Poultry Litter Application Increases Nitrogen Cycling Compared with Inorganic Nitrogen Fertilization

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ABSTRACT

Poultry litter, an inexpensive source of nutrients and available in abundant amounts in the southeastern USA, may increase N cycling and reduce N losses compared with inorganic N fertilization if applied for crop production. We evaluated the effect of long-term application of poultry litter and inorganic N fertilizer on crop N uptake, soil N fractions, and N losses in conservation and conventional tillage with or without cover crop at the 0- to 20-cm depth in a Decatur silt loam (clayey, kaolinitic, thermic, Typic Paleudults) in northern Alabama. 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). Nitrogen fractions were soil total N (STN), particulate organic N (PON), microbial biomass N (MBN), potential N mineralization (PNM), NH_4–N, and NO_3–N. Crop N uptake varied among treatments and years and total uptake 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}. After 10 yr, STN and PON contents at 0 to 20 cm were greater in NT with poultry litter than in other treatments, except in CT with poultry litter, resulting in N storage at 38 kg N ha^{-1} yr^{-1} with poultry litter compared with loss at 4 kg N ha^{-1} yr^{-1} with NH_4NO_3. The MBN, PNM, and NO_3–N contents were greater with poultry litter than with NH_4NO_3, regardless of tillage. Calculation of estimated N balance showed that poultry litter conserved N at 191 to 556 kg N ha^{-1} compared with –75 to 201 kg N ha^{-1} with NH_4NO_3. Poultry litter application can increase soil N storage and mineralization and reduce the potential for N loss compared with inorganic N fertilization, thereby reducing the need for N fertilization and environmental N contamination.

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 et al., 2000; Reddy et al., 2004). About 9.3 million Mg of poultry litter is produced from 5.2 billion broilers raised in this region (National Agricultural Statistics Service, 2007; Schomberg et al., 2009). Disposal of large amounts of poultry litter is of increasing environmental concern because of groundwater contamination of N and P from the litter through leaching and surface runoff. Application of poultry litter to crops, however, can increase soil organic matter and nutrients that can increase yields and improve soil quality and productivity (Kingery et al., 1994; Mitchell and Tu, 2005; Schomberg et al., 2009). Application of poultry litter along with conservation tillage and cover cropping can provide an opportunity to increase soil N storage and mineralization in the southeastern USA to reduce the need for N fertilization and improve soil, water, and air quality by reducing N leaching and N_2O emission, a greenhouse gas responsible for global warming.

Although N is harvested in crop grains, N in aboveground biomass (stems + leaves) is either harvested or returned to the soil. In contrast, N in belowground biomass (root) is recycled back to the soil. Information on soil N storage and mineralization is needed to optimize N availability for crop growth and reduce N losses from the soil profile. For these reasons, a better understanding of N cycling in crop and soil is needed. Besides above- and belowground biomass N, some of the important parameters of soil N cycling are STN, PON, MBN, PNM, NH_4–N, and NO_3–N. Since STN has a large pool size and inherent spatial variability, it takes a long time (>5 yr for most soils) to measure changes in STN due to management practices (Franzluebbers et al., 1995). As a result, measurement of STN alone does not adequately reflect changes in soil productivity and nutrient status (Franzluebbers et al., 1995; Bezdicek et al., 1996). Measurement of biologically active fractions of STN that change rapidly with time (e.g., within a growing season), such as MBN and PNM, could better reflect changes in soil quality and productivity that alter nutrient dynamics due to immobilization–mineralization (Saffigna et al., 1989; Bremner and Van Kissel, 1992). These fractions can provide an assessment of changes in STN and potential N mineralization induced by management practices, such as tillage, cropping systems, and poultry litter application (Campbell et al., 1989; Sainju et al., 2007). Similarly, PON has been considered as an intermediate fraction of N

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Abbreviations: CT, conventional till; MBN, microbial biomass N; MT, mulch till; NT, no-till; PNM, potential N mineralization; PON, particulate organic N; SOC, soil organic C; STN, soil total N.

between active and slow fractions that also changes rapidly due to changes in management practices (Cambardella and Elliott, 1992). The NH_4–N and NO_3–N fractions have been considered as available pools of N for crop uptake or soil residual N after crop harvest that can be lost due to leaching, volatilization, or surface runoff (Wood et al., 1990; Sainju et al., 2007).

Poultry litter application and inorganic N fertilization can have variable effects in N storage, mineralization, and availability in tilled and non-tilled soils with or without cover crop due to variations in N source, crop residue quantity, and mineralization rates. Conventional tillage enhances mineralization of soil organic N by incorporating crop residue and poultry litter, disrupting soil aggregates, and increasing aeration, thereby reducing N storage (Balesdent et al., 1990; Cambardella and Elliott, 1992). In contrast, conservation tillage can increase N storage in the surface soil by minimizing soil disturbance (Jastrow, 1996; Sainju et al., 2002). Nitrogen storage below the 7.5-cm depth, however, can be higher in tilled soils, depending on the soil texture, due to residue and litter incorporation at greater depths (Jastrow, 1996). Soil N storage may be impacted by the interaction of tillage with cover cropping and N fertilization source and rate (Sainju et al., 2002; Mitchell and Tu, 2006), soil texture and sampling depth (Ellert and Bettany, 1995), and time since treatments were initiated (Liang and Mackenzie, 1992).

