage × fertilizer × depth interaction for the corn ($P < 0.0408$) and soybean ($P < 0.0094$) cropping systems (Tables 3 and 4). Averaged across all fertilizer treatments, P was significantly higher (58%) in NT than CT plots at the 0- to 5-cm depth for the soybean cropping system (Table 4). The same pattern was observed for the corn cropping system, with NT containing 38% more P than CT at the 0- to 5-cm depth. No differences were observed below the 5-cm depth. Hargrove et al. (1982) reported a 120% increase in P under NT compared with CT at the 0- to 7.5-cm depth. Also, Motta et al. (2002) reported that (after 17 yr of management) P was greatest near the soil surface in less intensively tilled systems.

Soils amended with PL (averaged across all tillage treatments) showed a pattern similar to the tillage effect (Tables 3 and 4). Most P was at the 0- to 5-cm depth. Phosphorus was 78% and 175% greater in PL plots than IF plots for the soybean and corn cropping systems, respectively. Our results are also in agreement with those of Chang et al. (1991) and Eghball (2002), who found increases in extractable P in surface soils with the use of manure. No significant differences were observed in the soybean system below the 5-cm depth. For the corn cropping system, significant differences were observed at the 5- to 10-cm depth, where P was 234% higher with PL than IF. The same trend was observed at the 10- to 20-cm depth, with the PL treatment containing 147% more P than the IF treatment. It is important to note that PL was applied to soybean based on P recommendations, whereas the corn application was based on N recommendations. Thus the results suggest that the PL application rate can increase the surface P concentration and the chance of vertical movement through the soil profile. This is in agreement with Kingery et al. (1994), who observed six times higher extractable P (to a depth of 60 cm) due to long-term PL application to a tall fescue (*Festuca arundinacea* Schreb.) system. Similar to the CEC data, P levels were greatly affected by organic material (high amount of P in the poultry litter) being restricted to the soil surface under NT compared with the mixing of P to lower depths under CT, thus explaining the tillage × fertilizer × depth interaction.

A significant tillage effect for K was observed only in the corn cropping system ($P < 0.0002$), with NT containing 22% more K than CT at the 0- to 5-cm depth (Tables 3 and 4). No significant differences were observed below the 5-cm depth. Our findings are in contrast to Matowo et al. (1999), who reported minimal effects of tillage. Other researchers, however, have shown that as tillage intensity decreases, more K is retained near the soil surface (Ismail et al., 1994; Guzman et al., 2006).

Averaged across all tillage treatments, significant differences were also observed between fertilizer treatments at all depths (Tables 3 and 4). Soil from the soybean cropping system ($P <$ 0.0001) contained 32% (0–5 cm), 69% (5–10 cm), and 78% (10–20 cm) more K in PL plots than those that received IF. The same pattern was observed in the corn cropping system ($P <$ 0.0001), with PL plots containing 110% (0–5 cm), 195% (5–10 cm), and 202% (10–20 cm) more K than the IF plots. Schlegel (1992) reported an increase in soil K when using composted beef cattle feedlot manure compared with the same amount of inorganic fertilizer. A tillage × fertilizer interaction was observed only in the soybean cropping system at the 0- to 5-cm depth ($P < 0.0004$). Soil under NT-PL (soybean cropping system) retained more K than the other treatments, probably due to more surface residue under NT as well as the added K from PL addition (Tables 3 and 4). No interaction of tillage × fertilizer was observed in the corn cropping system, probably due to the large within-site variability in these measured parameters.

The tillage effect averaged across all fertilizer treatments significantly affected the amount of Ca retained in the soil by depth (tillage × depth interaction) for the soybean ($P < 0.0001$) and corn ($P < 0.0001$) cropping systems. Calcium was higher under NT (112% for soybean and 117% for corn) than CT at the 0- to 5-cm depth (Table 4). No significant differences were observed below 5 cm.

