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ORIGINAL ARTICLE

Agro-ecological nitrogen management in soils vulnerable to nitrate leaching: a case study in the Lower Suwannee Watershed

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Abstract Environmental benefits associated with reduced rates of nitrogen (N) application, while maintaining economically optimum yields have economic and social benefits. Although N is an indispensable plant nutrient, residual soil N could leach out to contaminate groundwater and surface water resources, particularly in sandy soils. A 2-year field study was conducted in an established bermudagrass (*Cynodon dactylon*) pasture in the Lower Suwannee Watershed, Florida, to evaluate N application rates on forage yield, forage quality, and nitrate (NO_3-N) leaching in rapidly permeable upland sandy soils. Four N application rates (30, 50, 70, and 90 kg N ha^{-1} $harvest^{-1}$) corresponding to 0.33, 0.55, 0.77 and IX, respectively, of recommended N rate (90 kg N ha^{-1} $harvest^{-1}$) for bermudagrass hay production in Florida were evaluated vis-à-vis an unfertilized (0 N) control. Suction cups were installed near the center of each plot at two depths (30 and 100 cm) to monitor NO_3-N leaching. The grass was harvested at 28 days intervals to determine dry matter yield, N uptake, and herbage nutritive value. Nitrogen application at the recommended rate produced the greatest total dry matter yield ($\sim$18.4 Mg ha^{-1} $year^{-1}$), but a modeled economically optimum N rate of $\sim$57 kg N ha^{-1} $harvest^{-1}$ ($\sim$60% of the recommended N rate) projected an average dry matter yield of $\sim$17.3 Mg ha^{-1} $year^{-1}$, which represents >90% of the observed maximum yield. Nitrogen application increased nutritive quality of the grass, but increases in N application rate above 30 kg N ha^{-1} did not result in significant increases in in vitro digestible organic matter concentration, and tissue crude protein was not significant above 50 kg N ha^{-1}. Across the sampling period, treatments with N rates $\leq$50 kg N ha^{-1} $harvest^{-1}$ had leachate NO_3-N concentration below the maximum contaminant limit of <10 mg l^{-1}. Conversely, applying N at rates $\geq$70 kg N ha^{-1} $harvest^{-1}$ resulted in leachate N concentration that exceeded the maximum contaminant limit, and suggest high risk of impacting groundwater quality, if such rates are applied to soils with coarse (sand) textures. The study demonstrates that recommendation of a single N application rate may not be appropriate under all agro-climatic conditions and, thus, a site-specific evaluation of best N management strategy is critical.

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Keywords Crude protein · Dry matter yield · In vitro digestible organic matter · Nitrogen uptake efficiency · Nitrogen use efficiency

Introduction

Nutrient management in croplands and grasslands, particularly in nutrient sensitive watersheds, has become critical in many production systems and is a major environmental issue that could undermine the long-term sustainability of agriculture in many watersheds (Woodard et al. 2002, 2003). Nitrogen and phosphorus (P) are essential nutrients for sustainable crop production, but if the supply of N and P exceed quantities taken up by crops, the residual soil content could be of environmental concern. For example, agricultural operations in many watersheds in southeastern United States have come under scrutiny in terms of N and P management in recent times. The Lower Suwannee Watershed, in particular, has received an increased attention because soils in the watershed are mostly coarse-textured sandy soils, and the underlying hydrogeology could result in nitrate leaching to contaminate the Upper Floridan Aquifer (Woodard et al. 2003). Andrews (1992) showed that the Upper Floridan Aquifer underlying the soils in the Lower Suwannee Watershed has unconfined layers with karstic features. These hydrogeological characteristics, in addition to the relatively high annual rainfall (exceeding 1,600 mm; Southeast Regional Climate Center 2011), make the Upper Floridan Aquifer highly susceptible to contamination. The Watershed is designated as “Category 1”, a watershed in greatest need of restoration due to elevated levels of NO_3-N in the surface water of the river and the underlying groundwater of the basins (Florida United Watershed Assessment 1999). Consequently, continued use of N inputs in production systems in the watershed must be re-evaluated.