Increased residue accumulation, followed by higher level of MBN, at the surface soil in no-till can enhance N immobilization (Zibilske et al., 2002), thereby resulting in a need for greater N fertilization rates to crops (Bronson et al., 2001). Application of poultry litter at ≥6.7 Mg ha^{-1} can increase MBN and enzyme activities responsible for N cycling (Acosta-Martinez and Harmel, 2006). Similarly, cover cropping can alter N availability from poultry litter and inorganic N fertilizer because of N uptake from the soil (Nyakatawa et al., 2000; Reddy et al., 2004).

Information on N cycling from long-term poultry litter application is limited. Because of slow N release and N mineralization over a longer period (Kingery et al., 1994; Mitchell and Tu, 2005), poultry litter may increase N storage and availability compared with inorganic N fertilization. This study provided a unique opportunity to examine the effect of poultry litter application on soil N storage, mineralization, availability, and N balance or N loss at the surface 20-cm layer compared with inorganic N fertilization in conservation and conventional tillage with or without cover crop from 1996 to 2006 in the southeastern USA. We hypothesized that poultry litter application in conservation tillage with cover crop would increase soil N storage and mineralization and reduce N losses at the 0- to 20-cm depth through soil processes compared with inorganic N fertilization in conventional tillage without cover crop. Our objectives were to: (i) determine the amount of N returned to the soil from crop residues as influenced by N source, tillage, and cropping system from 1997 to 2005; (ii) evaluate changes in soil N fractions (STN, PON, PNM, MBN, NH_4–N, and NO_3–N) at the 0- to 20-cm depth; and (iii) estimate N balance at the surface 20-cm layer due to soil processes as influenced by treatments in the humid southeastern USA.

MATERIALS AND METHODS

Experimental Site and Treatments

A long-term field experiment was conducted from 1996 to 2006 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, Typic Paleudults). Before the initiation of the experiment, soil samples collected randomly from 24 cores (5 cm i.d.) within the experimental plots in 1996 had an average pH of 6.2, sand concentration of 150 g kg^{-1}, silt concentration of 580 g kg^{-1}, clay concentration of 270 g kg^{-1}, soil organic C (SOC) content of 38.6 Mg C ha^{-1}, STN content of 3.7 Mg N ha^{-1}, and bulk density of 1.60 Mg m^{-3} at the 0- to 20-cm depth. Previous crop history for the past 5 yr was conventional-tilled continuous cotton with recommended rates of inorganic N, P, and K fertilizers. No poultry litter was applied. Details of the experiment and crop management practices were presented elsewhere (Nyakatawa et al., 2000; Reddy et al., 2004).

Treatments consisted of incomplete factorial combinations of three tillage practices [no-till (NT), mulch till (MT), and conventional till (CT)], two cropping systems [cotton–cotton–corn and rye/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 N cycling. 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 by 9 m. Treatments were continued in the same plot every year to determine their long-term influence on soil N storage and N cycling.

The CT included moldboard plowing to a depth of 15 to 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 to 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 yr of rye as winter cover crop

Table 1. Description of treatments used in the experiment.

Treatment no.	Tillage†	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

† Tillage is CT, conventional till; MT, mulch till; and NT, no-till.

and cotton as summer cash crop, followed by 1 yr of residual corn crop. Similarly, cotton–cotton–corn cropping system contained 2 yr of continuous cotton without rye cover crop, followed by 1 yr 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 yr.

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, Veedersburg, IN, USA) without fertilization. In April, 7 d after flowering, rye biomass yield was determined by harvesting biomass from a 1 by 1 m^2 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 d before planting in May. Both inorganic N fertilizer and poultry litter were incorporated to a depth of 5 to 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 to 50% greater with poultry litter than with NH_4NO_3 during the first 4 d of emergence (Nyakatawa and Reddy, 2000). The poultry litter applied in each year from 1997 to 2005 contained total C concentration at 337±22 g C kg^{-1} and total N concentration at 31±4 g N kg^{-1} on dry-weight basis (Table 2). Because of the variation in N concentration, the amount of poultry litter applied to cotton to supply 100 kg N ha^{-1} varied from year to year (Table 2). 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) to cotton in each year. The rates of P and K applied to cotton in inorganic N-fertilized plots were, in general, similar to that supplied by poultry litter in manure-applied plots.

Four weeks after 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 received appropriate herbicides and pesticides during their growth to control weeds and pests. Cotton also received 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 (for a total of 560 to 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 wk before lint and grain harvest in October to 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 by 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. After determining yields, samples of rye biomass, cotton lint and biomass, and corn grain and biomass were oven dried at 60°C for 3 to 7 d and ground to 1 mm. Nitrogen concentration in plant samples was determined by using a dry combustion C and N analyzer (LECO Corp., St. Joseph, MI, USA). Nitrogen content in rye biomass, cotton lint and biomass, and corn grain and biomass was determined by multiplying their yields by N concentration.