When averaged across all tillage treatments, the amount of Ca was 30% (soybean) and 58% (corn) higher with PL than IF at the 0- to 5-cm depth (Tables 3 and 4). No significant differences were observed below the 5-cm depth. There was a tillage × fertilizer interaction for the soybean cropping system ($P < 0.0326$); however, this interaction was not significant in the corn cropping system, which was probably due to corn needing more Ca for biomass production than soybean. Similar results were reported by Edwards et al. (1992), who observed more Ca being retained in soil under a soybean–wheat (*Triticum aestivum* L.) rotation than a corn–wheat rotation in a study conducted in the same region.

When averaged across all fertilizer treatments for the soybean ($P < 0.0001$) and corn ($P < 0.0001$) cropping systems, significantly higher Mg concentrations were observed in the surface depths as evidenced by a tillage × depth interaction (Tables 3 and 4). Magnesium was significantly higher under NT than CT at the 0- to 5-cm depth for both the soybean (94%) and corn (94%) cropping systems (Table 4). No significant differences were observed below 5 cm.

Magnesium was also impacted by PL addition. A significant fertilizer × depth interaction was observed only for the soybean cropping system ($P < 0.0051$). Although this same interaction was not significant for the corn cropping system, there were significant main effects of depth ($P < 0.0325$) and fertilizer ($P <$ 0.0001). Thus, PL addition accounted for 25% (soybean) and 39% (corn) more Mg at the 0- to 5-cm depth than plots with IF, which was in agreement with other reports (Lund and Doss, 1980; Chang et al., 1991).

Table 4. Analysis of variance results for K, Mg, Ca, and P.

Source	$P > F$ (0.05)			
	P	K	Ca	Mg
Soybean				
Depth	<0.0001	<0.0001	<0.0001	<0.0001
Litter	<0.0001	<0.0001	<0.0001	0.0325
Depth × litter	0.0062	0.8043	0.0599	0.2344
Tillage	<0.0001	0.3536	<0.0001	<0.0001
Depth × tillage	0.0075	0.7089	<0.0001	<0.0001
Litter × tillage	<0.0001	0.0004	0.0326	0.0581
Depth × litter × tillage	0.0094	0.6830	0.0821	0.5131
Corn				
Depth	<0.0001	<0.0001	<0.0001	<0.0001
Litter	<0.0001	<0.0001	<0.0001	<0.0001
Depth × litter	<0.0001	0.0247	0.0001	0.0051
Tillage	<0.0001	0.0002	<0.0001	<0.0001
Depth × tillage	0.0052	0.4929	<0.0001	<0.0001
Litter × tillage	0.0090	0.5009	0.4038	0.4142
Depth × litter × tillage	0.0408	0.8201	0.1992	0.6274

It should be noted that Ca and Mg fertilizers are not recommended for soybean and corn production in Alabama (Edwards et al., 1992) because plant requirements are typically met when lime is added for soil pH adjustments. Thus, increased levels of Ca and Mg observed near the soil surface under NT are probably attributable to dolomitic lime being restricted to the surface soil.

Total Soil Carbon

The amount of C retained in the soil was greatly affected by the imposed cultural practices. This was shown by the significant tillage × fertilizer × depth interaction for the soybean ($P <$ 0.0065) and corn ($P < 0.0387$) cropping systems. At the 0- to 5-cm depth, more soil C was sequestered than at greater depths. The tillage effect for NT (averaged across all fertilizer treatments) was 69 and 99% higher (Tables 1 and 2) than CT in the soybean and corn cropping systems, respectively. No significant differences were observed below 5 cm. Higher soil C under NT reflects increased C inputs from the reduced tillage intensity, which resulted in less breakdown or oxidation of SOM. On the other hand, soil C was lower under CT, probably due to increased oxidation and microbial activity resulting from soil mixing (Stevenson, 1986). Wood et al. (1991) reported that differences observed in the surface SOM between tillage systems can be attributed to a slightly higher return of crop residues under NT than under CT. The increase in C was restricted to the surface, indicating that changes in the soil environment were due to the lack of tillage. Tillage practice also altered soil C distribution by depth; more stratification was observed under NT than CT. Our findings are similar to other research on the long-term effects of conservation tillage systems (Franzluebbers et al., 1994; Torbert et al., 1997; Feng et al., 2002).