For bermudagrass hay, silage and green chop, N application rate of 90 kg ha^{-1} is recommended after each cutting of the forage, except the last cutting in the fall (Mylavarapu et al. 2007). However, studies of warm season grasses have shown that nutrient removal by forages is primarily a function of the grass species, cultivars, and yield, and ranged between 30 and 40% of the applied N (Dobermann et al. 2002; Newman et al. 2009). This suggests that for some grass species, a substantial portion of the applied N will build up in the soil, which could eventually be lost either through surface runoff and/or leaching. Further, the potential for nitrate leaching from applied N fertilizers could vary widely due to agro-environmental conditions and management practices. Hence, critical evaluation of N loads applied to forage produced in the Lower Suwannee Watershed, vis-à-vis the recommended N rates is imperative. The objective of this study was, therefore, to identify N application rate that optimizes yield quantity and quality of a widely grown forage grass in the watershed, with minimal N leaching losses in sandy soil, highly vulnerable to NO_3-N leaching.

Materials and methods

Site description

The experiment was located in the south western portion of the Lower Suwannee Watershed, Florida, USA (Fig. 1). The Suwannee River is a major aquatic resource that begins in state of Georgia (USA) and flows through north Florida and empties into the Gulf of Mexico. The Suwannee Watershed is made up of all the creeks, streams, and rivers and springs that feed the Suwannee River, which extends from south central Georgia to the Gulf of Mexico in northwest Florida, draining ~26,000 km^2 (Katz and Raabe 2004). Approximately 57% of the land area in the watershed is located in the state of Georgia while the other 43%, known as the “Lower Suwannee Basin”, is in Florida (Fig. 1). The Lower Suwannee Basin contains the highest concentration of first magnitude freshwater springs (i.e., spring that discharges water ≥ 2.83 m^{-3} s^{-1}) in the USA (Katz et al. 1997). More than half of the basin’s rivers and springs are reported to contain NO_3-N concentrations exceeding 10 mg N l^{-1} (USGS 1998). Consequently, the states of Florida and Georgia, the US Federal government, and other local organizations have identified the Suwannee River Basin as an ecosystem in need of protection because of its unique biota and important water resources.

The basin is generally flat with occasional rolling topography. Elevation ranges from sea level to ~55 m. More than 80% of the soils used for agricultural production are classified as Entisols, with ~20% classified as Ultisols, and Spodosols (Soil Survey Staff