Soil Sampling and Analysis

In February 2006, soil samples were collected with a hand probe (10 cm i.d.) from the 0- to 20-cm depth from five places in the central rows of the plot after removing crop residue from the soil surface. These were separated into 0- to 10- and 10- to 20-cm depths, composited within a depth, air-dried, ground, and sieved to 2 mm for determining N fractions. At the same time, a separate undisturbed soil core (10 cm i.d.) was taken from 0- to 10- and 10- to 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.

The STN concentration (g N kg^{-1}) was determined by the dry combustion method using a C and N analyzer (LECO Corp., St. Joseph, MI, USA). For determining PON, 10 g soil was dispersed with 30 mL of 5 g L^{-1} sodium hexametaphosphate by shaking for 16 h and the solution was poured through a 0.053-mm sieve (Cambardella and Elliott, 1992). The solution that passed through the sieve and contained mineral associated and water soluble N was dried at 50°C for 3 to 4 d and total N concentration was determined by using the analyzer as above. The PON concentration was determined by the difference between STN in whole-soil and that in the particles that passed through the sieve.

The PNM in air-dried soils was determined by the method modified by Haney et al. (2004). Two 10 g soils were moistened with water to 50% field capacity (0.25 m^3 m^{-3}) and incubated in a 1 L jar at 21°C for 10 d. At 10 d, one container was removed and extracted with 50 mL of 2 *M* KCl for 1 h. The NH_4–N and NO_3–N concentrations in the extract were determined by using the autoanalyzer (Lachat Instrument, Loveland, CO, USA). The PNM concentration was determined by the difference between the sum of NH_4–N and NO_3–N concentrations before and after incubation. The other container with moist soil was subsequently used for determining MBN by the modified fumigation–incubation method for air-dried soils (Franzluebbers et al., 1996). The moist soil was fumigated with ethanol-free chloroform for 24 h

Table 2. Poultry litter C and N concentrations (dry weight basis) and amount applied to supply 100 kg N ha^{-1} to cotton from 1997 to 2004.

Year	Poultry litter		Amount of poultry litter applied to supply 100 kg N ha^{-1}
	C concentration	N concentration	
	g C kg^{-1}	g N kg^{-1}	Mg ha^{-1}
1997	315	27	3.70
1998	340	30	3.33
2000	330	34	2.94
2001	359	35	2.86
2003	320	32	3.13
2004	358	28	3.57
Avg.	337	31	3.23

Table 3. Nitrogen content in residues of rye cover crop, cotton, and corn biomass (stems + leaves) returned to the soil from 1997 to 2005.

Treatment no.†	Rye						Cotton						Corn			Total N content
	1997	1998	2000	2001	2003	2004	1997	1998	2000	2001	2003	2004	1999	2002	2005	
	kg N ha^{-1}															
1	11	8	17	8	7	5	93	91	61	100	47	58	106	141	124	795
2	–	–	–	–	–	–	179	128	164	170	94	77	112	131	122	1177
3	–	–	–	–	–	–	213	150	151	196	105	77	122	161	142	1317
4	11	12	27	9	6	5	213	165	164	202	112	94	125	147	137	1429
5	11	10	23	12	5	4	140	140	169	154	74	83	119	149	134	1227
6	11	17	23	10	8	7	238	149	117	207	112	92	143	142	143	1419
7	11	8	17	12	5	5	144	120	153	145	79	92	104	151	127	1173
8	11	10	19	5	7	6	262	179	161	237	130	110	132	216	174	1659
9	11	20	22	9	8	7	188	150	150	185	68	92	132	160	146	1468
10	–	–	–	–	–	–	205	92	71	157	45	52	117	130	124	993
11	11	22	31	16	8	7	296	192	195	263	91	107	159	159	159	1716
12	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
LSD (0.05)	ns‡	7	ns	4	ns	ns	77	ns	40	66	26	31	31	ns	ns	257

† See Table 1 for complete description of treatment numbers.

‡ Not significant.

and incubated for 10 d at 21°C, after which NH_4–N and NO_3–N concentrations were determined as above after extracting with KCl. This container was incubated twice because MBN determination needed moist-soil and mineralizable C was flushed out during the first incubation (Franzluebbers et al., 1996). The MBN was calculated by the difference between the sum of NH_4–N and NO_3–N concentrations in the sample before and after fumigation–incubation and divided by a factor of 0.41 (Voroney and Paul, 1984). The NH_4–N and NO_3–N concentrations determined in the nonfumigated-nonincubated samples were used as available fractions of N.