When averaged across all tillage treatments, the soil amended with PL retained 33% more C under both cropping systems at the 0- to 5-cm depth compared with IF (Tables 1 and 2). At the 5- to 10-cm depth, there was a significant difference between PL and IF only in the corn cropping system. The PL treatment

Table 5. Effect of poultry litter vs. inorganic fertilization and no-till (NT) vs. conventional tillage (CT) on soil C and N mineralization and C turnover at the 0- to 5-, 5- to 10-, and 10- to 20-cm depths during the 90-d laboratory incubation for the soybean and corn cropping systems.

Depth and tillage	Fertilization	C mineralization	C turnover	N mineralization
cm		mg kg $^{-1}$		
		Soybean		
0–5				
NT	inorganic	935 b†	8.4 b	62.2 b
	litter	1062 a	5.8 c	76.2 a
CT	inorganic	857 b	9.5 b	63.1 b
	litter	890 b	10.5 a	57.7 b
5–10				
NT	inorganic	317 b	4.3 b	15.5 b
	litter	392 b	4.6 b	24.5 ab
CT	inorganic	566 a	7.7 a	32.2 a
	litter	569 a	7.6 a	31.9 a
10–20				
NT	inorganic	244 b	4.4 b	9.5 a
	litter	351 a	5.6 b	10.1 a
CT	inorganic	362 a	7.0 a	9.8 a
	litter	346 a	7.1 a	11.4 a
LSD(0.05)‡		111	1.7	11.8
		Corn		
0–5				
NT	inorganic	1053 b	9.5 a	63.5 b
	litter	1199 a	5.3 c	69.1 b
CT	inorganic	809 d	9.7 a	47.0 c
	litter	949 c	8.1 b	80.0 a
5–10				
NT	inorganic	443 b	5.2.b	23.1 b
	litter	470 b	4.5 b	27.2 b
CT	inorganic	559 b	7.4 a	25.6 b
	litter	659 a	7.1 a	43.4 a
10–20				
NT	inorganic	294 b	6.0 a	9.7 a
	litter	308 ab	4.5 b	10.6 a
CT	inorganic	311 ab	5.9 a	12.1 a
	litter	379 a	6.6 a	10.7 a
LSD(0.05)‡		108	1.2	13.3

† Means within a column followed by the same letter do not significantly differ for comparisons within a depth (0.05 level).

‡ Comparison of means among depth.

sequestered 22% more C than the IF treatment. This agrees with the results of Gao and Chang (1996), who reported that 18 yr of manure application increased C near the soil surface. Thus, NT-PL can build up surface SOM (sequestering more C). This increased SOM can impact soil fertility by supplying the soil–plant system with a higher nutrient storage capacity (Tisdale et al., 1985; Edwards et al., 1992). We also observed that increased surface SOM (total C × 1.72) was correlated with increased CEC, which is in agreement with the findings of others (Blevins et al., 1983; Ciotta et al., 2003; Tarkalson et al., 2006).

Total Soil Nitrogen

When averaged across fertilizer treatments, the tillage effect on soil N followed the same pattern as CEC and total C at the 0- to 5-cm depth; N values were 77 and 81% higher under NT than CT for the soybean ($P < 0.0001$) and corn ($P < 0.0001$) cropping systems (Tables 1 and 2), respectively. No significant differences were observed below 5 cm. Similar results have been reported in other investigations (Torbert et al., 1997; 1999).

