# Bermudagrass Management in the Southern Piedmont USA: VI. Soil-Profile Inorganic Nitrogen

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## ABSTRACT

**Fate of applied N in forage-based agricultural systems is important to long-term production and environmental impacts. We evaluated the factorial combination of N fertilization targeted to supply 20 g N $m^{-2}$ $yr^{-1}$ and harvest strategies on soil-profile inorganic N during the first 5 yr of 'Coastal' bermudagrass [*Cynodon dactylon* (L.) Pers.] management. Harvest strategy had much larger effects than fertilization strategy, most notably that soil-profile inorganic N was lower when hayed than under other systems. In the upper rooting zone (0- to 0.3-m depth), soil inorganic N (initially at 3.1 g $m^{-2}$) remained unchanged during the 5 yr under unharvested and low and high grazing pressures (0.00 ± 0.08 g $m^{-2}$ $yr^{-1}$), but declined with haying (−0.25 g $m^{-2}$ $yr^{-1}$). In the lower rooting zone (0.3- to 0.9-m depth), soil inorganic N (initially at 2.9 g $m^{-2}$) accumulated with unharvested and low and high grazing pressure (0.64 ± 0.20 g $m^{-2}$ $yr^{-1}$), but remained unchanged with haying (−0.06 g $m^{-2}$ $yr^{-1}$). Below the rooting zone (0.9- to 1.5-m depth), soil inorganic N (initially at 5.8 g $m^{-2}$) increased with unharvested and high grazing pressure (0.34 ± 0.03 g $m^{-2}$ $yr^{-1}$), was unchanged with low grazing pressure (−0.10 g $m^{-2}$ $yr^{-1}$), and declined with haying (−0.50 g $m^{-2}$ $yr^{-1}$). Applied N appears to have been efficiently utilized by forage with subsequent sequestration into soil organic matter and little movement of inorganic N below the rooting zone (<2% of applied N), irrespective of inorganic or organic fertilization strategy designed to supply sufficient N for high animal production from grazing.**

Nitrogen is an essential nutrient for developing and maintaining the productive capacity of grass management systems, especially on weathered soils of the warm, humid, southeastern USA. Bermudagrass hybrids are adapted to the conditions of the southeastern USA, responding with dramatic increases in biomass production to applied N at rates up to 50 g $m^{-2}$ $yr^{-1}$ when hayed (Wilkinson and Langdale, 1974; Robinson, 1996). However when cattle graze forages, most of the N accumulated in forage and subsequently consumed by cattle is redeposited to the soil via dung and urine (Follett and Wilkinson, 1995), resulting in a lower N input requirement.

The fate of recycled N in pasture systems is contingent on a number of environmental and biological factors, and therefore can be influenced by choice of management. Numerous transformations can contribute to sequestration or loss of N from an ecosystem (Russelle, 1996). Sequestration of N is most notable via incorporation into organic matter, which can be labile or recalcitrant depending on its biochemical structure (Stevenson, 1982). Losses of N can occur through ammonia volatilization, particularly from urine deposits (Whitehead et al., 1989). Denitrification requires a readily oxidizable source of C, the presence of $NO_3$, and low availability of oxygen, all of which can occur under wet pasture conditions (Ryden, 1986). Although perennial grass systems tend to be more efficient at capturing inorganic N in the soil than annual crop systems because of their extensive root system, $NO_3$ could also leach beyond the plant root zone if applied N and water were excessive (Ryden et al., 1984). Grass systems tend to have higher aggregate stability and infiltration rates than tilled crop systems, but surface runoff of inorganic and organic N could occur with heavy rainfall (Russelle, 1996).

Nitrate leaching under established grass systems has been reported at levels of 2.7 ± 1.7 g N $m^{-2}$ $yr^{-1}$ in Ohio (Chichester et al., 1979; Owens et al., 1983, 1992, 1994) and 0.3 to 1.2 g N $m^{-2}$ $yr^{-1}$ in North Carolina (Kilmer et al., 1974). In some studies, $NO_3$ leaching is reported to be several times greater under grazed than ungrazed grassland systems (Ball and Ryden, 1984; Ryden et al., 1984). In older grazing lands that have achieved steady state levels of organic matter accumulation, positive correlations can be found between the quantity of N applied as fertilizer and $NO_3$ leaching (Steenvoorden et al., 1986).

The cycling of N from fertilizer to soil to forage to cattle to manure to soil is a biologically mediated process that transforms inorganic N to organic N via mineralization and immobilization. In an analysis of surface N pools, it was shown that soil organic matter could potentially be a significant sink for organic N when degraded cropland was converted to improved grass management systems (Franzluebbers and Stuedemann, 2001). How harvest management and the source of nutrients might affect the quantity and distribution of inorganic N within and below the rooting zone in such an aggrading soil organic matter condition, however, has not been well defined.

Our objective was to evaluate the effect of fertilization and harvest strategies on soil-profile inorganic N distribution during the first 5 yr of Coastal bermudagrass establishment on a previously degraded soil in the Southern Piedmont USA.