The contents (Mg N ha^{-1} or kg N ha^{-1}) of STN, PON, PNM, MBN, NH_4–N, and NO_3–N at 0- to 10- and 10- to 20-cm depths were calculated by multiplying their concentrations (g N kg^{-1} or mg N kg^{-1}) by bulk density and thickness of the soil layer. The total contents at 0 to 20 cm were determined by summing the contents at 0 to 10 and 10 to 20 cm. Estimated N balance for each treatment at the 0- to 20-cm depth was calculated by deducting the sum of initial STN content in 1996 and total N fertilization rate from 1997 to 2005 from the sum of cotton lint and corn grain N removal from 1997 to 2005 and final STN content in 2006. Nitrogen inputs through atmospheric deposition, irrigation water, and nonsymbiotic N fixation, and outputs through losses due to leaching, volatilization, surface runoff, and denitrification, have not been taken into account to calculate the estimated N balance.

Data Analysis

Data for plant and soil parameters were analyzed using the MIXED procedure of SAS (Littell et al., 1996). For plant parameters, treatment was considered as the main factor and fixed effect, year as the repetitive measure factor, and replication and treatment × replication as random effects. For soil parameters, treatment was considered as the main factor and fixed effect, soil depth as the repetitive measure factor, and replication and treatment × replication as random effects. Since treatments were laid out in an incomplete factorial arrangement, Treatments 2, 3, 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 plant and soil parameters. Similarly, Treatments 4, 5, 6, 7, 8, and 9 containing complete combinations of tillage and N sources were used to determine the effect of tillage × N source interaction on these parameters. Means were separated by using the least square means test when treatments and interactions were significant (Littell et al., 1996). Since the experiment also provided the opportunity for comparing parameters between cropping and fallow treatments in NT, orthogonal contrasts were used to compare the mean of Treatments 3, 8, 9, 10, and 11 vs. Treatment 12. Statistical significance was evaluated at $P \leq 0.05$, unless otherwise stated.

RESULTS AND DISCUSSION

Crop Residue Nitrogen

Crop residue N varied among treatments and years (Table 3) due to variations in management practices and precipitation (Table 4). Rye residue N was ≤31 kg N ha^{-1} yr^{-1} and usually not different among treatments, except in 1998 and 2001 when residue N was greater in Treatment 11 than in most treatments due to application of 200 kg N ha^{-1} from poultry litter. Similar general increases with this treatment were noted in cotton residue N, although residue N varied among treatments in a year. Cotton residue N increased with N fertilization from NH_4NO_3 and poultry litter (Treatments 2 to 9 and 11) compared with no N fertilization (Treatments 1 and 10), regardless of tillage and cropping systems, indicating enriched residue N with N nutrition. Corn residue N was also greater with 200 kg N ha^{-1} from poultry litter (Treatment 11) than with most other treatments in 1999. Crop residue N generally responded positively with increased precipitation during the crop growing season. For example, rye residue N was greater in 1998 and 2000 than in other years due to increased precipitation during December–April (growing season) while cotton and corn residue N were greater in 1997, 1998, 2000, 2001, and 2002 than in other years due to increased precipitation during May–November (Tables 3 and 4). Mitchell and Tu (2005) also reported greater cotton and corn N uptake during years of higher precipitation, with greater differences among N sources than in years with lower precipitation. In Treatments 2, 3, and 10, rye residue N was absent because cover crop was not grown in these treatments (Table 1). Similarly, lack of crops grown in the fallow treatment (Treatment 12) resulted in the absence of crop residue N in this treatment.

Table 4. Total monthly rainfall from 1996 to 2005 at the experimental site in Belle Mina, AL.

Month	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	70-yr avg.
	mm										
Jan.	215	175	218	328	27	182	146	59	82	96	153
Feb.	74	130	194	94	78	147	71	210	190	119	146
Mar.	213	101	129	152	164	173	165	56	140	91	183
Apr.	164	121	130	115	257	116	46	110	110	137	130
May	50	108	73	141	22	192	308	200	81	35	123
Jun.	100	195	54	196	123	263	26	130	130	95	122
Jul.	128	51	159	109	22	128	136	120	200	169	111
Aug.	142	121	54	6	80	105	50	76	74	88	133
Sep.	242	176	26	17	51	167	159	220	88	86	104
Oct.	77	229	41	37	1	114	96	27	84	2	109
Nov.	132	69	86	146	208	93	117	140	110	98	90
Dec.	137	128	250	90	132	191	186	84	120	130	158
Dec.–Apr.†	–	664	799	939	616	750	619	621	606	563	–
May–Nov.	871	949	493	652	507	1062	892	913	767	573	792
Jan.–Dec.	1674	1735	1431	1731	1165	1871	1506	1432	1409	1146	1562

† Total rainfall from December of previous year to April of the following year.

The individual and combined effects of treatments on crop residue N returned to the soil were obtained by evaluating tillage × cropping system and tillage × N source interactions (Table 5). Total crop residue N from 1997 to 2005, averaged across tillage, was greater in rye/cotton–rye/cotton–corn than in cotton–cotton–corn, indicating increased N contribution from rye cover crop residue. In contrast, when inorganic N fertilizer and poultry litter were applied at 100 kg N ha^{-1}, total residue N, averaged across tillage, was lower with poultry litter than with NH_4NO_3. This indicates that slower N availability from poultry litter than from NH_4NO_3 during the crop growing season (May–November) probably reduced crop N uptake, although soil NO_3–N content was greater with poultry litter when the sample was collected in February 2006, as shown below. Several researchers (Glover et al., 1998; Mitchell and Tu, 2005) also reported lower cotton and corn N uptake with poultry litter than with NH_4NO_3 when applied at 134 to 260 kg N ha^{-1} due to lower N availability from poultry litter. Tillage and its interaction with cropping system or N source did not influence total residue N.

