Nitrogen mineralization from broiler litter applied to southeastern Coastal Plain soils

R.K. Hubbard
USDA-ARS

D.D. Bosch
USDA-ARS

L.K. Marshall
USDA-ARS

T.C. Strickland
USDA-ARS

D. Rowland
USDA-ARS

See next page for additional authors

Nitrogen mineralization from broiler litter applied to southeastern Coastal Plain soils

R.K. Hubbard, D.D. Bosch, L.K. Marshall, T.C. Strickland, D. Rowland, T.S. Griffin, C.W. Honeycutt, S.L. Albrecht, K.R. Sistani, H.A. Torbert, B.J. Wienhold, B.L. Woodbury, and J.M. Powell

Abstract: A field study was conducted to determine nitrogen (N) mineralization from broiler litter (BL) in two Coastal Plain soils of differing texture, sandy (Tifton loamy sand) or clayey (Greenville sandy clay loam). These soils represented the broad range in surface textures commonly found in soils used for agricultural production in the southeastern Coastal Plain. Published protocols used for the study were designed by the ARS mineralization team. In addition to measuring ammonium (NH_4-N) and nitrate (NO_3-N) in the soil as a measure of N mineralization, both total C and total N were measured to determine the impact of a single BL amendment on C sequestration and N accumulation. Amounts of N in the soil from BL mineralization over 70 days were identical for both soils, 46.4 mg N kg^{-1} soil (0.046%), but differences occurred in timing of the mineralization processes. In the sandy Tifton soil, depletion of NH_4-N and nitrification of the NH_4-N to NO_3-N occurred simultaneously. The NH_4-N from the BL was depleted in 21 days while peak NO_3-N concentrations in the soil were found at 28 days. In the clayey Greenville soil, NH_4-N concentrations from BL mineralization increased for 21 days and then decreased until reaching background levels by 70 days. Nitrate concentrations never did increase in the BL amended Greenville soil, indicating both that the nitrification rate was much slower than the ammonification rate, and most likely, that what NO_3-N was produced was lost from the soil by denitrification under wet conditions. The combination of soil textural and microclimate differences along with greater protection of the BL residues in the clayey soil than in the sandy soil are believed responsible for the observed N mineralization differences between the two soils. Previous research has shown that N mineralization rate is positively correlated with sand content and negatively correlated with clay content of soils, and the results of this study concurred with those findings. Measurements of total C and total N in both Coastal Plain soils showed that overall increases were small with a single BL amendment, and it was concluded that long-term studies are needed to investigate C sequestration and N accumulation. It was concluded from the study that there is a high probability that BL mineralization rates will be significantly slower on the more clayey Coastal Plain soils than on very sandy ones, and that farm managers should take these rates into consideration when planning timing and amounts of BL applications.

Key words: ammonium—broiler litter—nitrate—nitrogen mineralization—southeastern Coastal Plain soils—water quality

In 2005, broiler chicken production in Georgia valued nearly $4 billion, representing the highest farm gate value of all agricultural commodities for the state (Boatright and McKissick 2006). For many years, Georgia has produced more birds and generated more value from broilers than any other state in the United States. At present the major production is in the Piedmont and mountain regions of the state, but current expansion is occurring in the Southern Coastal Plain. One major reason for the current expansion is the abundance of agricultural cropland in the Southern Coastal Plain for disposal (use) of the waste (broiler litter [BL]) and the lack of the same in the northern portions of the state.

The nitrogen (N) content of BL can range from 25 g kg^{-1} (2.5%) (Gascho et al. 2001) to 33 g kg^{-1} (3.3%) (Vest et al. 1996). Nitrogen contained in BL is of environmental concern because nitrates (NO_3-N) can be leached below the rooting zone when land application rates are high. Wood et al. (1996) measured NO_3-N concentrations at 1 m (3.3 ft) that were in direct proportion to the rate of BL applied. Kingery et al. (1994) found NO_3-N accumulations in soil or pore water nearly to bedrock from BL application at a Sand Mountain, Alabama site. In contrast, Sharpley et al. (1993) determined that the accumulation of NO_3-N in soil or pore water from BL decreased rapidly with depths greater than 5 cm (2 in) in an Oklahoma soil.

When BL is added to soils, heterogeneous microorganisms attack the organic N compounds resulting in mineralization. Ammonification is the primary step in organic N mineralization and is defined as the biological process by which organic forms of N are transformed to ammonium (NH_4-N) (DeBusk et al. 2001). The second step in mineralization is nitrification, which is an obligate aerobic process involving oxidation of NH_4-N to NO_3-N (Debusk et al. 2001).

Many studies have been conducted on N mineralization of poultry litter. Gale and Gilmour (1986) compared N mineralization between the fine and coarse fractions of poultry litter over a range of temperatures and characterized mineralization according to three phases of decomposition—rapid, intermediate, and slow. Nahm (2005) conducted studies on factors influencing N mineralization during poultry litter composting. Their work included equations for predicting amount of N mineralized.

Robert K. Hubbard is a soil scientist, **David D. Bosch** is a research hydraulic engineer, **Laura K. Marshall** is a hydrologist, and **Timothy C. Strickland** is a supervisory soil scientist at USDA Agricultural Research Service (ARS), Tifton, Georgia. **Dianne Rowland** is a plant physiologist with USDA ARS, Dawson, Georgia. **Timothy S. Griffin** is an agronomist, and **C. Wayne Honeycutt** is a supervisory soil scientist with USDA ARS, Orono, Maine. **Stephan L. Albrecht** is a microbiologist with USDA ARS, Pendleton, Oregon. **Karamat R. Sistani** is a supervisory soil scientist with USDA ARS, Bowling Green, Kentucky. **H. Allen Torbert** is a soil scientist with USDA ARS, Auburn, Alabama. **Brian J. Wienhold** is a soil scientist with USDA ARS, Lincoln, Nebraska. **Brian L. Woodbury** is an agricultural engineer with USDA ARS, Clay Center, Nebraska. **J. Mark Powell** is a soil scientist with USDA ARS, Madison, Wisconsin.

Hadas et al. (1983) reported on the effects of pelleting, temperature, and soil type on mineral N release from poultry and dairy manures. They described mineralization kinetics of manures in soil as occurring by an initial rapid process followed by a slow release of mineral N, which could be described as two simultaneous first-order reactions.

A number of parameters affect N mineralization of animal wastes including soil temperature, soil moisture (which relates to soil texture), and in upland soils, pH (McLaren 1969; Sabey et al. 1969; Mahli and McGill 1982; McInnes and Fillery 1989). Hadas et al. (1983) showed that the accumulation of NH_4-N during the early stages of aerobic incubation, indicative of organic N mineralization, increased with incubation temperature. Stark (1996) provided estimates of nitrification rate for two California oak woodland-annual grassland soils over a broad range of temperatures (5°C to 50°C [41°F to 122°F]), with maximal rates occurring in the range 30°C to 35°C (86°F to 95°F). Grundmann et al. (1995) conducted a similar assessment on a French alfisol but found optimal temperatures to be 20°C to 25°C (68°F to 77°F).

The impact of soil water on N transformations is varied and in many cases has been related to the experimental procedures employed. Numerous incubation experiments have held soil water content constant at different levels. Stanford and Epstein (1974) concluded that N mineralization was a linear function of soil water content when between 0.33 and 15 bars (field capacity to wilting point), although there was a clear interaction with soil type. The effects of fluctuating soil water content have been more difficult to assess. In general, drying soil to air-dry status, followed by rewetting, commonly causes a flush of N (and C) mineralization (Birch 1964; Cabrera 1993). This can be attributed to the biocidal effects of desiccation on soil microorganisms.