The significant fertilizer × depth interaction indicated soil N differences at the 0- to 5-cm depth in the corn cropping system; PL was 34% greater than IF. In contrast, this same interaction was not significant for the soybean cropping system. The ability of soybean to fix N_2 probably minimized the effect of added N from PL application.

Poultry litter treated NT plots were significantly higher than the other treatments for the soybean ($P < 0.0106$) and corn ($P < 0.0439$) cropping systems, as indicated by the tillage × fertilizer interaction. Since PL is probably more resistant to decay, N was not as readily available compared with IF. Also, more crop residues are normally left on the soil surface under NT than CT, thereby supplying the soil with more residual organic matter. Therefore, the N that is in organic form (litter and crop residues) slowly decomposes, causing a buildup of soil N.

Soil Carbon/Nitrogen Ratio

Research has shown that soil C/N ratios generally increase with less tillage and more crop residues (Black, 1973). The C/N ratios for both cropping systems tended to increase with NT at all depths for both cropping systems (Table 3). Significant differences were observed only at the 10- to 20-cm depth for the soybean cropping system, however, accounting for the tillage × depth and fertilizer × depth interactions (Table 4). Conventional tillage had the lowest C/N ratio, which was probably due to mixing of crop residue within the soil profile. The reason for a lower C/N ratio under NT-PL compared with NT-IF at the 10- to 20-cm depth is unknown.

Soil Incubation Carbon Mineralization

Laboratory incubation studies are useful for investigating the impacts of long-term management practices on soil nutrient availability. A comparison of tillage effects (averaged across all fertilizer treatments) showed that tillage significantly affected soil mineralization. Soil respired CO_2 (C mineralized) under NT was 14 and 28% higher than under CT for both soybean ($P < 0.0001$) and corn ($P < 0.0001$) systems at the 0- to 5-cm depth, thereby accounting for the tillage × depth interaction (Tables 5 and 6). Similar observations have been reported by others (Franzluebbers et al., 1995; Torbert et al., 1999; Wright and Hons, 2004; Wood and Edwards, 1992; Salinas-Garcia et al., 1997). At the 5- to 10-cm depth, the opposite pattern was observed, with CT mineralizing 60 and 33% more than NT for the soybean and corn cropping systems, respectively. The amount of C mineralized due to fertilizer treatment (averaged across tillage treatments) was significantly higher in PL treatments than IF treatments in the soybean ($P < 0.0051$) and corn ($P < 0.0001$) cropping systems. Carbon mineralization was 9 and 15% greater in the PL treatment compared with IF at the 0- to 5-cm depth for soybean and corn cropping systems, respectively (Table 5 and 6). Below 5 cm, C mineralization was not impacted by fertilizer treatments. Differences observed in mineralized C are an indication of the amounts of labile organic C accumulated from different tillage and fertility practices. The tillage × fertilizer interaction for the soybean ($P < 0.0131$) cropping system (Tables 5 and 6) indicates that the highest C mineralization occurred under NT-PL; similar trends were also noted in the corn cropping system. Our findings are in general agreement with a similar study conducted in this region (Kingery et al., 1996).

Table 6. Analysis of variance results for C and N mineralization and turnover C.

	$P > F$ (0.05)		
Source	C mineralization	C turnover	N mineralization
	Soybean		
Depth	<0.0001	<0.0001	<0.0001
Litter	0.0051	0.9436	0.2186
Depth × litter	0.6157	0.1157	0.6464
Tillage	0.0130	<0.0001	0.4377
Depth × tillage	<0.0001	0.2199	0.0025
Litter × tillage	0.0131	0.1795	0.0320
Depth × litter × tillage	0.8599	0.0048	0.2785
	Corn		
Depth	<0.0001	<0.0001	<0.0001
Litter	0.0001	<0.0001	0.0002
Depth × litter	0.1205	<0.0001	0.0028
Tillage	0.4814	<0.0001	0.1896
Depth × tillage	<0.0001	0.1970	0.0995
Litter × tillage	0.2426	0.0024	0.0124
Depth × litter × tillage	0.6374	0.1465	0.0239