Table 5. Effects of tillage, cropping system, and N source on total N content in biomass (stems + leaves) residues of cotton, rye, and corn returned to the soil from 1997 to 2005.

Cropping system	N source†	Total N content
		kg N ha^{-1}
Rye/cotton–rye/cotton–corn		1544a‡
Cotton–cotton–corn		1247b
	NH_4NO_3	1502a
	poultry litter	1289b
Tillage (T) × cropping system (C) interaction		*P* value
T		0.114
C		0.017
T × C		0.718
Tillage (T) × N source (S) interaction		
T		0.221
S		0.027
T × S		0.948

† N was applied at 100 kg N ha^{-1}.

‡ 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.

Soil Bulk Density

Soil bulk density at 0 to 10 cm was greater with poultry litter than with NH_4NO_3 at 100 kg N ha^{-1} (Table 6). At 10 to 20 cm, cropping and fertilization reduced bulk density compared with fallow and no-fertilization in NT. Bulk density was not influenced by tillage and its interaction with cropping system or N source. Similarly, bulk density was not influenced by soil depth.

The lack of significant differences in bulk density among tillage and cropping systems suggests 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., 2002). 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

Table 6. Effects of tillage, cropping system, and N source on soil bulk density at the 0- to 20-cm depth in 2006.

N source†	Bulk density	
	0–10 cm	10–20 cm
	Mg m^{-3}	
NH_4NO_3	1.55b‡	1.57a
Poultry litter	1.65a	1.61a
Contrast		
Cropping vs. fallow in no-till	–0.06	–0.08*
	P values	
Tillage (T) × N source (S) interaction		
T	0.814	0.613
S	0.004	0.928
T × S	0.237	0.246
Tillage (T) × cropping system (C) interaction		
T	1.000	0.261
C	0.822	0.678
T × C	0.079	0.368

* Significant at $P \leq 0.05$.

† N was applied at 100 kg N ha^{-1}.

‡ 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.

higher bulk density with poultry litter than with inorganic N fertilizer were not known. Since bulk density influences the conversion of N fractions from a mass to volume basis, both mass/mass (g N kg^{-1}) basis as influenced by depth and mass/volume (Mg N ha^{-1}) basis of N fractions are discussed below.

Soil Total and Particulate Organic Nitrogen

The STN concentrations at 0 to 10 and 10 to 20 cm were not significant for tillage × N source and tillage × cropping system interactions (Table 7). In contrast, STN content at 0 to 20 cm was greater in NT with poultry litter than in MT with poultry litter or in NT, MT, and CT with NH_4NO_3. Averaged across tillage, STN concentration at 0 to 10 cm and content at 0 to 20 cm were greater with poultry litter than with NH_4NO_3. As a result, STN increased from 1996 (3.7 Mg N ha^{-1}) to 2006 with poultry litter but decreased with NH_4NO_3 in NT and CT. This resulted in N storage rates of 21 to 49 kg N ha^{-1} yr^{-1} with poultry litter compared with –23 to 15 kg N ha^{-1} yr^{-1} with NH_4NO_3. Cropping and fertilization increased STN concentration and content compared with fallow in NT, resulting in a N storage rate of 67 kg N ha^{-1} yr^{-1}. Although poultry litter application at 200 kg N ha^{-1} increased crop residue N (Table 3), it did not increase STN compared with application at 100 kg N ha^{-1} (data not shown). Tillage and its interaction with cropping system did not influence STN. As expected, STN concentration decreased with soil depth.

The PON concentration and content varied with treatments similar to STN (Table 8). The PON content at 0 to 20 cm was greater in NT with poultry litter than in NT and CT with NH_4NO_3. Averaged across tillage, PON concentration at 0 to 10 cm and content at 0 to 20 cm were greater with poultry litter than with NH_4NO_3. Cropping and fertilization increased PON concentration at 0 to 10 cm compared with fallow in NT.

The decrease in STN and PON in the fallow treatment in NT after 10 yr could be a result of limited N input due to reduction or absence of plant growth and N fertilization. Reduced amount of crop residue N returned to the soil, followed by increased decomposition of soil organic N due to fallow as a result of increased soil temperature and water content, can reduce STN (Halvorson et al., 2002). In contrast, increases in N inputs due to cropping and N fertilization as a result of increased biomass production in other treatments (Table 3) probably increased STN and PON. Increases in STN and PON due to increased cropping intensity (Sherrod et al., 2003; Sainju et al., 2007, 2009) and N fertilization (Omay et al., 1997) as a result of increased crop residue N returned to the soil have been known.