## MATERIALS AND METHODS

### Site Characteristics

A 15-ha upland field (33°22′ N, 83°24′ W) near Farmington, GA, had previously been conventionally cultivated with traditional annual grain and fiber crops for several decades before grassland establishment by sprigging of Coastal bermudagrass in 1991. Sampled on a 30-m grid, the frequency of soil series was 46% Madison, 22% Cecil, 13% Pacolet, 5% Appling, 2% Wedowee (fine, kaolinitic, thermic Typic Kanhapludults), 11% Grover (fine-loamy, micaceous, thermic Typic Hapludults), and 1% Louisa (loamy, micaceous, thermic, shallow

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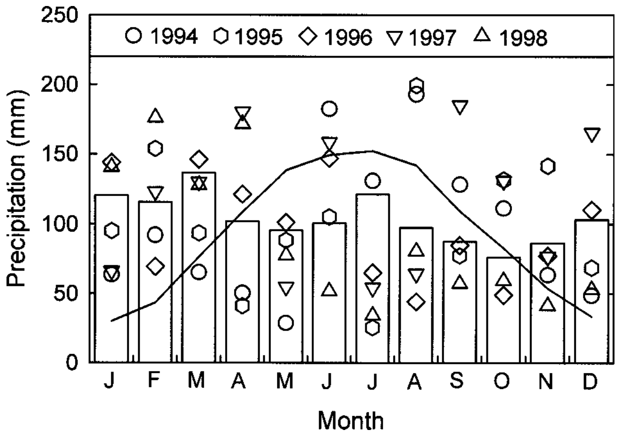


**Fig. 1. Seasonal distribution of long-term mean precipitation (*bars*), long-term mean potential evapotranspiration calculated from Turcs method (*line*), and actual precipitation during the 5-yr study (*symbols*).**

Ruptic–Ultic Dystrudepts). Soil textural frequency of the Ap horizon (21 ± 12 cm depth) was 75% sandy loam, 12% sandy clay loam, 8% loamy sand, and 4% loam. Mean annual temperature is 16.5°C, rainfall is 1250 mm, open pan evaporation is 1560 mm, and elevation is 205 to 215 m above mean sea level. Seasonal distribution of long-term mean precipitation and potential evapotranspiration and observations during this 5-yr study period are shown in Fig. 1.

## Experimental Design

The experimental design was a randomized complete block with treatments in a split-plot arrangement in each of three blocks, which were delineated by landscape features (i.e., slight, moderate, and severe erosion classes). Main plots were fertilization strategy ($n = 3$) and split-plots were harvest strategy ($n = 4$) for a total of 36 experimental units. Grazed paddocks were 0.69 ± 0.03 ha. Each paddock contained a 3 by 4 m shade, mineral feeder, and water trough placed in a line 15 m long near the top of the landscape. Unharvested and hayed exclosures within each paddock were 100 $m^2$.

Fertilization strategy was targeted to supply 20 g total N $m^{-2}$ $yr^{-1}$ using one of the following fertilization regimes: (i) inorganically as $NH_4NO_3$ broadcast in split applications in May and July, (ii) with half of the N assumed fixed and released by crimson clover cover crop during the winter–spring and the other half as $NH_4NO_3$ broadcast in July, and (iii) by broiler litter broadcast in split applications in May and July (Table 1). Crimson clover was direct drilled in clover treatments at 1 g $m^{-2}$ in October each year. All paddocks were mowed in late April and residue allowed to decompose (i.e., clover biomass in clover plus inorganic treatment and winter annual weeds in other treatments).

Harvest strategy mimicked a gradient in forage utilization consisting of (i) unharvested (biomass cut and left in place at the end of growing season), (ii) low grazing pressure (put-and-take system to maintain a target of 300 g $m^{-2}$ of available forage), (iii) high grazing pressure (put-and-take system to maintain a target of 150 g $m^{-2}$ of available forage), and (iv) hayed monthly in summer to remove aboveground biomass at 4-cm height. Actual forage levels averaged about 30% higher than target levels. Hay yield averaged 760 g $m^{-2}$ $yr^{-1}$ (A.J. Franzluebbers, unpublished data, 2002). Yearling Angus steers grazed paddocks during a 140-d period from mid-May until early October each year, except during the first year of treatment implementation (1994) when grazing began in July due to repairs to infrastructure following a tornado. Animals were weighed, available forage determined, and paddocks restocked on a monthly basis.

**Table 1. Rate of N fertilization (g $m^{-2}$ $yr^{-1}$) to 'Coastal' bermudagrass [*Cynodon dactylon* (L.) Pers.].**

| Fertilization regime | 1994 | 1995 | 1996 | 1997 | 1998 | 5-yr mean |
|---|---|---|---|---|---|---|
| Inorganic | 21.1 | 20.2 | 25.0 | 23.8 | 22.4 | 22.5 |
| Clover + inorganic† | 21.1 | 10.1 | 13.2 | 12.0 | 11.1 | 13.5 |
| Broiler litter | 19.5 | 21.6 | 16.4 | 22.3 | 17.2 | 19.4 |

† An additional 11 g N $m^{-2}$ $yr^{-1}$ was assumed to be released from biologically fixed N in clover (*Trifolium incarnatum* L.) cover crop biomass produced from 1995 to 1998.