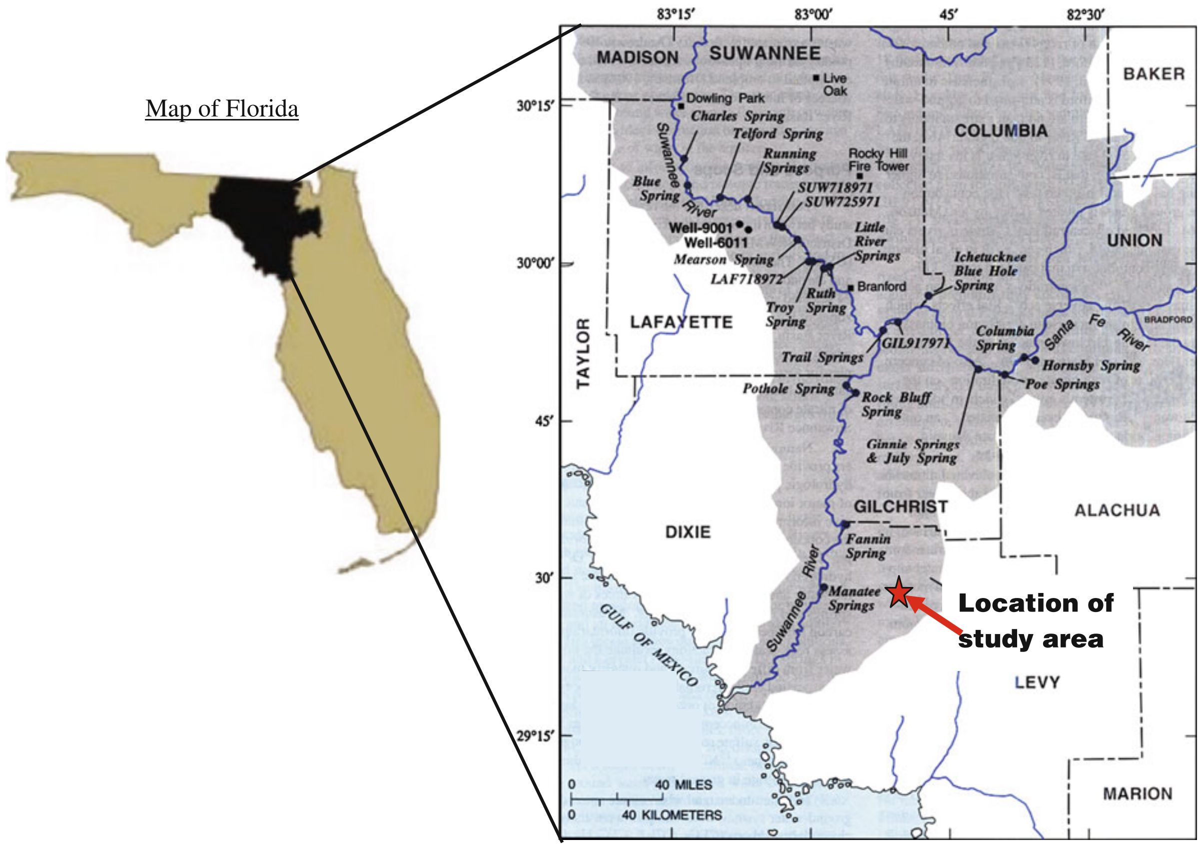

Fig. 1 Lower Suwannee Watershed located in northwestern Florida, USA. *Source*: United States Geological Survey (USGS 1998)

2009). Regardless of soil order, the root zone (A horizon) texture in the basin is usually coarse to fine sand with low water holding capacity (25–60 g kg^{-1}). Agriculture in the Lower Suwannee Basin is diverse, including beef, dairy, poultry, field crop, forage, vegetable, and nursery production. The agricultural land use (cultivated land + pasture) represents more than 60% of total land area of the basin (Obreza and Means 2006). Pastureland is widespread throughout the Basin, and is the most common agricultural land use. Forages commonly grown in the watershed include bermudagrass, bahiagrass (warm season) and ryegrass (cold season). Fertilizer application is necessary to achieve maximum economic crop yields due to the low native fertility and nutrient retention capacity of the top soil (Obreza and Means 2006).

Field layout and treatment application

The study was conducted in an established ‘Tifton 85’ bermudagrass (*Cynodon* spp. Pers.) hay field in a commercial cattle farm within the Lower Suwannee Watershed. ‘Tifton 85’ bermudagrass, released in 1992 (Burton et al. 1993), has gained attention as a highly productive forage grass in watershed (Clavijo et al. 2010; Liu et al. 2011), and it is gradually but steadily becoming the new grass standard for comparison of bermudagrass variety performance (Clavijo et al. 2010; Liu et al. 2011). The ‘Tifton 85’ bermudagrass at the experimental site was established in 2006 and covers a total area of 50 ha. It is used primarily for hay and green chop production with an annual dry matter yield of ~4 Mg ha^{-1} $year^{-1}$ under minimal (>5 kg N ha^{-1} $year^{-1}$) fertilization to selected portions of the field. The site of the field selected for this study has received no N fertilization since the establishment of the grass, and was deemed appropriate for the experiment.

The soil at the experimental site is classified as Otela-Candler complex (sandy, siliceous, Hyperthermic, uncoated Lamellic Quartzipsamments), which consists of very deep, excessively drained, rapidly permeable upland soil that has no profile development other than an A horizon, with no diagnostic horizons. The soil is formed in thick beds of eolian or marine deposits of coarse textured materials with water table below a depth of >2 m, and gently rolling topography (Soil Service Staff 2009).