Amounts and rates of N mineralized from BL or other animal wastes have been related to soil texture. Chae and Tabatabai (1986) compared the percentage of organic N mineralized from BL added to five soils (with pH values ranging from 5.1 to 7.6) and found that mineralization varied widely among textures. Using 12 acid surface soils ranging in texture from sandy loam to silty clay, Lyngstad (1992) reported that amounts of N mineralized during a four-week incubation period varied greatly among soils. Griffin et al. (2002) found that under conditions that are near-optimal for mineralization and nitrification (20°C to 30°C [68°F to 86°F] and soil water content at 50% to 65% water-filled pore space), textural differences influenced the availability of applied BL N. They concluded that variations in soil texture that result in differences in soil water content or aeration may confound attempts to estimate the rate and extent of N transformations as influenced by texture. Thomsen and Olesen (2000) found that increased sand content generally led to increased C and N mineralization from manures, presumably due to both increased aeration in sandy soils and increased physical protection of C and N substrates as the soil clay content increased.

Castellanos and Pratt (1981) incubated several animal manures in a San Emigdio fine sand and Holtville silty clay and reported more N mineralized in the fine sand for all types of manures. After incubating three BLs and two turkey litters on one loam and two loamy sand soils, Westerman et al. (1988) noted that more N was mineralized from the loamy sand soils for all litters. Sorensen and Jensen (1995) found increasing net N immobilization with increasing clay concentrations, and in a related study using N from sheep urine, found more N immobilization in a sandy loam compared to a sandy soil. Egelkraut et al. (2000) reported that soils with higher clay concentrations had longer time periods of initial N immobilization and mineralized less N from added residues than those with lower clay concentrations.

A limited amount of research has been conducted on N mineralization from BL in southeastern Coastal Plain soils. Tyson and Cabrera (1993) conducted a study on N mineralization in soils amended with composted and uncomposted poultry litter. Their results indicated that composted poultry litter released N more slowly than uncomposted poultry litter and therefore posed less environmental risk than uncomposted poultry litter. Gordillo and Cabrera (1997) applied the same BL to nine soils, and measured net N mineralization over 146 days. Both the rate and extent of mineralization of BL showed a strong positive correlation with sand content of the soil, and a strong negative correlation with silt plus clay content. Mitchell and Tu (2006) conducted experiments on nutrient accumulation and movement from poultry litter at a Coastal Plain site in Alabama. They found that long term application of BL as a source of N maintained or increased soil pH and also increased soil concentrations of C, Ca, Mg, P, K, NH_4-N, and NO_3-N.

The objective of this study was to determine in-field mineralization of organic N from BL in Coastal Plain soils under natural weather variables (rainfall, solar radiation, wind, and air and soil temperatures). The primary variable for the study was soil texture. Under naturally occurring conditions soil microclimate in response to weather variables is largely affected by soil texture. The null hypothesis for the study was that N mineralization from BL in Coastal Plain soils is not affected by differences in soil texture. We selected soils with surface textures representing the range commonly found in Coastal Plain agricultural soils—very sandy or very clayey. In addition to measuring in-field mineralization of BL organic N, we measured soil C, N, and C:N ratios in the BL amended and unamended soils over time. The objective of this task was to evaluate increases in soil C and N associated with addition of BL. Increases in C levels improve soil quality, and C sequestration in soil is of scientific and societal interest. Determination of N increases in soils from BL is important for both crop production and environmental quality concerns. Information from the study is needed to assist poultry producers/land managers in selecting proper rates and timing when using BL as a soil amendment/fertilizer to both meet crop N needs and to increase soil C, while minimizing negative environmental impacts on soil and water quality.

Materials and Methods

Soils. The study was conducted at two Georgia Coastal Plain sites having different soil types. The study was part of a larger ARS mineralization research project with sites located in multiple states including Alabama, Georgia, Kentucky, Maine, Nebraska, Oregon, and Wisconsin with measurements being made in different calendar years. In 2004, BL N mineralization was determined on a Tifton loamy sand (fine-loamy, kaolinitic, thermic Plinthic Kandiudults) at a site located near Tifton, Georgia (figure 1). In 2005, BL N mineralization was determined on a Greenville sandy clay loam (fine, kaolinitic, thermic Rhodic Kandiudults) at a site located near Dawson, Georgia. The Tifton soil is characteristic of loamy plinthic soils having

Table 1
Properties of soils used.

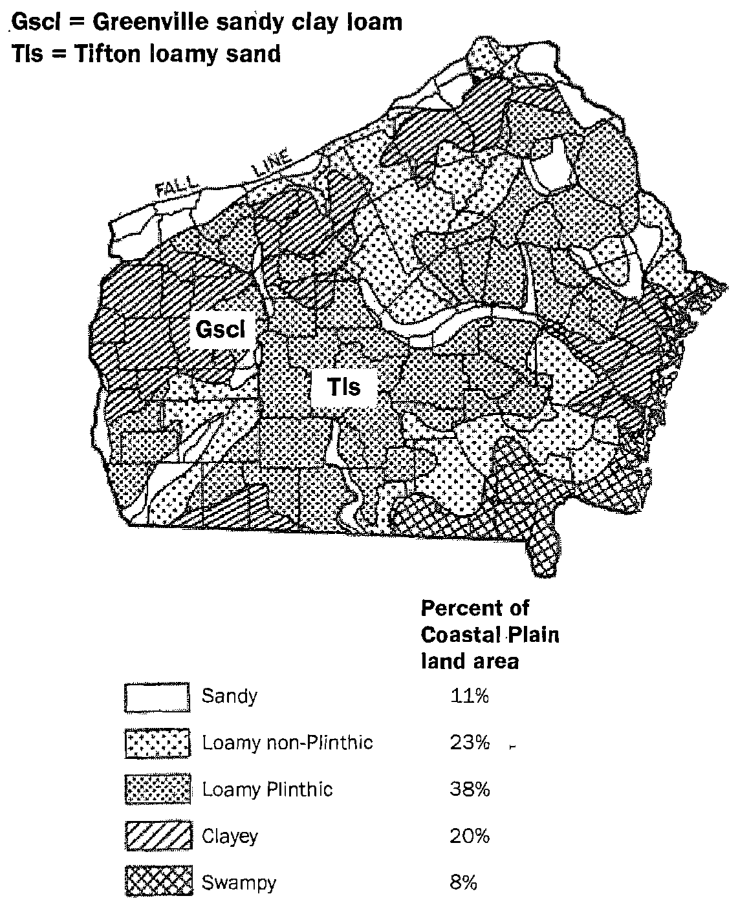
Series	Taxonomic class	pH	Total carbon (g kg^{-1})	Total nitrogen (g kg^{-1})	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})
Tifton	Fine-loamy, kaolinitic, thermic, Plinthic Kandiudults	5.8	5.2	0.3	900	60	40
Greenville	Fine, kaolinitic, thermic, Rhodic Kandiudults	5.1	6.2	0.4	670	100	230

Note: Surface texture measured on samples from 0 to 15 cm.

a very sandy A horizon, while the Greenville soil is characteristic of the clayey soils of the Georgia coastal plain (Hubbard et al. 1990). The Tifton soil contained 90% sand while the Greenville soil contained 23% clay (table 1). The two sites were about 80.45 km (50 mi) apart, with the Tifton site located in the Tifton Upland Physiographic Area while the Dawson site was located in the Dougherty Plain Physiographic Area. There was no record of either site having ever received BL. The study on the Tifton loamy sand was conducted from July to October 2004, while the study on the Greenville sandy clay loam was conducted from May to July 2005.

Broiler Litter. Broiler litter for each site was obtained from broiler operations located near Cairo, Georgia. The litter was scraped from the poultry houses by the operator and stacked for one/two months prior to use for our studies. The litter for the 2004 study was obtained on April 12, 2004, while that for the 2005 study was obtained on April 8, 2005. For each study we used the freshest BL available from our source. We did not retain BL from spring 2004 to use in 2005 because it would have been substantially deteriorated by that time. Each batch of BL was analyzed for chemical constituents (except for pH and total C) at the University of Georgia Soil Testing Laboratory in Athens, Georgia (table 2). Total C and pH were measured at the Southeast Watershed Research Laboratory, Tifton, Georgia. Total N at the University of Georgia laboratory was determined by the Dumas method (Bremner and Mulvaney 1982). All other elements at the University of Georgia were determined by inductively coupled plasma analysis after digestion with nitric and hydrochloric acid. Detailed laboratory procedures for the University of Georgia Soil Testing Laboratory can be found online (University of Georgia 1996). At the Tifton laboratory a 1:1 litter to water ratio was used for pH determination. Total C was measured at Tifton according to the method of Nelson and Sommers (1996) with samples ball milled and then analyzed on a Carlo Erba NA 1500 Series 2 nitrogen/carbon analyzer. Total N content of the BL was used when calculating application rates according to the experimental protocol.