Increases in STN and PON due to poultry litter application compared with inorganic N fertilization in NT and CT suggests that some of the nonmineralized N (40%) from poultry litter could have converted to soil organic N, in contrast to inorganic N fertilizer which is used mostly for crop N uptake. Kelling et al. (1995) stated that only 60% of N from poultry litter was available to crops in the first year. This resulted in lower crop residue N with poultry litter than with NH_4NO_3 (Table 3). Several researchers (Aoyama et al., 1999; Mitchell and Tu, 2006) have also reported greater STN with manure application than without. Sørensen and Amato (2002) and Sørensen (2004) reported that a fraction

Table 7. Effects of tillage, cropping system, and N source on soil total N (STN) at the 0- to 20-cm depth in 2006.

Tillage†	N source‡	STN concentration 0–10 cm	STN concentration 10–20 cm	STN content 0–20 cm	Changes in STN from 1996 to 2006 0–20 cm	N storage rate 0–20 cm
		g N kg^{-1}		Mg N ha^{-1}		kg N ha^{-1} yr^{-1}
NT	NH_4NO_3	1.23	1.03	3.44	–0.23	–23
	poultry litter	1.52	1.02	4.19	0.49	49
MT	NH_4NO_3	1.42	1.01	3.84	0.15	15
	poultry litter	1.49	0.92	3.91	0.21	21
CT	NH_4NO_3	1.31	0.98	3.67	–0.03	–3
	poultry litter	1.51	1.04	4.11	0.41	41
LSD (0.05)		–	–	0.24	0.24	24
Means						
	NH_4NO_3	1.55b§	1.59a	3.65b	–0.04b	–4b
	poultry litter	1.65a	1.59a	4.07a	0.38a	38a
Contrast						
Cropping vs. fallow in no-till		0.42**	0.08	0.67***	0.67***	67***
		P values				
Tillage (T) × N source (S) interaction						
T		0.392	0.432	0.562	0.562	0.562
S		0.004	0.718	<0.001	<0.001	<0.001
T × S		0.236	0.319	0.004	0.004	0.004
Tillage (T) × cropping system (C) interaction						
T		0.269	0.857	0.341	0.341	0.341
C		0.603	0.980	0.708	0.708	0.708
T × C		0.982	0.411	0.876	0.876	0.876

** Significant at $P \leq 0.01$.

*** Significant at $P \leq 0.001$.

† Tillage is CT, conventional till; MT, mulch till; and NT, no-till.

‡ N was applied at 100 kg N ha^{-1}.

§ 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.

of labeled NH_4–N added to liquid dairy cattle and swine manure was found in the soil after 2.5 yr, suggesting that manure application increased N immobilization and soil organic N. The lack of increase in STN and PON with poultry litter application at 200 kg N ha^{-1} compared with the application at 100 kg N ha^{-1} was probably due to increased N loss. This was contrary to that found by Grignani et al. (2007) who reported that increased N rate from bovine slurry and farmyard manure increased STN. The reasons for similar STN and PON levels between poultry litter and NH_4NO_3 applications in MT were not known.

The PON represents a coarse undecomposed fraction of STN (Cambardella and Elliott, 1992). Application of poultry litter at 100 kg N ha^{-1} increased PON by 18.7% and STN by 11.5% compared with NH_4NO_3 (Tables 7 and 8), suggesting that PON changes rapidly with N management compared with STN. Out of 600 kg N ha^{-1} applied from poultry litter and NH_4NO_3 to cotton from 1997 to 2004, poultry litter increased PON by one-third (200 kg N ha^{-1}) and STN by one-half (420 kg N ha^{-1}) compared with NH_4NO_3, indicating that changes in PON measure significant portion of changes in soil N storage.

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 and N storage rates at 0 to 20 cm as influenced by tillage and N sources after 10 yr (Table 7). No-till with poultry litter application sequestered the greatest amount of N compared with other tillage and N source treatments, possibly due to reduced N mineralization as a result of less soil disturbance. The greater N storage rate with poultry litter than with NH_4NO_3, regardless of tillage, was probably a result of increased organic N supplied by poultry litter to the soil. In contrast, the negative N storage rate with NH_4NO_3 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.

Table 8. Effects of tillage, cropping system, and N source on soil particulate organic N (PON) at the 0- to 20-cm depth in 2006.

Tillage†	N source‡	PON concentration 0–10 cm	PON concentration 10–20 cm	PON content 0–20 cm
		g N kg^{-1}		Mg N ha^{-1}
NT	NH_4NO_3	0.35	0.27	0.94
	poultry litter	0.57	0.29	1.42
MT	NH_4NO_3	0.52	0.24	1.20
	poultry litter	0.54	0.19	1.18
CT	NH_4NO_3	0.44	0.24	1.10
	poultry litter	0.51	0.25	1.22
LSD (0.05)		–	–	0.25
Means				
	NH_4NO_3	0.44b§	0.25a	1.07b
	poultry litter	0.54a	0.24a	1.27a
Contrast				
Cropping vs. fallow in no-till		0.20***	–0.05	0.21
		P values		
Tillage (T) × N source (S) interaction				
T		0.237	0.487	0.834
S		0.011	0.852	0.011
T × S		0.068	0.761	0.026
Tillage (T) × cropping system (C) interaction				
T		0.204	0.599	0.618
C		0.280	0.741	0.476
T × C		0.550	1.000	0.623

*** Significant at $P \leq 0.001$.

† Tillage is CT, conventional till; MT, mulch till; and NT, no-till.