The 2-year (2009 and 2010) study consisted of four N application rates (30, 50, 70, and 90 kg ha^{-1} $harvest^{-1}$), which corresponded to 0.3, 0.55, 077, and 1 X, respectively, of the recommended N rate for bermudagrass hay production in most Florida soils (Mylavarapu et al. 2007). The N application rates for the present study were selected based on the results of a preliminary study at the site (data not presented). The experimental design was a randomized complete block design consisting of three blocks with each block evaluating the four N application rates and an unamended (0 N) control, with a plot size of 144 m^2 and 2-m wide alleys between blocks. Ammonium nitrate was the sole N source and was broadcast applied after each harvest. At the commencement of the study in each year, all the required P (45 kg P_2O_5 ha^{-1}) and one-half of the required K (54 kg K_2O ha^{-1}) were applied, and the remainder one-half of the required K was applied after the third harvest in each year as recommended by Mylavarapu et al. (2007). Triple superphosphate and muriate of potash were the P and K sources, respectively. Two suction cups, spaced 1.2 m apart, were installed near the center of each plot. Each suction cup, a round-bottom, porous ceramic cup (5.1-cm outer diameter × 6-cm length, one bar high flow; Soil Moisture Equipment Corporation, Santa Barbara, CA) was attached to the end of a polyvinyl chloride tubing as described by Woodard et al. (2002). The ceramic cups were placed at either 30 or 100 cm below the soil surface, representing depths within and below the root zone, respectively.

Soil chemical analysis

Each plot was divided into two subplots from which a composite soil sample (formed by mixing twenty 2.5-cm-diameter core samples) was collected to characterize the initial soil conditions. Thereafter, soil samples were collected 1 week after each N fertilizer application and after each harvest in a similar manner to monitor changes in soil N concentration following fertilizer application, and subsequent N uptake by the plants. Samples were taken from the top 30 cm of the A horizon, 30–60, and 60–100 cm below the soil surface for selected physico-chemical analysis.

Air-dried soil samples (>2 mm particle size) were analyzed for total N using a modified Kjeldahl procedure (Florence and Milner 1979). Additionally, ammonium (NH_4) and NO_3 were extracted from a 10 g subsample with 40 ml of 1.0 M KCl (Keeney and Nelson 1982). The resulting suspension was shaken for 1 h and filtered using Whatman No. 42 filter paper. The filtered solution was analyzed for NH_4 and NO_3 concentrations using a Lachat autoanalyzer (QuikChem 8500, Lachat Instruments, Loveland, CO, USA). Soil organic carbon concentration was determined using the Walkley and Black (1934) method. Mehlich-3 P, Ca, Mg, and K concentrations were determined using 5 g of soil and 20 ml of Mehlich-3 solution as described in Mehlich (1984). The concentrations of P, Ca, Mg, and K were determined using inductively coupled plasma-atomic emission spectroscopy (ICP-AES; PerkinElmer Plasma 3200; PerkinElmer, Wellesley, MA). Cation exchange capacity (CEC) of the soil was determined using the ammonium acetate (pH 7) method (Rhoades 1982).

All sample collection/handling/chemical analysis was conducted according to a standard quality assurance/quality control (QA/QC) protocol (Kennedy et al. 1994). For each set of samples, a standard curve was constructed ($r^2 = 0.998$). Method reagent blanks and certified standards (NIST Standard Reference Materials®, National Institute of Standards and Technology, Gaithersburg, MD, USA) were appropriately used. Percentage recovery ranged from 97 to 103% of values obtained by the calibration curve. A 5% matrix spike of the set was used to determine the accuracy of the data obtained, with recoveries ranging from 96 to 103% of the expected values. Another 5% of the set was used to determine the precision of the measurements (triplicates). Analyses that did not satisfy these QA/QC protocol were rerun.