Figure 1
Site diagram showing study site locations on soils map of the Georgia Coastal Plain according to textural groupings (from Hubbard et al. 1990).



Note: The symbols are shown on the map at the approximate locations where the studies were conducted.

Experimental Protocol. The study followed the protocol for the field component of the ARS mineralization study as described in detail by Honeycutt et al. (2005). Ninety-six cylinders (15.2-cm [6-in] long by 7.6-cm [3-in] diameter) made of Schedule 40 PVC pipe were installed on the Tifton soil in April 2004 and on the Greenville soil in April 2005 using a completely randomized design. Randomization at each site was used to minimize possible soil variability effects on N mineralization. The cylinders were gently driven into the soil with an impact hammer so as to contain minimally disturbed cores.

Table 2

Chemical properties of the broiler litter used in the experiments.

Soil	Tifton loamy sand	Greenville sandy clay loam
Year	2004	2005
Percent moisture (%)	15.1*	19.0
pH	8.4†	8.5
TN (%)	2.6	2.7
Ammonium N (%)	0.2	0.5
Nitrate N (%)	0.03	0.01
TC (%)	26.5	27.6
C:N ratio	10.3	10.4
P_2O_5 (%)	3.0	2.2
K_2O (%)	2.9	2.4
Ca (%)	2.1	1.6
Mg (%)	0.5	0.4
S (%)	0.4	0.4
Mn (ppm)	378	383
Fe (ppm)	3,270	4,468
Al (ppm)	5,804	4,465
B (ppm)	41.6	63.4
Cu (ppm)	351	506
Zn (ppm)	268	274
Na (ppm)	4,890	5,064

* Percent moisture was calculated relative to oven dry weight of the litter.

† Values reported are the means of two litter samples analyzed for each mineralization test.
All samples were analyzed at the Soil, Plant, and Water Laboratory of the University of Georgia, except for total carbon percent and pH, which were analyzed at the Southeast Watershed Research Laboratory, USDA Agricultural Research Service. Results from the University of Georgia laboratory are reported on an as-received wet basis. Results from the Southeast Watershed Research Laboratory have been corrected for moisture content.

The cores remained in the field on the Tifton soil for about three months and on the Greenville soil for about one month before application of BL. This allowed for natural rainfall and drying over time to minimize any disturbance to the cores caused when the cylinders were driven into the soil. Cylinders were carefully excavated from each site and brought to the laboratory where the treatments were applied. The cylinders were then immediately returned to the same field and placed into a new set of holes at the start of each study.

There were two treatments: amendment with BL and no BL amendment. For the amendment with BL treatment, calculations were made based on BL N contents so that each core received sufficient BL to supply 350 kg N per ha-furrow-slice (312.55 lb N per ac-furrow-slice). This amounted to applying the equivalent of approximately 15 mg N kg^{-1} soil (0.015%) from the BL to the entire core. Approximately 2.5 cm (1 in) of soil was removed from the top of each core, the BL was mixed with it, and then this mixture was returned to the top of the core. For the treatments with no BL, the same depth of soil was excavated from the core, mixed, and then returned to the core without BL so that all cores received similar disturbance. At the same time as BL amendment (or no amendment) anion exchange resin beads (Anion Exchange Resin, IONAC A-554, Cl^- Form, Type II, Beads [16-50 Mesh]) contained in cloth bags were placed at the bottom of each core. These were held in place at the bottom of each cylinder using plastic caps with drainage holes. The purpose of the anion resin beads was to capture NO_3-N leaching through the soil. The basic design was six replicates of each treatment (with or without BL amendment) and eight sampling dates following experiment initiation. Twelve cylinders (six amended with BL and six without BL) were collected from each site and returned to the laboratory at 0, 3, 7, 14, 21, 28, 49, and 70 days after BL amendment. The sampling days (dates when 12 cylinders were removed from the field and transported to the laboratory for analyses) on the Tifton soil were July 23, July 26, July 30, August 6, August 13, August 20, September 10, and October 1, 2004, while the sampling days for the Greenville soil were May 17, May 20, May 24, May 31, June 7, June 14, July 5, and July 26, 2005.

Precipitation. Precipitation was monitored at each site at nearby climate stations. At the Tifton site, precipitation was collected from the Little River Natural Resources Conservation Service Soil Climate Analysis Network site. The Soil Climate Analysis Network site (No. 2027) was located approximately 3,500 m (11,500 ft) northeast of the Tifton study location. At the Greenville site, precipitation data was collected from the Georgia Automated Environmental Monitoring Network site at the Hooks-Hanner Environmental Resource Center. The Automated Environmental Monitoring Network climate station was located approximately 100 m (328 ft) southeast of the study site. At both the Soil Climate Analysis Network and Automated Environmental Monitoring Network stations, precipitation was measured using tipping-bucket rain gauges.

Soil Temperature and Moisture. Soil temperature and moisture were monitored at each site. Four sets of type-T (copper-constantan) thermocouples were used to monitor soil temperature. Soil temperature was monitored both within a set of cores designated for that purpose and in the surrounding soil. At the Tifton site the Little River Scan Site moisture monitor at 5 cm (2 in) depth was used to measure soil moisture. At the Greenville site Model 223 Delmhorst cylindrical gypsum soil moisture blocks were used to indicate soil moisture. Blocks were placed both within a set of cores designated for that purpose and in the surrounding soil. Monitoring of soil temperature at both sites and soil moisture at the Tifton site was accomplished using a Campbell Scientific CR10X datalogger. Volumetric soil moisture content was expressed from soil moisture release curves for each soil type. These curves were determined using standard methods for Tempe Cells and pressure plates (Hubbard et al. 1985).

Laboratory Analyses. On each sampling date, 12 cores were removed from the field, packed in ice, and transported to the laboratory for extraction and analyses. The soil in each core was removed, mixed thoroughly (in moist condition), and thereafter duplicate samples (20 g [0.044 lb]) were taken. The soil samples were extracted with 100 ml

(3.38 oz) of 2 M KCl (Keeney and Nelson 1982). On the other hand, the cloth bags containing the anion exchange resin beads were slit and the beads were extracted with 250 ml (8.44 oz) of 2 M KCl. The extractants were analyzed for NH_4-N and NO_3-N (soil samples) or NO_3-N (anion exchange beads). When immediate extraction of the soils and beads was not feasible, they (both soils and beads) were immediately frozen and then extracted at a later time (generally within one week of sample colletion). Ammonium and NO_3-N were measured using standard methods (American Public Health Association 1989) on a Lachat Flow Injection Analyzer (QuikChem AE, Lachat Chemicals Inc., Milwaukee, Wisconsin). All subsample extractions were run in duplicate, and where substantial disagreement (greater than 10%) occurred, samples were reanalyzed. Two additional soil samples (1 g [0.002 lb] each) were taken from each core and ball milled before analyzes. Total C and N contents on the ball milled samples were determined using a Carlo Erba NA 1500 series 2 Nitrogen and Carbon Analyzer (Nelson and Sommers 1996). After each sampling, the remaining soil in the core was discarded.

Statistical Analyses. Overall analyses of variance for NH_4-N, NO_3-N, total inorganic N (sum of NH_4-N plus NO_3-N), total N and total C percentages, and C:N ratios found in the soil cores was determined using PROC GLM (Statistical Analysis Systems 1985). Statistical comparisons were made between treatments overall and by study day using the t-test least significant difference procedure of the General Linear Models at the 0.05 level of significance (Statistical Analysis Systems 1985).

Results and Discussion

Precipitation and Soil Moisture. On the Tifton soil (2004) measureable precipitation occurred on 24 of the 70 study days (figure 2). A major precipitation event occurred on study day 45, when over 15 cm (5.9 in) of precipitation was recorded. This large event was associated with Hurricane Frances, which made landfall near St. Mark's, Florida, on September 6, 2004, and then moved through Georgia as a tropical depression, causing extensive flooding (National Climatic Data Center 2004). On study days 65 to 66 the Tifton soil received 16 cm (6.3 in) of precipitation associated with Hurricane Jeanne.