‡ N was applied at 100 kg N ha^{-1}.

§ 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.

Labile Nitrogen Fractions

Poultry litter increased MBN concentration at 0 to 10 cm and MBN, PNM, and NO_3–N contents at 0 to 20 cm compared with NH_4NO_3, regardless of tillage (Table 9). Cropping and fertilization increased MBN concentration at 0 to 10 and

Table 9. Effects of tillage, cropping system, and N source on soil microbial biomass N (MBN), potential N mineralization (PNM), and NO_3–N at the 0- to 20-cm depth in 2006.

N source†	MBN concentration 0–10 cm	MBN concentration 10–20 cm	MBN content 0–20 cm	PNM concentration 0–10 cm	PNM concentration 10–20 cm	PNM content 0–20 cm	NO_3–N concentration 0–10 cm	NO_3–N concentration 10–20 cm	NO_3–N content 0–20 cm
	mg N kg^{-1}		kg N ha^{-1}	mg N kg^{-1}		kg N ha^{-1}	mg N kg^{-1}		kg N ha^{-1}
NH_4NO_3	83b‡	42a	195b	16.3a	6.8a	36.1b	9.7a	3.2a	20.0b
Poultry litter	124a	34a	259a	23.2a	8.7a	52.1a	12.4a	3.4a	25.8a
Contrast									
Cropping vs. fallow in no-till	35*	17*	78**	6.8	4.6	16.9*	1.7	0.9*	3.5
	P values								
Tillage (T) × N source (S) interaction									
T	0.203	0.595	0.429	0.545	0.599	0.510	0.415	0.075	0.093
S	0.007	0.252	0.010	0.129	0.296	0.026	0.153	0.408	0.041
T × S	0.642	0.521	0.826	0.675	0.670	0.685	0.782	0.293	0.686
Tillage (T) × cropping system (C) interaction									
T	0.166	0.141	0.941	0.144	0.276	0.869	0.295	0.736	0.353
C	0.534	0.721	0.417	0.546	0.271	0.449	0.830	0.628	0.954
T × C	0.583	0.589	0.186	0.800	0.471	0.275	0.847	0.851	0.865

* Significant at $P \leq 0.05$.

** Significant at $P \leq 0.01$.

† N was applied at 100 kg N ha^{-1}.

‡ 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.

10 to 20 cm, PNM content at 0 to 20 cm, and NO_3–N concentration at 10 to 20 cm compared with fallow in NT. Treatment did not influence NH_4–N concentration and content (data not reported). Tillage and its interaction with N source or cropping system were not significant for labile N fractions. As with STN and PON, MBN, PNM, and NO_3–N concentrations decreased with soil depth. Poultry litter application at 200 kg N ha^{-1} did not influence labile N fractions compared with the application at 100 kg N ha^{-1} (data not reported).

While increased N inputs due to cropping and fertilization may have increased MBN, PNM, and NO_3–N contents compared with fallow, greater values with poultry litter than with NH_4NO_3 suggests that, after 10 yr of repeated fertilization, treatments receiving poultry litter have higher N mineralization potential than those receiving inorganic N fertilizer due to greater N mineralization–immobilization processes that resulted in increased N availability. Acosta-Martinez and Harmel (2006) reported that MBN increased more with poultry litter application than without after 4 yr. Significant amounts of NH_4–N in dairy cattle and pig slurry are microbially immobilized immediately after application due to presence of easily decomposable organic matter, such as volatile fatty acids (Kirchmann and Lundvall, 1993). Several researchers (Bittman et al., 2005; Forge et al., 2005) also found greater MBN and PNM with manure application than with inorganic or no N fertilization treatments. Kingery et al. (1996) observed greater labile N fractions with poultry litter (6.7%) than with mineral (4.1%) or no N fertilizer (4.7%). Increases in labile N fractions with poultry litter application compared with inorganic N fertilization or with cropping and fertilization compared with fallow suggests that poultry litter application and continuous cropping can increase N mineralization and availability that may reduce the rate of N fertilization for sustaining crop yields and improving environmental quality. Although several researchers (Kingery et al., 1994; Mitchell and Tu, 2005, 2006) found lower or similar NO_3–N content to a depth of 60 cm with poultry litter than with inorganic N fertilizer during the crop growing season, greater NO_3–N content with poultry litter than with NH_4NO_3 in February 2006 in this experiment suggests that N is mineralized from poultry litter even after the crop growing season. This N, however, can be subjected to losses due to leaching, surface runoff, and volatilization due to absence of crops for N uptake. Kingery et al. (1994) found significant accumulation of NO_3–N at the 1- to 3-m depth with poultry litter compared with inorganic N fertilizer due to its downward movement from the overlying layers.