## Sampling and Analyses

Soil was sampled between grazing seasons each year. Soil cores were excavated to a depth of 1.5 m with a 4.1-cm (i.d.) hydraulic probe at sites on a 30-m grid in April 1994, November 1994, February 1996, October 1996, and October 1997. Due to the nonuniform dimensions of paddocks, sampling sites within a paddock varied from four to nine, averaging 7 ± 1. Each hayed and unharvested exclosure had two fixed sampling locations. From 1994 to 1997, cores were sectioned into depths (0–0.06, 0.06–0.15, 0.15–0.3, 0.3–0.6, 0.6–0.9, 0.9–1.2, and 1.2–1.5 m), dried (55°C for 48 h), ground to <2 mm, and analyzed individually. In February 1999, three soil cores were randomly collected and composited along each of three arcs at 5, 30, and 70 m from shades within grazed paddocks. Two cores were randomly collected and composited within unharvested and hayed exclosures. Soil sampling depth in 1999 was 0 to 0.15, 0.15 to 0.3, 0.3 to 0.6, 0.6 to 0.9, 0.9 to 1.2, and 1.2 to 1.5 m. For statistical analyses across years, inorganic N concentration in the 0- to 0.15-m depth in 1999 was assumed equally derived from 0 to 0.06 and 0.06 to 0.15 m.

Inorganic N ($NH_4$–N + $NO_2$–N + $NO_3$–N) was determined by salicylate–nitroprusside ($NH_4$–N) and Cd-reduction autoanalyzer techniques (Bundy and Meisinger, 1994). A filtered extract was obtained from a 10-g subsample of soil shaken with 20 mL of 2 *M* KCl for 30 min.

Data from multiple samples within an experimental unit were averaged and not considered as a source of variation in the analysis of variance across years (SAS Inst., 1990). Within-depth, across-depth, within-year, and across-year analyses were conducted according to the split-plot design with three blocks. Linear regression with an intercept common to all treatments within a depth was used to test the significance of temporal changes among treatments. Areal estimates of soil-profile inorganic N were calculated by accounting for differences in soil bulk density and depth. Soil bulk density, as suggested from results from the same type of soils in other studies, was assumed to be 1.225 Mg $m^{-3}$ at 0 to 0.06 m, 1.35 Mg $m^{-3}$ at 0.06 to 0.15 m, 1.40 Mg $m^{-3}$ at 0.15 to 0.3 m, and 1.50 Mg $m^{-3}$ at depths below 0.3 m. The soil profile was divided into three sections representing the upper rooting zone (0–0.3 m), the lower rooting zone (0.3–0.9 m), and the zone generally below roots (0.9–1.5 m). Effects were considered significant at $P \leq 0.1$.

# RESULTS AND DISCUSSION

During the first 5 yr of this study, yearly rainfall was near normal each year, e.g., 1994 was 7% lower, 1995 was 2% lower, 1996 was 7% lower, 1997 was 11% higher, and 1998 was 14% lower than normal (1250 mm). Precipi-

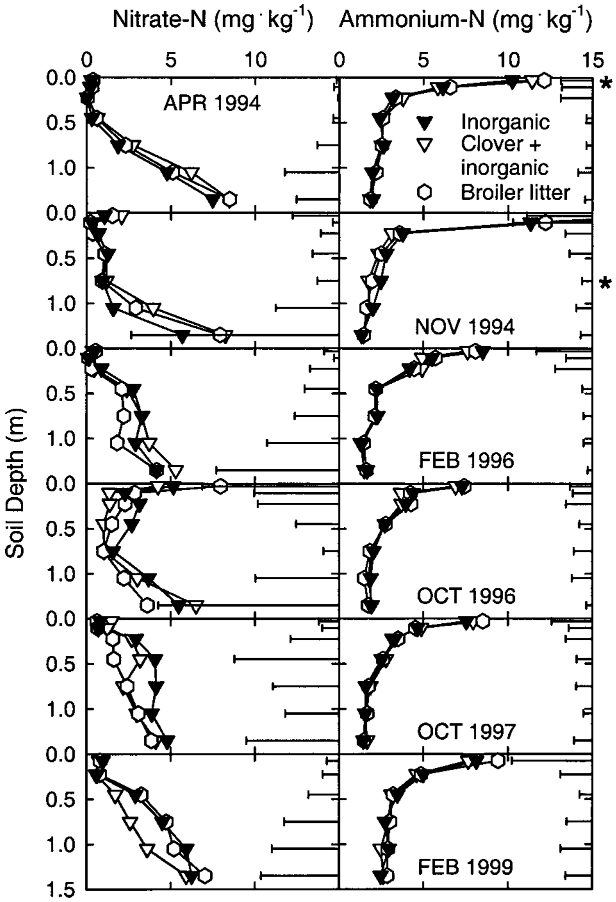


**Fig. 2. Depth distribution of $NO_3$–N and $NH_4$–N as affected by type of fertilization during the first 5 yr of bermudagrass management. Error bars at the right side of each panel indicate LSD at $P = 0.1$ to separate means of fertilization type within a soil depth. *Indicates significant difference between at least two treatments.**

tation typically exceeds evapotranspiration during winter from November through March, and during these 5 yr this almost always occurred. During the summer (May–September), when bermudagrass is active and fertilizers were applied, precipitation typically is less than evapotranspiration and this occurred for 72% of the observations.

## Type of Fertilization

In April 1994 at the initiation of the study, soil inorganic N was similarly distributed within the soil profile among fertilization types (Fig. 2). With time, this distribution was somewhat altered, but not significantly due to fertilization type.