Figure 2

Precipitation and volumetric soil moisture content at the Tifton loamy sand (ls) site by study day.

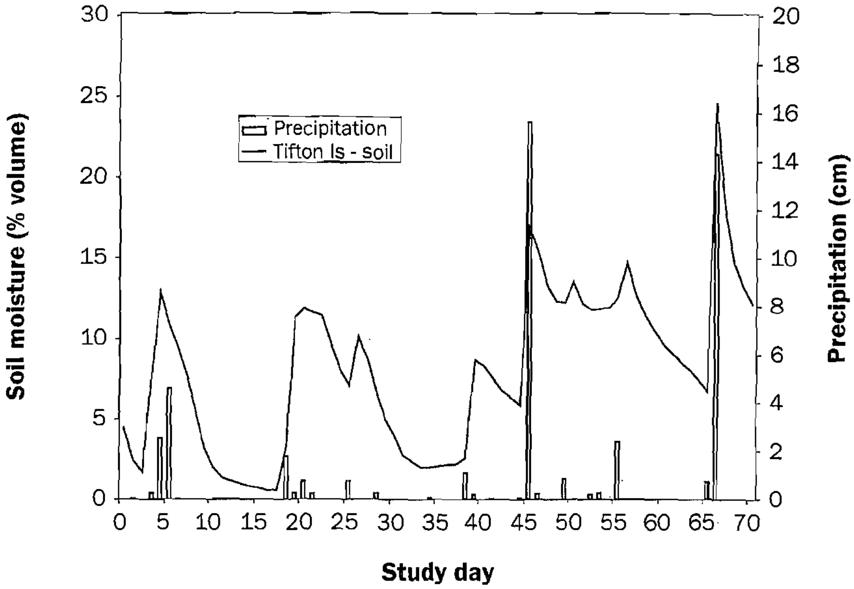
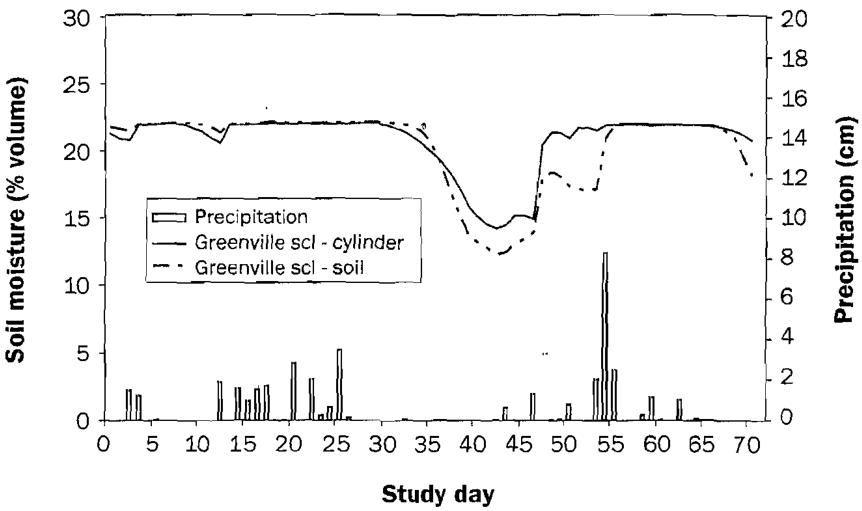


Figure 3

Precipitation and volumetric soil moisture content at the Greenville sandy clay loam (scl) site by study day.



Hurricane Jeanne made landfall at Stuart, Florida, near midnight on September 27, 2004, and then tracked across Georgia as a weakened tropical storm.

During the study, the Tifton volumetric soil moisture content varied from a low of 1% to a high of 25% (figure 2). Following several days with precipitation, the volumetric soil moisture content generally reached a range of 9% to 13%. The volumetric soil moisture content of the Tifton soil was much greater following the two hurricanes which each delivered more than 15 cm (5.9 in) of precipitation. The greatest volumetric soil moisture content measured was 25%, following Hurricane Jeanne on days 65 to 66. During the last 15 days of the study, days 45 to 70, the soil was wetter than during the earlier period (figure 2).

On the Greenville soil (2005), measurable

Figure 4
Soil temperature at the Tifton loamy sand (ls) site by study day.

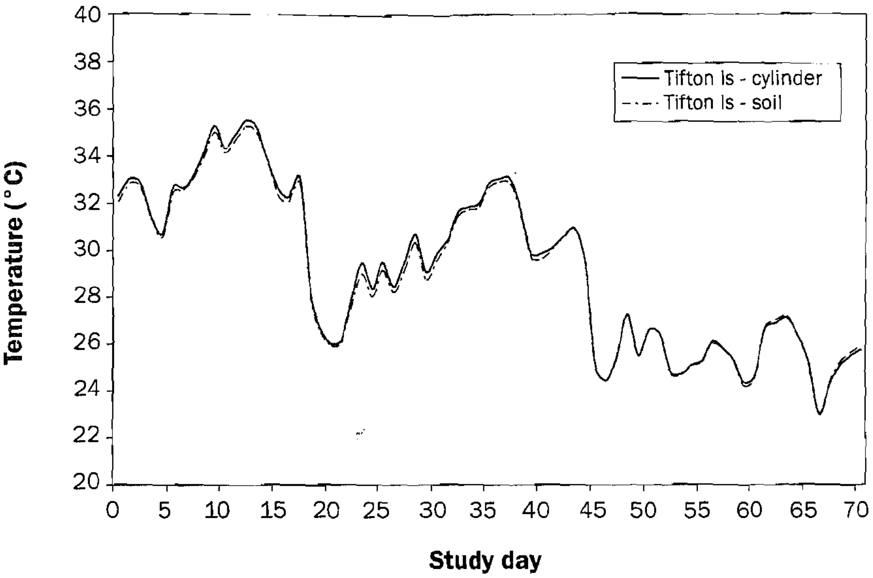
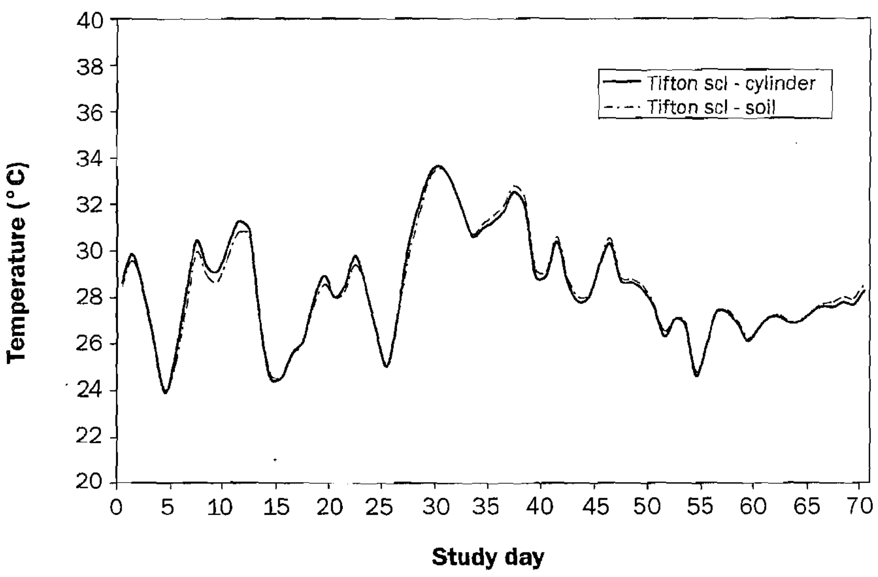


Figure 5
Soil temperature at the Greenville sandy clay loam (scl) site by study day.



precipitation occurred on 30 of the study days (figure 3). Greater precipitation levels occurred during study days 53 to 55, with all three days having rainfall in excess of 2 cm (0.8 in). The greatest amount occurred on study day 54, July 10, 2005, when about 8.25 cm (3.25 in) of precipitation was received in association with Hurricane Dennis. Hurricane Dennis made US landfall near Pensacola, Florida on July 10, as a category 3 storm (National Climatic Data Center 2005).