Nitrogen Balance

Differences in cotton lint and corn grain N removal and STN levels in 2006 among treatments have led us to calculate the estimated N balance from the agroecosystem (Table 10). As for STN level in 2006, tillage × N source interaction and cropping and fertilization vs. fallow in NT were significant for the estimated N balance.

Estimated N balance was greater with poultry litter than with NH_4NO_3 in NT and CT (Table 10), suggesting that poultry litter may conserve N and reduce its losses through leaching, volatilization, and denitrification compared with inorganic N fertilizer. Nitrogen conservation with poultry litter was greater in NT (56 kg N ha^{-1} yr^{-1}) than in CT (40 kg N ha^{-1} yr^{-1}). This suggests that NT may conserve N from poultry litter better than CT due to reduced soil disturbance and nonsymbiotic N fixation. Power and Peterson (1998) have reported a N conservation rate of 9 to16 kg N ha^{-1} yr^{-1} in NT compared with a loss of 26 to 47 kg N ha^{-1} yr^{-1} in CT in dryland soils at the 0- to 30-cm depth. They suspected that N conservation in NT was due to nonsymbiotic N fixation but N loss in CT was due to leaching loss. The negative N balance in NT with NH_4NO_3 indicates that N from inorganic N fertilizer placed at the soil surface in NT may be subjected to losses due to surface runoff, leaching, and volatilization. Cropping and fertilization also conserved N better than fallow in NT, indicating that cropping may increase N storage and cycling

Table 10. Effects of tillage, cropping system, and N source on estimated N balance as a result of N fertilization to cotton, N removal from cotton lint and corn grain, and soil total N (STN) content at the 0- to 20-cm depth at the initiation of the study (1996) and after 10 yr (2006).

Tillage†	N source‡	STN content in 1996 (A)	Total from 1997 to 2005			STN content in 2006 (E)	Estimated N balance§
			N fertilization rate (B)	Cotton lint N removal (C)	Corn grain N removal (D)		
		kg N ha^{-1}					
NT	NH_4NO_3	3670	600	165	590	3440	–75
	poultry litter	3670	600	141	495	4190	556
MT	NH_4NO_3	3670	600	146	485	3840	201
	poultry litter	3670	600	131	420	3910	191
CT	NH_4NO_3	3670	600	138	461	3670	–1
	poultry litter	3670	600	147	420	4100	397
LSD (0.05)		—	—	28	102	240	105
Means							
	NH_4NO_3	3670a¶	600a	150a	512a	3650b	42a
	poultry litter	3670a	600a	140a	445b	4070a	385b
Contrast							
Cropping vs. fallow in no-till		0	600	146	471	670***	65**

** Significant at $P \leq 0.01$.

*** Significant at $P \leq 0.001$.

† Tillage is CT, conventional till; MT, mulch till; and NT, no-till.

‡ N was applied at 100 kg N ha^{-1}.

§ Estimated N balance = Column (C) + (D) + (E)– (A)– (B).

¶ 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.

and use N more efficiently, probably by increasing N uptake and returning N to the soil through crop residue. Nitrogen loss during fallow period increases due to continuous soil N mineralization as a result of increased temperature and water content (Eck and Jones, 1992) and absence of crops to conserve soil mineral N (Eck and Jones, 1992; Sainju et al., 2009).

Our results showed that increased soil N storage with repeated application of poultry litter compared with inorganic N fertilization increased N immobilization, remineralization potential, and availability. Such application of poultry litter compared with inorganic N fertilization, however, did not increase crop N uptake over time (Table 3). This suggests that N released from poultry litter may not be significant enough to influence crop yields, probably due to increased N loss due to leaching, denitrification, surface runoff, and volatilization during nongrowing crop season. These were consistent with those reported by several researchers (Sørensen and Amato, 2002; Sørensen, 2004; Grignani et al., 2007) who worked on bovine, pig, and dairy cattle slurry and farmyard manure compared with chemical fertilizers. Probably longer that 10 yr may be required to obtain the significant effect of poultry litter N on crop yields and N uptake compared with inorganic N fertilization so that N fertilization rate can be reduced.

CONCLUSIONS

Poultry litter application reduced crop N uptake and potential for soil N losses through surface runoff, leaching, volatilization, and denitrification and increased soil N storage, mineralization, and availability compared with inorganic N fertilization, regardless of tillage. Nitrogen storage and estimated N balance with poultry litter was greater in no-tilled than in tilled soils. Increasing the N application rate from 100 to 200 kg N ha^{-1} through poultry litter application, however, did not alter N storage, mineralization, and availability, although it increased crop N uptake. Similarly, cropping and fallow increased N storage, mineralization, and availability and reduced N loss compared with fallow in no-tilled soils. Although inorganic N fertilization increased crop N uptake, increased N storage and availability from poultry litter application may not be enough to increase crop N uptake, probably due to increased N losses during nongrowing crop season. Poultry litter, instead of being disposed as a waste material, should be applied for growing crops and can improve soil productivity, sustain crop yields, and reduce environmental degradation compared with inorganic N fertilization. To sustain crop yields, poultry litter may have to be applied at higher N rates than commercial N fertilizers by taking into account the N mineralization potential of the litter within a growing season.

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