Within a sampling event, the only differences among fertilization types occurred in the $NH_4$–N pool at a depth of 0 to 0.06 m in April 1994 (broiler litter > inorganic) and at a depth of 0.6 to 0.9 m in November 1994 (inorganic > clover + inorganic) (Fig. 2). Averaged across the six sampling events during 5 yr, $NO_3$–N and $NH_4$–N were not different among fertilization types at any depth, except for $NH_4$–N at 0.9 to 1.2 m (inorganic > clover + inorganic) (Table 2). Averaged across the entire soil profile and all sampling events, there were no differences among fertilization types in either $NO_3$–N (2.9 mg $kg^{-1}$) or $NH_4$–N (2.8 mg $kg^{-1}$). Although $NO_3$–N increased with depth in the soil profile to values of 3 to 6 mg $kg^{-1}$ below the rooting zone (0.9–1.5 m), these values should not be considered excessive and are within commonly observed levels. Under variably fertilized switchgrass (*Panicum virgatum* L.) soil $NO_3$–N was 1 to 5 mg $kg^{-1}$ (Vogel et al., 2002). At a depth of 0.9 to 1.2 m, $NO_3$–N was 9 ± 5 mg $kg^{-1}$ among various soils with application of 10 g N $m^{-2}$ $yr^{-1}$ to meet economically optimum N requirements of maize (*Zea mays* L.) in Pennsylvania (Roth and Fox, 1990).

The distribution between the two species of N shifted throughout the soil profile. At the soil surface, $NH_4$ dominated the inorganic N pool, while at lower depths $NO_3$ dominated the inorganic N pool. Averaged across sampling events and treatments, the percentage of total N as $NO_3$–N was 15% at 0 to 0.06 m, 11% at 0.06 to 0.15 m, 24% at 0.15 to 0.3 m, 42% at 0.3 to 0.6 m, 50% at 0.6 to 0.9 m, 65% at 0.9 to 1.2 m, and 77% at 1.2 to 1.5 m. Ammonium accumulates more at the soil surface due to its interaction with cation exchange sites on soil organic matter complexes and steady rate of ammonification from organic matter concentrated near the soil surface. Nitrate tends to accumulate more at lower depths as the process of nitrification is completed within the upper rooting zone and plant roots may not assimilate all of this mobile anion before its movement deeper in the profile with water percolation.

## Harvest Strategy

In April 1994 at the initiation of the study, soil inorganic N was not different among harvest strategies at any of the soil depths, averaging 2.4, 3.5, and 7.8 g $m^{-2}$ at depths of 0 to 0.3, 0.3 to 0.9, and 0.9 to 1.5 m, respectively, across fertilization regimes. Differences in

**Table 2. Mean soil $NO_3$–N and $NH_4$–N (mg $kg^{-1}$) as affected by fertilization regime (inorganic, clover + inorganic, and broiler litter) averaged across bermudagrass harvest strategy and six sampling events during 5 yr.**

| | $NO_3$–N | | | | $NH_4$–N | | | |
|---|---|---|---|---|---|---|---|---|
| Soil depth, m | Inorganic | Clover | Litter | $LSD_{(P=0.1)}$ | Inorganic | Clover | Litter | $LSD_{(P=0.1)}$ |
| 0–0.06 | 1.6 | 1.7 | 2.3 | 2.1 | 10.8 | 10.1 | 11.0 | 2.0 |
| 0.06–0.15 | 0.7 | 0.7 | 0.9 | 1.3 | 6.5 | 6.2 | 6.8 | 1.9 |
| 0.15–0.3 | 1.5 | 1.1 | 1.0 | 2.0 | 3.9 | 3.8 | 3.9 | 1.2 |
| 0.3–0.6 | 2.4 | 1.7 | 1.6 | 1.9 | 2.7 | 2.6 | 2.6 | 0.6 |
| 0.6–0.9 | 2.5 | 2.0 | 2.0 | 1.3 | 2.2 | 2.1 | 2.1 | 0.3 |
| 0.9–1.2 | 3.4 | 3.6 | 3.0 | 3.8 | 1.9 | 1.7 | 1.8 | 0.2† |
| 1.2–1.5 | 5.4 | 6.3 | 5.4 | 10.0 | 1.7 | 1.8 | 1.7 | 0.5 |
| 0–1.5 | 3.0 | 3.0 | 2.7 | 2.9 | 2.8 | 2.7 | 2.8 | 0.3 |

† Indicates significant difference between at least two treatments.

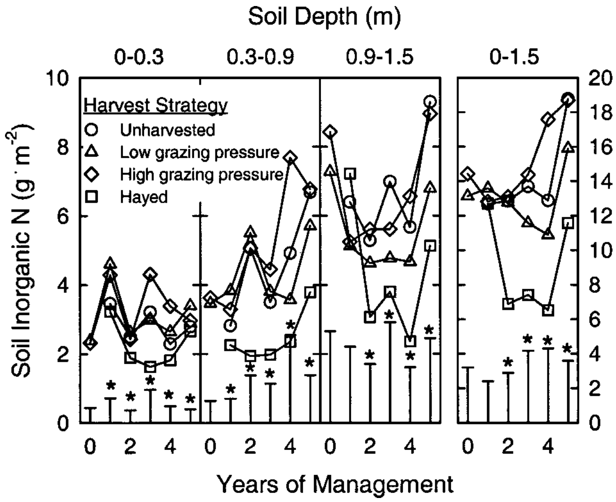


**Fig. 3. Soil inorganic N during the first 5 yr of bermudagrass management as affected by harvest strategy in the upper rooting zone (0–0.3 m), in the lower rooting zone (0.3–0.9 m), below the rooting zone (0.9–1.5 m), and within the entire soil profile (0–1.5 m). Error bars at the bottom of each panel indicate LSD at $P = 0.1$ to separate means of harvest strategy within a year. *Indicates significant difference between at least two treatments.**

soil inorganic N among harvest strategies started to appear at the end of 1 yr of management in November 1994, where haying started to have lower soil inorganic N than other harvest strategies at depths of 0 to 0.3 and 0.3 to 0.9 m (Fig. 3). Lower soil inorganic N with haying than other harvest strategies became more prominent with time under all fertilization regimes, especially at a depth of 0.3 to 0.9 m, because of the strong demand for N by bermudagrass without significant recycling of N back to the soil, which would have occurred in other harvest strategies via unharvested biomass or cattle feces and urine.