Comparison of the precipitation patterns between the two sites showed that the Tifton soil received less rainfall and was drier during the first 2/3 of the study than the Greenville soil, which had considerable precipitation from study days 12 through 25. Both soils were relatively wet during the last 1/3 of the study periods, with much of the precipitation coming from hurricanes. Also, measurements of volumetric soil moisture content both within cores and in the surrounding soil on the Greenville indicated that a micro effect occurred such that the soil in the cores stayed wetter than the surrounding soil.

Soil Temperature. Mean soil temperatures recorded during the 2004 study on the Tifton soil ranged from 23°C to 35°C (73°F to 95°F) (figure 4). Decreases in soil temperatures occurred during and following days with precipitation. The 2004 study was conducted in the late summer to early fall, and soil temperatures reflected summer heat followed by fall cooling plus the effects of the excessive precipitation from the two hurricanes. Grundmann et al. (1995) found optimum soil temperatures for mineralization to be 20°C to 25°C (68°F to 77°F), while Stark (1996) found optimum soil temperatures for mineralization to be 30°C to 35°C (86°F to 95°F). Temperatures in the Tifton soil ranged from 23°C to 35°C (73°F to 95°F), which spanned the optimum ranges for mineralization found by Grundmann et al. (1995) and Stark (1996).

In 2005, the study was conducted during the spring, and there was a 6°C (11°F) range in soil temperatures along with more variability than what was measured in the Tifton soil the previous summer (figure 5). The range in temperatures in the Greenville soil (24°C to 34°C [75°F to 93°F]) was also optimum for mineralization processes. After study day 36, both soils had very similar temperatures, even though one study was entering the fall months while the other was entering the late spring months.

Broiler Litter Mineralization in the Tifton soil. Statistical analyses of mean NH_4-N, NO_3-N and total inorganic N (sum of NH_4-N plus NO_3-N) concentrations in the Tifton soil revealed significant treatment differences between BL amendment and no amendment within each study day (table 3). Mean NH_4-N concentrations in the BL amended soil were significantly greater than those in the unamended soil on study days 0, 3, 7, and 14. Mean NH_4-N concentrations in the BL amended soil were greatest at the beginning of the study and decreased over time. By study day 21 there was no difference in mean NH_4-N concentrations between treatments, indicating that all of the NH_4-N from the BL had been nitrified during the first three weeks of the study. The mean

Table 3
Effects of broiler litter on nitrogen mineralization during a 70-day period (Tifton loamy sand).

Treatment	Day	NH_4-N (mg kg^{-1})	LSD (mg kg^{-1})	NO_3-N (mg kg^{-1})	LSD (mg kg^{-1})	Total inorganic N (mg kg^{-1})	LSD (mg kg^{-1})	Net inorganic N (mg kg^{-1})
Unamended	0	1.2b	0.7	0.0a	0.0	1.2b	0.7	6.2
BL amended	0	7.4a	0.7	0.0a	0.0	7.4a	0.7	
Unamended	3	1.0b	1.6	0.6b	2.6	1.7b	2.5	8.2
BL amended	3	5.9a	1.6	3.9a	2.6	9.9a	2.5	
Unamended	7	3.1b	0.7	10.5b	3.4	13.6b	3.5	11.7
BL amended	7	7.2a	0.7	18.2a	3.4	25.3a	3.5	
Unamended	14	3.2b	0.5	10.2b	5.5	13.4b	5.5	19.5
BL amended	14	6.4a	0.5	26.4a	5.5	32.9a	5.5	
Unamended	21	2.7a	0.1	15.4b	12.4	18.1b	12.4	32.2
BL amended	21	2.7a	0.1	47.5a	12.4	50.2a	12.4	
Unamended	28	2.6a	0.2	21.3b	10.9	23.9b	10.8	46.4
BL amended	28	2.6a	0.2	67.7a	10.9	70.4a	10.8	
Unamended	49	1.4a	0.1	23.7b	3.7	25.0b	3.7	6.8
BL amended	49	1.4a	0.1	30.4a	3.7	31.8a	3.7	
Unamended	70	0.9b	0.1	10.8b	4.5	11.7b	4.5	26.0
BL amended	70	1.1a	0.1	36.0a	4.5	37.1a	4.5	

Notes: Table values are means of six observations. Values are the cumulative N (NH_4-N, NO_3-N, or Total N) in the soil (or soil plus resin beads) from day 0 through the sampling day. NO_3-N = the sum of that in the soil and that captured by the resin beads. Total inorganic N = (NH_4-N + NO_3-N). Net inorganic N = broiler litter amended soil − broiler litter unamended soil. LSD = least significant difference. Statistical analyses were done within each study day. Where letters (a, b) are different, treatment means were significantly different at the 0.05 level.

NH_4-N concentration of the BL amended soil was significantly greater than that of the unamended soil on study day 70, but both values were very close numerically and in the same range as the values for the unamended soil at the start of the study.

Mean NO_3-N concentrations in the Tifton soil (calculated as the sum of those in the soil plus those captured by the resin beads) were zero on study day 0 for both the BL amended and unamended treatments and increased to a maximum of 67.7 mg N kg^{-1} soil (0.068%) for the BL amended cores on day 28 (table 3). Beginning with study day 3, there were statistically significant differences between mean NO_3-N concentrations in the BL amended soil as compared to those of unamended soil for all study days. The mean NO_3-N concentrations were greatest in the cores amended with BL.

Mean total inorganic N concentrations were significantly greater in the soil receiving BL amendment than in the unamended soil for all study days. Mean total inorganic N concentrations increased with study day for the BL amended soil until day 28, where a maximum of 70.4 mg N kg^{-1} soil (0.07%) was reached. For the cores not amended with BL, the greatest value was observed on study day 49.

The greatest net inorganic N, the difference between the cores amended with BL and those unamended, occurred on study day 28. Net inorganic N from the BL was lower on study days 49 and 70 as compared to study day 28. The decrease in net inorganic N in the Tifton soil found after study day 28 may be attributable to loss of NO_3-N from the soil by denitrification associated with wet soil conditions. Denitrification occurs under high water conditions (Maag and Vinther 1999). Our site received over 15 cm (5.9 in) of precipitation on study day 45 associated with Hurricane Frances. The site received another 16 cm (6.3 in) of precipitation when Hurricane Jeanne passed through the area on study days 65 to 66. Our soil moisture sensors showed that the cores were very wet following each of the hurricanes. From the net inorganic N concentration from study day 28 it can be concluded that on the Tifton soil the BL released 46.4 mg N kg^{-1} soil (0.046%) through mineralization processes.

Broiler Litter Mineralization in the Greenville soil. Statistical analyses of the mean NH_4-N, NO_3-N, and total inorganic N concentrations in the Greenville soil revealed differences by study day, primarily for the NH_4-N and total inorganic N (table 4). Statistical differences in mean soil NH_4-N concentrations between the BL amended and the unamended Greenville soil were found for all study days except day 70. Mean NH_4-N concentrations were always greater in the soils with BL amendment than in the unamended soils on study days 0 to 49. Mean NH_4-N concentrations increased in the BL amended soils from study days 0 through 21, and then decreased thereafter until there was no difference between BL amended and unamended soils on study day 70. The mean NH_4-N concentrations on day 70 were in the same range as those found for the unamended soil at the beginning of the study. Accumulation of NH_4-N in the soil, as indicated by the increasing mean NH_4-N concentrations on study days 3, 7, 14, and 21, indicated that the organic N from the BL was being converted to NH_4-N, but that the nitrification step of mineralization was not proceeding at a similar rate.

There were no significant differences in mean soil NO_3-N concentrations between treatments for study days 0 through 14. Statistical differences in mean soil NO_3-N concentrations between treatments occurred only on study days 21 and 28, when mean concentrations were greater in the unamended cores than in the BL amended cores. The lack of increase in mean NO_3-N concentrations over time in the Greenville soil can be explained by very slow nitrification of the NH_4-N to NO_3-N. It can also be

Table 4
Effects of broiler litter on nitrogen mineralization during a 70 day period (Greenville sandy clay loam).