Nitrogen Mineralization

There was a significant tillage × depth interaction with the soybean cropping system ($P < 0.0025$), with NT mineralizing 15% more than the CT system at the 0- to 5-cm depth. At the 5- to 10-cm depth, the amount of N mineralized was 64% greater under CT than NT for the soybean cropping systems. This is consistent with previous research that indicated higher N mineralization for CT at lower depths (Torbert et al., 1999; Wright and Hons, 2004).

A significant tillage × fertilizer interaction (Tables 5 and 6) indicated that NT-PL mineralized more N than other treatments in the soybean cropping system ($P < 0.032$). This was attributed to increased surface SOM from long-term NT management practices with PL. Buildup of SOM supports increased microbial populations and activity, thereby resulting in higher N mineralization of the available substrate (Kingery et al., 1996). The opposite was observed for corn. In this case, the significant tillage × fertilizer × depth interaction ($P < 0.0239$) indicated that CT-PL at the 0- to 5-cm depth mineralized the most N. This was probably because corn residue had not yet been tilled under. Risasi et al. (1999) reported that corn root residues immobilize N for as much as 24 wk. Fortuna et al. (2003) also reported that decreased N availability (immobilization) reduced yields in a continuous corn system with compost (50% oak [*Quercus* spp.] leaves and 50% dairy manure).

Soil Carbon Turnover

At each depth, the lowest C turnover was observed (averaged across all fertilizer treatments) in the NT system (Tables 5 and 6). Conventional tillage generated 41 and 20% more C turnover at the 0- to 5-cm depth than NT for the soybean ($P < 0.001$) and corn ($P < 0.0001$) cropping systems, respectively; a similar pattern was observed at lower depths. The main effect of fertilizer was not significant at any depth in the soybean cropping system. Although residue quality data were not collected in this study, the lower C turnover was probably due to soybean residue having more N than corn residue. Soybean residues have been shown to decompose more rapidly (Parr and Papendick, 1978; Wood and Edwards, 1992) and contribute less to SOM accumulation (Wood and Edwards, 1992).

Significant differences were observed between fertilizer treatments (when averaged across the tillage treatments). Poultry litter plots had higher C turnover (43%) than IF plots at the 0- to 5-cm depth in the corn ($P < 0.0001$) cropping system (Tables 5 and 6). This probably results from corn residue decomposing at a slower rate, thereby contributing to organic matter buildup. A significant tillage × fertilizer interaction ($P < 0.0024$) indicated that NT-PL may sequester more C (corn cropping system) due to lower C turnover. Therefore, management practices that add PL and minimize tillage can improve the capacity of the soil to store C.

CONCLUSIONS

Soil organic matter is the most important indicator of soil fertility and nutrient availability; therefore, understanding the impact of long-term tillage and PL addition on SOM is important. This study showed that long-term conservation tillage practices can greatly affect the capacity of soil to sequester C and retain nutrients essential for plant growth. Poultry litter in agricultural production not only functions as a means of waste disposal but also plays a major role in supplying soil with residual C and N and other macro- and micronutrients. The combination of tillage and PL application had the greatest impact on SOM. Although PL addition to NT had the greatest nutrient buildup, the nutrients were restricted to near the surface. Thus, a more pronounced stratification of nutrients was observed under NT-PL compared with other treatments. This was mainly attributed to nutrient accumulation near the soil surface as opposed to mixing of nutrients under CT. Furthermore, this study validates the initial benefits of increased soil fertility observed in short-term studies, thus ensuring that the benefits of conservation practices are indeed long lasting. Therefore, farmers in the southeastern region could help improve the environment and promote the quality of highly eroded soils by using conservation tillage practices and organic amendments.

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