Averaged across fertilization regimes and sampling events during the first 5 yr, $NO_3$–N was significantly lower under haying than under all other harvest strategies at all soil depths down to 1.2 m (Table 3). Across the entire soil profile to 1.5 m, $NO_3$–N under haying was only 37 to 50% of that under other harvest strategies. The supply and demand of N under hayed management was significantly different than that of other harvest strategies. Unlike other strategies, haying resulted in an export of more than half of the applied N from the field (Table 4). Haying also limited the accumulation of soil organic N compared with other harvest strategies, which would have limited the supply of mineralizable N (Franzluebbers and Stuedemann, 2001).

Nitrate-N under unharvested management was significantly greater than under low and high grazing pressure at a depth of 0 to 0.06 m, but at depths of 0.06 to 0.15, 0.15 to 0.3, and 0.3 to 0.6 m values were lower than under high grazing pressure and not different from those under low grazing pressure (Table 3). Across the entire soil profile to 1.5 m, $NO_3$–N under unharvested management was not significantly different than under either low or high grazing pressure. Therefore, whether the return of plant residues to the soil surface was from senescent residues or from partially digested animal feces, it had no major effect on soil inorganic N pools.

**Table 3. Mean soil $NO_3$–N and $NH_4$–N (mg kg$^{-1}$) as affected by bermudagrass harvest strategy (UH is unharvested, LG is low grazing pressure, HG is high grazing pressure, and H is hayed) averaged across fertilization regime and six sampling events during 5 yr.**

| | Harvest strategy | | | | |
|---|---|---|---|---|---|
| Soil depth, m | UH | LG | HG | H | $LSD_{(P=0.1)}$ |
| | mg kg$^{-1}$ | | | | |
| | $NO_3$–N | | | | |
| 0–0.06 | 3.2 | 1.8 | 2.2 | 0.3 | 0.6† |
| 0.06–0.15 | 0.7 | 0.8 | 1.4 | 0.1 | 0.3† |
| 0.15–0.3 | 1.0 | 1.3 | 2.1 | 0.3 | 0.7† |
| 0.3–0.6 | 1.9 | 2.1 | 3.2 | 0.3 | 1.0† |
| 0.6–0.9 | 3.0 | 2.2 | 3.1 | 0.4 | 0.9† |
| 0.9–1.2 | 4.3 | 3.2 | 4.6 | 1.2 | 1.4† |
| 1.2–1.5 | 6.4 | 5.3 | 6.3 | 4.8 | 2.5 |
| 0–1.5 | 3.5 | 2.8 | 3.8 | 1.4 | 1.1† |
| | $NH_4$–N | | | | |
| 0–0.06 | 10.7 | 11.2 | 10.8 | 9.8 | 1.2† |
| 0.06–0.15 | 5.7 | 7.6 | 7.3 | 5.4 | 1.1† |
| 0.15–0.3 | 4.0 | 4.0 | 4.1 | 3.4 | 0.4† |
| 0.3–0.6 | 2.7 | 2.7 | 2.7 | 2.4 | 0.2† |
| 0.6–0.9 | 2.1 | 2.3 | 2.1 | 2.0 | 0.2† |
| 0.9–1.2 | 1.8 | 1.8 | 1.8 | 1.7 | 0.2 |
| 1.2–1.5 | 1.8 | 1.7 | 1.7 | 1.7 | 0.2 |
| 0–1.5 | 2.7 | 2.9 | 2.9 | 2.6 | 0.1† |

† Indicates significant difference between at least two treatments.

Averaged across fertilization regimes and sampling events during the first 5 yr, $NO_3$–N was significantly higher under high grazing pressure than under low grazing pressure at depths of 0.06 to 0.15, 0.15 to 0.3, 0.3 to 0.6, 0.6 to 0.9, and 0.9 to 1.2 m (Table 3). Across the entire soil profile to 1.5 m, however, $NO_3$–N was not statistically different between low and high grazing pressures. Accumulation of $NO_3$–N below the upper rooting zone could pose a threat to ground water quality, if excessive rainfall were to occur. The average $NO_3$–N concentration below the 0.3-m depth was 3.2 mg kg$^{-1}$ under low grazing pressure and 4.3 mg kg$^{-1}$ under high grazing pressure. These values were below the average $NO_3$–N concentration at a depth of 0.3 to 2.1 m of 12.0 ± 2.6 mg kg$^{-1}$ with various N fertilization rates applied and of 6.7 mg kg$^{-1}$ with no N fertilizer applied during