Treatment	Day	NH_4-N (mg kg^{-1})	LSD (mg kg^{-1})	NO_3-N (mg kg^{-1})	LSD (mg kg^{-1})	Total inorganic N (mg kg^{-1})	LSD (mg kg^{-1})	Net inorganic N (mg kg^{-1})
Unamended	0	3.0b	7.2	14.3a	9.4	17.3b	10.6	23.6
BL amended	0	29.0a	7.2	11.8a	9.4	40.9a	10.6	
Unamended	3	1.8b	2.4	21.8a	11.9	23.6b	13.2	31.0
BL amended	3	34.7a	2.4	19.9a	11.9	54.5a	13.2	
Unamended	7	3.1b	8.8	18.5a	8.8	21.6b	13.6	26.5
BL amended	7	36.4a	8.8	11.7a	8.8	48.1a	13.6	
Unamended	14	1.4b	8.0	3.2a	7.3	4.6b	11.6	46.4
BL amended	14	45.4a	8.0	5.7a	7.3	51.1a	11.6	
Unamended	21	1.5b	3.4	20.1a	9.6	21.6b	9.3	23.0
BL amended	21	41.2a	3.4	3.4b	9.6	44.6a	9.3	
Unamended	28	1.5b	10.9	19.8a	8.9	21.3a	15.2	9.9
BL amended	28	24.4a	10.9	6.8b	8.9	31.2a	15.2	
Unamended	49	0.7b	8.4	15.6a	14.2	16.3a	15.4	8.3
BL amended	49	12.1a	8.4	12.5a	14.2	24.6a	15.4	
Unamended	70	1.5a	0.6	21.9a	11.9	23.4a	11.9	3.4
BL amended	70	1.7a	0.6	25.1a	11.9	26.8a	11.9	

Notes: Table values are means of six observations. Values are the cumulative N (NH_4-N, NO_3-N, or Total N) in the soil (or soil plus resin beads) from day 0 through the sampling day. NO_3-N = the sum of that in the soil and that captured by the resin beads. Total inorganic N = (NH_4-N + NO_3-N). Net inorganic N = broiler litter amended soil − broiler litter unamended soil. Statistical analyses were done within each study day. Where letters are different, treatment means were significantly different at the 0.05 level.

explained by denitrification of what NO_3-N was produced, rather than accumulation in the soil or trapping on the beads. The significantly lower mean NO_3-N concentrations in the BL amended soils than in the unamended soils on study days 21 and 28 indicated that denitrification associated with the BL was probably occurring. From study days 12 to 26, there were 11 days with precipitation, and 7 of these had amounts in excess of 1.5 cm (0.6 in). With a wet clayey soil and BL as a C source for the denitrifiers, the potential for denitrification would have been great.

Mean total inorganic N concentrations were significantly greater where BL was applied than in the unamended soil for study days 0 through 21. This was due to the NH_4-N fraction of total inorganic N being significantly greater where BL was applied. The greatest total inorganic N was found in the BL amended soil on study day 21.

Net inorganic N was greatest on study day 14 (46.4 mg N kg^{-1} soil [0.046%]). Although N released from the BL by mineralization on the Greenville soil was equal to that found on the Tifton, the pattern of BL mineralization was different, since nitrification was very delayed on the clayey soil, and NO_3-N was lost (presumably by denitrification) rather than retained in this soil.

Soil Carbon, Nitrogen, and C:N Ratios. Statistical analyses of percent total C and total N and C:N ratios in the Tifton loamy sand soil over all study days revealed significant treatment effects for all three parameters (table 5). No significant treatment by day effects were found for the three parameters. Over all study days, total C and total N were significantly greater with BL amendment while the C:N ratio was significantly greater when no BL was applied.

Statistical analyses of percent total C and total N and C:N ratios in the Greenville sandy clay loam showed significant treatment effects for all three parameters, but significant treatment by day effects only for total C and total N (table 6). Total C and total N percentages were greater on study days 0 and 3 for the soils receiving BL than for the unamended soils, but there were no treatment differences for the remainder of the study. The C:N ratio was always greater for the unamended soil than the BL amended soil, primarily because of the lower total N in the unamended soil. Total N levels in the soil were numerically greater with BL amendment for most sampling days until after study day 28. Similarly, there was more C in the soils for most sampling days until after study day 28.

The results for total C and total N percentages on both soils showed only very short term small increases due to amendment with BL. On the Tifton soil, there was no treatment by day effect, although over the whole time period, both percent total C and percent total N were statistically greater with BL amendment. On the Greenville soil percent total C and percent total N were statistically greater with BL amendment only on study days 0 and 3, although over the whole time period, both were greater with BL amendment. It must be concluded that one addition of BL to Coastal Plain soils does not greatly increase either soil C or N levels. It can be concluded that determination of C sequestration and increases in N in Coastal Plain soils due to BL amendment must be addressed through long term multiyear studies.

Comparison of Broiler litter Nitrogen Mineralization Between Soil Textures. The study showed differences in BL N mineralization rates between the two soils. In the sandy Tifton soil, mineralization processes were complete early in the study, by day 28, which had the greatest total inorganic N for the BL amended soil and net inorganic N difference between the two treatments (table 3). The NH_4-N depletion on the Tifton soil was complete by study day 21, while NO_3-N accumulated through day 28. On the clayey Greenville soil, NH_4-N from

Table 5
Variations in total soil carbon and nitrogen contents and C:N ratios during a 70-day study period as affected by broiler litter (BL) treatments (Tifton loamy sand).

	Total carbon			Total nitrogen			C:N ratio		
Day after application	No BL (%)	BL (%)	LSD (%)	No BL (%)	BL (%)	LSD (%)	No BL	BL	LSD
0	0.522	0.720	0.213	0.029	0.040	0.017	19.6	18.2	4.5
3	0.632	0.696	0.211	0.026	0.035	0.012	24.7	20.1	2.6
7	0.572	0.630	0.151	0.027	0.035	0.011	21.4	18.6	2.3
14	0.547	0.570	0.158	0.029	0.032	0.008	19.8	17.1	1.3
21	0.588	0.777	0.225	0.032	0.044	0.011	18.7	17.5	2.0
28	0.577	0.654	0.062	0.032	0.042	0.002	17.9	15.4	1.7
49	0.564	0.611	0.134	0.026	0.032	0.005	21.8	18.8	2.5
70	0.521	0.573	0.104	0.028	0.034	0.006	18.4	16.8	1.9
Mean	0.568b	0.650a	0.052	0.028b	0.037a	0.003	20.3a	17.8b	0.8

Notes: Total soil carbon and nitrogen contents and C:N ratios were statistically compared within study days between treatments using ANOVA. Where letters (a, b) are the same, treatment means are not significantly different at the 0.05 level. LSD = least significant difference.

Table 6
Variations in total soil carbon and nitrogen contents and C:N ratios during a 70-day study period as affected by broiler litter (BL) treatments (Greenville sandy clay loam).

	Total carbon			Total nitrogen			C:N ratio		
Day after application	No BL (%)	BL (%)	LSD (%)	No BL (%)	BL (%)	LSD (%)	No BL	BL	LSD
0	0.607b	0.914a	0.217	0.042b	0.076a	0.017	14.5	12.1	1.0
3	0.643b	0.847a	0.173	0.044b	0.063a	0.012	14.6	13.4	0.8
7	0.615a	0.678a	0.306	0.041a	0.054a	0.022	15.0	12.4	0.9
14	0.790a	0.712a	0.224	0.054a	0.054a	0.016	14.6	13.2	0.8
21	0.739a	0.845a	0.232	0.047a	0.062a	0.016	15.7	13.5	0.8
28	0.600a	0.802a	0.232	0.040b	0.061a	0.016	15.0	13.1	1.5
49	0.621a	0.572a	0.180	0.040a	0.043a	0.011	15.6	13.1	1.0
70	0.738a	0.672a	0.196	0.046a	0.048a	0.013	16.4	13.9	1.0
Mean	0.669b	0.755a	0.070	0.044b	0.058a	0.005	15.2a	13.1b	0.3

Notes: Total soil carbon and nitrogen contents and C:N ratios were statistically compared within study days between treatments using ANOVA. Where letters (a, b) are the same, treatment means are not significantly different at the 0.05 level. For C:N ratio there was no significant interaction between treatment and study day, although treatments were significantly different overall as shown by the mean values. LSD = least significant difference.

the BL accumulated up to about day 21, and then was not depleted to background levels until day 70 (table 4). The greatest net inorganic N on the Greenville soil occurred on day 14, although this value mostly reflected the NH_4-N accumulation in the BL amended soil. The net inorganic N from BL mineralization was identical for both soils, 46.4 mg N kg^{-1} soil (0.046%) (tables 3 and 4).