**Table 4. Changes in the components of an in situ N balance as affected by bermudagrass harvest strategy (UH is unharvested, LG is low grazing pressure, HG is high grazing pressure, and H is hayed) averaged across fertilization regimes during 5 yr. Negative values represent a decline in that component during 5 yr.**

| | Harvest strategy | | | |
|---|---|---|---|---|
| N component† | UH | LG | HG | H |
| | — % of fertilizer input of 21.4 g m$^{-2}$ yr$^{-1}$ — | | | |
| Surface residue | 3.7 | 5.0 | 1.9 | −4.0 |
| Soil organic, 0–0.06 m | 33.7 | 64.0 | 71.0 | 14.0 |
| Soil organic, 0.06–0.2 m | 19.6 | 30.6 | 24.5 | 12.0 |
| Soil inorganic, 0–0.3 m | 0.4 | 0.0 | 0.4 | −1.2 |
| Soil inorganic, 0.3–0.9 m | 2.8 | 2.2 | 4.0 | −0.3 |
| Soil inorganic, 0.9–1.5 m | 1.7 | −0.5 | 1.5 | −2.3 |
| Harvest | 0.0 | 2.8 | 3.3 | 56.8 |
| Total | 61.9 | 104.1 | 106.6 | 75.0 |

† Surface residue, soil organic, and harvest N components were derived from values calculated in Franzluebbers and Stuedemann (2001). Harvest N was from cattle live-weight gain under low and high grazing pressure and from hay removal under hayed management.

**Table 5. Net change in soil inorganic N as affected by fertilization regime (inorganic, clover + inorganic, and broiler litter) and bermudagrass harvest strategy [unharvested (UH), low grazing pressure (LG), high grazing pressure (HG), and hayed (H)] as determined by linear regression analysis.**

| Soil | | Inorganic | | | | | Clover + inorganic | | | | | Broiler litter | | | | | $LSD_{(P=0.1)}$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| depth | Intercept | UH | LG | HG | H | Mean | UH | LG | HG | H | Mean | UH | LG | HG | H | Mean | All | Means |
| m | g m$^{-2}$ | g m$^{-2}$ yr$^{-1}$ | | | | | | | | | | | | | | | | |
| 0–0.3 | 3.1 | −0.1 | −0.0 | 0.1 | −0.2‡ | 0.0 | −0.2‡ | −0.0 | 0.1 | −0.3‡ | −0.0 | −0.0 | 0.1 | 0.0 | −0.2‡ | 0.0 | 0.2† | 0.2 |
| 0.3–0.9 | 2.9 | 0.8‡ | 0.7‡ | 1.0‡ | −0.1 | 0.7‡ | 0.2 | 0.2 | 1.1‡ | −0.1 | 0.4‡ | 0.8‡ | 0.5‡ | 0.4‡ | 0.1 | 0.3‡ | 0.4† | 0.3† |
| 0.9–1.5 | 5.8 | 0.6‡ | 0.2 | 0.3 | −0.7‡ | 0.0 | 0.1 | −0.5‡ | 0.8‡ | −0.3 | −0.0 | 0.4‡ | 0.0 | −0.2 | −0.4‡ | −0.1 | 0.6† | 0.4 |
| 0–1.5 | 11.8 | 1.4‡ | 0.9‡ | 1.4‡ | −1.1‡ | 0.7‡ | 0.1 | −0.4 | 2.0‡ | −0.8‡ | 0.4 | 1.2‡ | 0.6 | 0.3 | −0.6 | 0.2 | 0.9† | 0.6† |

† Indicates significant difference between at least two treatments.
‡ Indicates slope significantly different from zero at $P = 0.1$.

3 yr of maize production in Maryland (Angle et al., 1993). Nitrate-N concentration below the upper rooting zone in grazed bermudagrass does not appear to have accumulated to an environmentally threatening level.

Averaged across fertilization regimes and sampling events during the first 5 yr, $NH_4$–N was significantly lower under haying than (i) under low grazing pressure at depths of 0 to 0.06 and 0.6 to 0.9 m, (ii) under low and high grazing pressure at a depth of 0.06 to 0.15 m, and (iii) under all other harvest strategies at depths of 0.15 to 0.3 and 0.3 to 0.6 m (Table 3). Ammonium-N was also lower under unharvested management than (i) under low and high grazing pressure at a depth of 0.06 to 0.15 m and (ii) under low grazing pressure at a depth of 0.6 to 0.9 m. There were no significant differences in $NH_4$–N between low and high grazing pressure at any soil depth. Lower $NH_4$–N in the upper rooting zone under haying than under other harvest strategies was probably related to lower soil organic N (Table 4), which provides a steady supply of $NH_4$ in soil from ammonification, a microbially mediated process. Compared with differences in $NO_3$–N among treatments, these differences in $NH_4$–N were only of minor significance and suggested its major contributions to N cycling near the soil surface, with much diminished contribution below the upper rooting zone.

## Temporal Changes in Soil Inorganic Nitrogen

Significant temporal changes in soil inorganic N based on linear regression occurred in (i) 4 of 12 treatment combinations at a depth of 0 to 0.3 m, (ii) 7 of 12 treatment combinations at a depth of 0.3 to 0.9 m, and (iii) 6 of 12 treatment combinations at a depth of 0.9 to 1.5 m (Table 5). In the upper rooting zone (0–0.3 m), a significant decline in soil inorganic N with time occurred under haying with all fertilization types and under unharvested management with clover + inorganic fertilization. In the upper rooting zone, the major change was due to a reduction in soil inorganic N because of the high demand by haying.

In the lower rooting zone (0.3–0.9 m), a significant increase in soil inorganic N occurred under high grazing pressure with all fertilization types, under low grazing pressure with inorganic and broiler litter fertilization, and under unharvested management with inorganic and broiler litter fertilization (Table 5). At this depth, accumulation of soil inorganic N predominated, although significant interactions between fertilization type and harvest strategy limited our ability to attribute reasons in a generalized manner. For example, the greater increase in soil inorganic N at this depth under inorganic fertilization (0.7 g m$^{-2}$ yr$^{-1}$) compared with clover + inorganic (0.4 g m$^{-2}$ yr$^{-1}$) and broiler litter fertilization (0.3 g m$^{-2}$ yr$^{-1}$) might be ascribed to greater leaching potential from the point of application because of the immediate availability of inorganic N rather than slow availability from organic sources, although this occurred in only 3 of 8 individual comparisons. Also, higher grazing pressure might be considered to reduce the rooting depth of bermudagrass with subsequent accumulation of soil inorganic N in the lower rooting zone, but this effect only occurred with clover + inorganic fertilization and not with other fertilization types.

Below the rooting zone (0.9–1.5 m), a significant decline in soil inorganic N occurred under haying with inorganic and broiler litter fertilization and under low grazing pressure with clover + inorganic fertilization. At this depth, a significant increase occurred under unharvested management with inorganic and broiler litter fertilization and under high grazing pressure with clover + inorganic fertilization. The decline in soil inorganic N under haying was likely due to the strong harvest sink. It is unclear why there was a significant change in soil inorganic N between low and high grazing pressure only with clover + inorganic fertilization. Accumulation of soil inorganic N with time below the rooting zone under unharvested management may have been due to the strong recycling supply of N from surface organic residues in addition to external fertilizer inputs, which could have resulted in excess supply of N.

Across the entire soil profile to a depth of 1.5 m, soil inorganic N (i) declined significantly with time under haying with inorganic and clover + inorganic fertilization and (ii) increased significantly with time under unharvested management with inorganic and broiler litter fertilization, under low grazing pressure with inorganic fertilization, and under high grazing pressure with inorganic and clover + inorganic fertilization. Interactions between fertilization and harvest strategies were significant. Most of the significant interactions were due to variable responses in soil inorganic N among fertilization regimes between low and high grazing pressure treatments. These interactions may have been caused by differences in synchronization between peak demand for N depending on forage regrowth stage among harvest strategies and availability of N depending on tem-

**Table 6. Soil inorganic N (g $m^{-2}$) in February 1999 as affected by fertilization regime (inorganic, clover + inorganic, and broiler litter) and distance in meters from shade and water averaged across low and high grazing pressure of bermudagrass.**

| | Inorganic | | | Clover + inorganic | | | Broiler litter | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Soil depth | 0–30 | 30–70 | 70–120 | 0–30 | 30–70 | 70–120 | 0–30 | 30–70 | 70–120 | $LSD_{(P=0.1)}$ |
| m | | | | | | | | | | |
| 0–0.3 | 2.7 | 3.3 | 3.0 | 3.2 | 2.9 | 3.4 | 4.1 | 2.7 | 3.4 | 0.7† |
| 0.3–0.9 | 7.7 | 5.6 | 6.0 | 6.4 | 5.3 | 4.4 | 11.7 | 5.3 | 3.9 | 4.0† |
| 0.9–1.5 | 10.2 | 8.9 | 6.9 | 8.8 | 7.4 | 6.3 | 11.2 | 6.6 | 4.7 | 3.8† |
| Total, 0–1.5 | 20.5 | 17.8 | 15.9 | 18.3 | 15.6 | 14.1 | 27.0 | 14.6 | 11.9 | 7.1† |

† Indicates significant difference between at least two treatments.

perature and moisture variables that controlled mineralization and immobilization of N.

Averaged across fertilization types, soil inorganic N in the upper rooting zone (0–0.3 m) was significantly lower under haying than under most other harvest strategies throughout the study period (Fig. 3). From regression analysis, the change in soil inorganic N with time was ranked as: haying ($-0.25$ g $m^{-2}$ $yr^{-1}$) < unharvested ($-0.09$ g $m^{-2}$ $yr^{-1}$) < low grazing pressure (0.01 g $m^{-2}$ $yr^{-1}$) = high grazing pressure (0.08 g $m^{-2}$ $yr^{-1}$) (Table 5). In the lower rooting zone (0.3–0.9 m), soil inorganic N under haying was also lower than most other harvest strategies throughout the study (Fig. 3). The change in soil inorganic N with time in the lower rooting zone was ranked as: haying ($-0.06$ g $m^{-2}$ $yr^{-1}$) < low grazing pressure (0.46 g $m^{-2}$ $yr^{-1}$) = unharvested (0.60 g $m^{-2}$ $yr^{-1}$) < high grazing pressure (0.86 g $m^{-2}$ $yr^{-1}$) (Table 5). Below the rooting zone (0.9–1.5 m), soil inorganic N under haying required at least 2 yr for a significant difference to occur while differences occurred at 1 yr in the rooting zone (Fig. 3). Below the rooting zone, the change in soil inorganic N with time was ranked as: haying ($-0.50$ g $m^{-2}$ $yr^{-1}$) < low grazing pressure ($-0.10$ g $m^{-2}$ $yr^{-1}$) < high grazing pressure (0.31 g $m^{-2}$ $yr^{-1}$) = unharvested (0.36 g $m^{-2}$ $yr^{-1}$) (Table 5).