The primary difference in N mineralization processes between the two soils was that the nitrification step occurred much later in the clayey soil than in the sandy soil. Since this was a field experiment (we did not control soil temperature or moisture) microclimate varied between the two soils. Microclimate is known to affect N mineralization, so the observed differences in N mineralization processes cannot be attributed only to soil textural differences. Two soil microclimate variables which strongly affect N mineralization are temperature and moisture. Comparison of soil temperatures between the two soils for the first 21 study days (the period when NH_4-N accumulated in the Greenville soil) showed that the temperature of the Tifton soil was more uniform than that of the Greenville soil (figures 4 and 5). The temperature of the Tifton soil ranged from 31°C to 35°C (88°F to 95°F) until about study day 18, when it dropped to 26°C (79°F). It mostly stayed between 33°C and 35°C (91°F and 95°F) for the first 18 days of the study. In contrast, the Greenville soil temperature ranged from 24°C to 31°C (75°F to 80°F) and reached a low of 24°C (75°F) twice during this period. Part of the observed delayed nitrification in the Greenville soil as compared to the Tifton soil could have been related to lower temperatures, since microbial activity increases with soil temperature. However, Stark (1996) gave 30°C to 35°C (86°F to 95°F) as the range for maximal nitrification rates, while Grundman (1995) found optimal temperatures to be 20°C to 25°C (68°F to 77°F). Although soil temperature differences may have had some involvement in the delayed nitrification observed on the Greenville soil, these differences don't appear to be great enough to be the primary cause for the delay.

Examination of the moisture records of the two soils (figures 2 and 3) for the first 21 days shows that the Tifton soil had lower moisture

content than the Greenville soil, and that the Tifton soil went through two wetting and drying cycles. In contrast, the Greenville soil stayed uniformly wet for the first 21 days of the study. Stanford and Epstein (1974) concluded that N mineralization was a linear function of soil water content between field capacity and wilting point, which implies that mineralization (including nitrification) should have occurred more rapidly on the wetter clayey soil (Greenville) than on the sandy soil (Tifton). However, both Birch (1964) and Cabrera (1993) found that drying soil to air-dry status, followed by rewetting, commonly causes a flush of N mineralization, and the Tifton soil experienced the drying followed by wetting twice during the first 21 days of the study. Griffin et al. (2000) found that variations in soil water content or aeration due to soil textural differences may confound attempts to estimate rate and extent of N transformation. Egelkraut (2000) reported that soils with higher clay concentrations had longer periods of initial N immobilization and mineralized less N from added residues than those with lower clay concentrations. Thomsen and Olesen (2000) found that increased sand content generally led to increased C and N mineralization from manures, presumably due to both increased aeration in sandy soils and increased physical protection of C and N substrates as the soil clay content increased.

Although differences in soil temperatures between the two soils during the first 21 study days occurred, with the clayey soil having somewhat lower temperatures than the sandy soil, differences in soil moisture were much greater. Hence it appears most likely that the combination of soil textural and moisture microclimate effects played a greater role than temperature in the differences in N mineralization rates and timing found between the two soils. Since the clayey Greenville soil remained uniformly wet for the first 21 days of the study, the BL would also have been protected by the clay particles, while the wetting and drying in the Tifton soil would have both exposed the BL to microbial populations and contributed to the flush in N mineralization observed by both Birch (1964) and Cabrera (1993). If the Tifton soil had received the same rainfall as the Greenville soil, it still would not have had as wet a soil microclimate as the clayey soil, due to the lower moisture holding capacity of sands as compared to clays, and the BL residues would not have been as protected from microbial action as in the clayey soil.

The second main difference in N mineralization processes between the two soil textures was that NO_3-N never accumulated in the clayey soil. With nitrification occurring later, and a C source from the BL, significant denitrification in the Greenville soil apparently occurred. Gordillo and Cabrera (1997) and Thomsen and Olesen (2000) found increased rates of N mineralization of manure N on sandy soils and decreased rates on clayey soils. We found delayed nitrification on the clayey soil, which, if mineralization is considered incomplete until the organic N has been converted to NO_3-N, is consistent with their findings. From a farmer or land management perspective we can conclude from our study that NO_3-N from BL mineralization generally becomes available faster on sandy than on clayey Coastal Plain soils. Enhanced probability for denitrification on clayey soils under wet conditions, with the C from BL providing an energy source for the denitrifiers, may also mean that N from BL is less available on the clayey than on the sandy soils.

Summary and Conclusions

A study was conducted to determine BL mineralization rates on southeastern Coastal Plain soils. Two soil series were selected to represent the sandy to clayey range commonly found in agronomic soils. The standardized field protocol of the Agricultural Research Service mineralization team was used. Soil cores were amended with BL (or no BL), returned to the field, and NO_3-N, NH_4-N, total N, total C, and C:N ratios in the cores were measured from study days 0 to 70. The study on the sandy soil was conducted during late summer 2004, while that on the clayey soil was conducted during late spring to early summer 2005. Patterns in N mineralization were examined using total concentrations of NO_3-N and NH_4-N in these soils. The soils were also analyzed for total N, total C, and C:N ratios to determine increases over time associated with amendment with BL.

Soil temperatures at both sites were in ranges reported as optimal for mineralization. Both sites were affected by excessive precipitation from hurricanes during the 70-day study period. Two hurricanes occurred during the latter part of the 2004 study (Frances and Jeanne) while one (Dennis) occurred about 2/3 of the way through the 2005 study. Volumetric soil moisture content was greater on the clayey soil than on the sandy soil.

Using net inorganic N, the difference between total inorganic N in the BL amended soil and that in the unamended soil, it was determined that mineralized N from the BL was identical for both soils, 46.4 mg N kg^{-1} soil (0.046%). Mineralization to NO_3-N was complete in the sandy soil by 28 days. However, in the clayey soil, nitrification was delayed, such that NH_4-N accumulated in the soil for the first 21 days. It then declined to background levels by study day 70, but NO_3-N did not accumulate in this soil, most likely due to denitrification under wet conditions with C for the denitrifiers supplied by the BL. Soil textural and microclimate differences along with greater protection of the BL residues in the clayey than in the sandy soil are all believed to have contributed to the observed differences in N mineralization between the two soils. Previous research has shown a positive correlation for mineralization of organic N with sand content of the soil and a negative correlation with clay content; results from this study concurred with those findings.

The study showed that as compared to carefully controlled laboratory studies, where good correlations between variables including temperature, moisture, and texture can be obtained, that multiple variables strongly affect results under field conditions. However, it can be concluded from this study that there is a high probability that BL mineralization rates will be significantly slower on the more clayey Coastal Plain soils than on very sandy ones, and that farm managers should take these rates into consideration when planning timing and amounts of BL applications.

Acknowledgements

The authors thank our technicians: Bobby Shiver, Regina Hornbuckle, DeeAnn Webb, and Lorine Lewis for their support during this study. Mention of trade names or commercial products in this article is solely for the purpose of providing specific information, and does not imply recommendation or endorsement by the USDA.

References

American Public Health Association. 1989. Standard Methods for Examination of Water and Wasteweater., 17th ed. Washington, DC: American Public Health Association.

Birch, H.F. 1964. Mineralisation of plant nitrogen following alternate wet and dry conditions. Plant and Soil 20(1):43-49.