The continuous removal of N in forage biomass with haying placed greater demand on the soil inorganic N pool, such that a significant decline occurred with time in the upper rooting zone and below the rooting zone. Except for a relatively steady level of soil inorganic N with haying, all other harvest strategies led to a significant increase with time in the lower rooting zone. The combination of increasing soil inorganic N availability below the upper rooting zone (Table 5) and increasing soil organic C and total soil N in the upper rooting zone (Franzluebbers et al., 2001; Franzluebbers and Stuedemann, 2001) in grazed systems compared with haying demonstrates the change in nutrient recycling that can occur in pastures (Table 4). With low and high grazing strategies, accounting for applied N throughout the 5 yr was complete (values of 104 and 107% are considered within reasonable error limits for this accounting procedure) and greater than for unharvested (62%) and hayed strategies (75%). Loss of N through volatilization from dried plant material is the only plausible explanation for unaccounted N in either hayed or unharvested systems.

## Lateral Distribution within Grazed Pastures

At the end of 5 yr of management, distribution of soil inorganic N among three locations (0–30, 30–70, and 70–120 m from shade and water sources) in grazed paddocks was investigated. In the upper rooting zone (0–0.3 m), soil inorganic N was uniformly distributed among the three locations within grazed pastures with inorganic and clover + inorganic fertilization, but was significantly higher nearest shade and water sources compared with other locations with broiler litter fertilization (Table 6). This same effect occurred for soil inorganic N in the lower rooting zone (0.3–0.9 m) and below the rooting zone (0.9–1.5 m). Although not significant, there was also a trend toward consistently higher soil inorganic N near shade and water sources compared with farther away at soil depths below the upper rooting zone in other fertilization regimes. Cattle spend a greater amount of time near shade and water sources than in other parts of the pasture, because of the need to frequently drink water, consume mineral salt, and seek shelter from the sun. This animal behavior appears to have had some influence on the accumulation of soil inorganic N within pastures, although the accumulation of soil inorganic N below the rooting zone was not excessive at the end of 5 yr. A similar redistribution of extractable soil P occurred with concentration near shade and water sources in the surface soil of this study, especially with broiler litter fertilization (Franzluebbers et al., 2002). With permanent placement of shade and water sources, land managers should be aware that accumulation of soil inorganic N could occur. With this in mind, these zones should be maintained well vegetated and fertilizer applications should be minimized to avoid excessive accumulation of soil inorganic N, which could be susceptible to leaching loss below the rooting zone. Although we attempted to uniformly distribute fertilizer in this study, it is possible that areas near shades received somewhat more fertilizer than other parts of the paddock due to particular geometries of paddocks that forced traffic in concentrated areas.

Inorganic N distribution in the soil profile and within grazed paddocks was similar to previous results observed at a nearby site. In a separate study of 8- to 15-yr-old tall fescue (*Festuca arundinacea* Schreb.) pastures fertilized with 26.9 ± 9.9 g N $m^{-2}$ $yr^{-1}$, soil inorganic N averaged (i) 10.7, 5.4, and 5.6 g $m^{-2}$ at shade, mid, and far zones, respectively, at a depth of 0 to 0.3 m; (ii) 9.3, 3.7, and 3.6 g $m^{-2}$ at a depth of 0.3 to 0.9 m; and (iii) 12.7, 8.2, and 9.0 g $m^{-2}$ at a depth of 0.9 to 1.5 m (Franzluebbers et al., 2000).

## SUMMARY AND CONCLUSIONS

Soil inorganic N was only marginally affected by the type of fertilization strategy, which supplied 21.4 ± 2.4 g

$m^{-2}$ $yr^{-1}$ (mean ± standard deviation among years and strategies). There was no evidence to suggest that soil inorganic N accumulated to a greater degree or had greater potential leaching loss whether fertilizer came from inorganic, organic (broiler litter), or a combination (clover + inorganic) of sources. The percentage of soil inorganic N derived from $NO_3$–N increased with increasing depth in the soil profile (i.e., 17% at a depth of 0–0.3 m, 46% at a depth of 0.3–0.9 m, and 72% at a depth of 0.9–1.5 m). Unlike fertilization strategy, harvest strategy of bermudagrass had a significant effect on soil inorganic N during these first 5 yr of management. Soil inorganic N was lower under haying than other harvest strategies at all soil depths, probably because of the high demand for inorganic N due to continuous biomass removal that limited nutrient recycling. Soil inorganic N under unharvested and low and high grazing pressures was not different at any depth when averaged across years, except at a depth of 0 to 0.3 m, where N was 16% greater under high grazing pressure than unharvested management. Soil inorganic N either was unchanged or declined with time at a depth of 0 to 0.3 m, accumulated with time at a depth of 0.3 to 0.9 m, and either increased or decreased with time at a depth of 0.9 to 1.5 m, depending on harvest strategy. Significant redistribution of soil inorganic N as a function of distance from shade and water sources only occurred with broiler litter fertilization, although a similar trend was observed with other fertilization strategies. At least during the first 5 yr of establishment, there was little evidence to suggest that any of the management strategies evaluated might be leading to significant $NO_3$ leaching and potential ground water pollution in this kaolinitic Ultisol. The strong sink for N by vigorous bermudagrass growth appears to have adequately controlled downward movement of inorganic N in the soil profile. These first 5 yr of investigation represented a management period that appears to have captured a large portion of applied N as stable compounds in the steadily aggrading surface soil organic matter condition. Additional research is needed to understand the partitioning of N into organic and inorganic components at points in time leading up to and beyond the achievement of steady state soil organic N levels under these different management systems.

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