Boatright, S.R., and J.C. McKissick. 2006. 2005 Georgia Farm Gate Value Report. The University of Georgia, College of Agricultural and Environmental Sciences. AR-06-01.

Cabrera, M.L. 1993. Modeling the flush of nitrogen mineralization caused by drying and rewetting soils. Soil Science Society of America Journal 57(1):63-66.

Castellanos, J.Z., and P.F. Pratt. 1981. Mineralization of manure nitrogen-correlation with laboratory indexes. Soil Science Society of America Journal 45(2):354-357.

Chae, Y.M., and M.A. Tabatabai. 1986. Mineralization of nitrogen in soils amended with organic wastes. Journal of Environmental Quality 15(2):193-198.

DeBusk, W.F., J.R. White, and K.R. Reddy. 2001. Carbon and nitrogen dynamics in wetland soils. Chapter 3. *In* Modeling carbon and nitrogen dynamics for soil management, ed. M.J. Shaffer, L. Ma, and S. Hansen. Lewis Publishers.

Egelkraut, T.M., D.E. Kissel, and M.L. Cabrera. 2000. Effect of soil texture on nitrogen mineralized from cotton residues and compost. Journal of Environmental Quality 29(5):1518-1522.

Gale, P.M., and J.T. Gilmour. 1986. Carbon and nitrogen mineralization kinetics for poultry litter. Journal of Environmental Quality 15(4):423-426.

Gascho, G.J., R.K. Hubbard, T.B. Brenneman, A.W. Johnson, D. Sumner, and G.H. Harris. 2001. Effects of broiler litter in an irrigated, double-cropped, conservation-tilled rotation. Agronomy Journal 93(6):1315-1320.

Gordillo, R.M., and M.L. Cabrera. 1997. Mineralizable nitrogen in broiler litter. II. Effect of selected soil characteristics. Journal of Environmental Quality 26(6):1679-1686.

Griffin, T.S., C.W. Honeycutt, and Z. He. 2002. Effects of temperature, soil water status, and soil type on swine slurry nitrogen transformations. Biology and Fertility of Soils 36(6):442-446.

Grundmann, G.L., P. Renault, L. Rosso, and R. Bardin. 1995. Differential effects of soil water content and temperature on nitrification and aeration. Soil Science Society of America Journal 59(5):1342-1349.

Hadas A., B. Bar-Yosef, S. Davidov, and M. Sofer. 1983. Effect of pelleting, temperature, and soil type on mineral nitrogen release from poultry and dairy manures. Soil Science Society of America Journal 47(6):1129-1133.

Honeycutt, C.W., T.S. Griffin, B.J. Wienhold, B. Eghball, S.L. Albrecht, J.M. Powell, B.L. Woodbury, K.R. Sistani, R.K. Hubbard, H.A. Torbert, R.A. Eigenberg, R.J. Wright, and M.D. Jawson. 2005. Protocols for nationally coordinated laboratory and field research on manure nitrogen mineralization. Communications in Soil Science and Plant Analysis 36(19-20):2807-2822.

Hubbard, R.K., L.E. Asmussen, and H.F. Perkins. 1990. Use of ground-penetrating radar on upland Coastal Plain soils. Journal of Soil and Water Conservation 45(3):399-405.

Hubbard, R.K., C.R. Berdanier, H.F. Perkins, and R.A. Leonard. 1985. Characteristics of Selected Upland Soils of the Georgia Coastal Plain. ARS-37. USDA Agricultural Research Service.

Keeney, D.R., and D.W. Nelson. 1982. Nitrogen: Inorganic forms. *In* Methods of Soil Analysis. Part 2. 2nd ed. Agronomy Monograph 9, ed. A.L. Page et al., 643-698. Madison, WI: ASA and SSSA.

Kingery, W.L., C.W. Wood, D.P. Delaney, J.C. Williams, and G.L. Mullins. 1994. Impact of long-term land application of broiler litter on environmentally related soil properties. Journal of Environmental Quality 23(1):139-147.

Lyngstad, I. 1992. Effect of liming on mineralization of soil nitrogen as measured by plant uptake and nitrogen released during incubation. Plant and Soil 144(2):247-253.

Maag, M., and F.P. Vinther. 1999. Effect of temperature and water on gaseous emissions from soils treated with animal slurry. Soil Science Society of America Journal 63(4):858-865.

Mahli, S.S., and W.B. McGill. 1982. Nitrification in three Alberta soils: Effect of temperature, moisture and substrate concentration. Soil Biology and Biochemistry 14(4):393-399.

McInnes, K.J., and I.R.P. Fillery. 1989. Modeling and field measurements of the effect of nitrogen source on nitrification. Soil Science Society of America Journal 53(4):1264-1269.

McLaren, A.D. 1969. Steady state studies of nitrification in soil: Theoretical considerations. Proceedings of Soil Science Society of America 33(2):273-275.

Mitchell, Charles C., and Shuxin Tu. 2006. Nutrient accumulation and movement from poultry litter. Soil Science Society of America Journal 70(6):2146-2153.

Nahm, K.H. 2005. Factors influencing nitrogen mineralization during poultry litter composting and calculations for available nitrogen. World's Poultry Science Journal, 61(2):238-255.

National Climatic Data Center. 2004. Climate of 2004 Atlantic Hurricane Season. http://www.ncdc.noaa.gov/oa/climate/research/2004/hurricanes04.html.

National Climatic Data Center. 2005. Climate of 2005 Atlantic Hurricane Season. http://www.ncdc.noaa.gov/oa/climate/research/2005/hurricanes05.html.

Nelson, D.W., and L.E. Sommers. 1996. Chapter 34. Total carbon, organic carbon, and organic matter. In Methods of Soil Analysis Part 3. Chemical Methods SSSA and ASA Book Series 5.

Sabey, B.R., L.R. Frederick, and W.V. Bartholomew. 1969. The formation of nitrate from ammonium nitrogen in soils. IV. Use of the delay and maximum rate phases for making quantitative predictions. Proceedings of Soil Science Society of America 33(2):276-278.

Statistical Analysis Systems. 1985. Statistical Analysis Systems User's Guide: Basics. Cary, NC: Statistical Analysis Systems Institute, Inc.

Sharpley, A.N., S.J. Smith, and W.R. Bain. 1993. Nitrogen and phosphorus fate from long-term poultry litter applications to Oklahoma soils. Soil Science Society of America Journal 57(4):1131-1137.

Sorensen, P., and E.S. Jensen. 1995. Mineralization-immobilization and plant uptake of nitrogen as influenced by the spatial distribution of cattle slurry in soils of different texture. Plant and Soil 173(2):283-291.

Stanford, G., and E. Epstein. 1974. Nitrogen mineralization-water relations in soils. Proceedings of Soil Science Society of America 38(1):103-107.

Stark, J.M. 1996. Modeling the temperature response of nitrification. Biogeochemistry 35(3):433-445.

Thomsen, I.K., and J.E. Olesen. 2000. C and N mineralization of composted and anaerobically stored ruminant manure in differently textured soils. Journal of Agricultural Science 135(2):151-159.

Tyson, S.C., and M.L. Cabrera. 1993. Nitrogen mineralization in soils amended with composted and uncomposted poultry litter. Communications in Soil Science and Plant Analyses 24(17-18):2361-2374.

University of Georgia. 1996. Methods for the analysis of Soil, Plant, Water, and Environmental Samples. http://aesl.ces.uga.edu/protected/methods/details/stl-litter/1.html.

Vest, L., B. Merka, and W.I. Segars. 1996. Poultry waste: Georgia's 50 million dollar forgotten crop. Athens, GA: Georgia Cooperative Extension Leaflet 206.

Westerman, P.W., L.M. Safley, Jr., and J.C. Barker. 1988. Available nitrogen in broiler and turkey litter. Transactions of the American Society of Agricultural Engineers, 31(4):1070-1075.

Wood, B.H., K.S. Yoon, D.P. Delaney, C.W. Wood, and K.H. Yoo. 1996. Nutrient accumulation and nitrate leaching under broiler litter amended corn fields. Communications in Soil Science and Plant Analysis 27(15-17):2875-2894.