Extraction of soil water and analysis

Soil water samples ($\sim$150 ml) were collected, using the suction cups, after each rainfall event that exceeded 10 mm. Samples were placed in a cooler within 15 min of extraction, and samples that could not be analyzed immediately were acidified (pH $\sim$ 2) and kept in a refrigerator until analysis. A total of 24 and 26 water samples were collected from each plot at each of the two sampling depths in 2009 and 2010, respectively. The soil water sampling and analysis was conducted with standard operating procedures required by the Florida Department of Environmental Protection (FLDEP 2002). The nitrate plus nitrite N concentration (represented by the term NO_3-N) was determined using the United States Environmental Protection Agency (USEPA) Method 353.2 (USEPA 1983) with a Flow IV, air segmented, automated spectrophotometer (O–I Analytical, College Station, TX). For this method, a filtered sample is passed through a column containing granulated copper-cadmium to reduce nitrate to nitrite. The nitrite (that originally present plus reduced nitrate) is determined by diazotizing with sulfanilamide and coupling with N-(1-naphthyl)-ethylenediamine dihydrochloride to form a highly colored azo dye which is measured colorimetrically. Ammonium-N was determined using the USEPA Method 350.1 (automated phenate colorimetry) (USEPA 1993).

Forage harvest and nutritive value analysis

The forage was harvested at 28 days intervals following the recommendation of Burton et al. (1993). A 3-m strip within each plot was randomly selected and mowed to 6-cm stubble height with a flail mower. The fresh forage weight from each strip was recorded, and a subsample of approximately 800 g (fresh weight) was collected for tissue nitrogen and digestible dry matter analyses. The remaining forage was removed using the flail mower with clipping catchment container. A total of five harvests from each plot were obtained in 2009, and six in 2010. Forage samples were oven dried at 60°C for dry matter yield determination. The dried samples were ground in a Wiley mill (Model 4 Thomas-Wiley Laboratory Mill, Thomas Scientific, Swedeboro, NJ) to pass a 1-mm screen for tissue analyses. Tissue N concentration was determined using a micro-Kjeldahl method, a modification of the aluminum block digestion technique described by Gallaher et al. (1975), followed by automated colorimetry with a Technicon Auto Analyzer. Tissue crude protein concentration was estimated by multiplying N concentration by 6.25 (Johnson et al. 2001). Samples were analyzed for in vitro digestible organic matter using the modified two-stage technique (Moore and Mott 1974).

Determination of nitrogen use and uptake efficiency

Nitrogen uptake was calculated as the product of dry matter yield and tissue N concentration. Nitrogen use efficiency was determined according to the methods described by Eghball and Maranville (1993) as follows:

$$\mathrm{NUE} = \frac{\mathrm{TDM} - \mathrm{TDM}_{\mathrm{control}}}{\mathrm{NS}} \qquad (1)$$

where NUE = nitrogen use efficiency (g g^{-1}); TDM = total above-ground dry matter (g); NS = N supplied in the fertilizer added (g).

Nitrogen uptake efficiency was computed as:

$$\mathrm{NUpE} = \frac{\mathrm{Nt} - \mathrm{Nt}_{\mathrm{control}}}{\mathrm{NS}} \qquad (2)$$

where NUpE = N uptake efficiency (g g^{-1}); Nt = total N in the plant tissue (g).

Statistical analyses

The yield response to N rates was analyzed using the Mitscherlich yield response models, a statistical model commonly used to describe the relationship between fertilizer rates and yield responses (Schabenberger and Pierce 2002). The Mitscherlich model can be expressed in the form:

$$y = a\left(1 - e^{-bx}\right) \qquad (3)$$

where y is the yield response, a is the maximum yield, b is the constant that governs the rate of yield response (steepness of the yield response curve), and x is the N fertilizer rate.

The Marquardt–Levenberg algorithm was used to find the coefficients (parameters) of the independent variables that give the best fit between the equation and the data using SigmaPlot 11.0 program (SYSTAT Software, San Jose, CA, USA). This algorithm seeks the values of the parameters that minimize the sum of the squared differences between the observed and predicted values of the dependent variable. The Shapiro–Wilk test was used to determine whether the weighted residuals (observed yield increase-estimated yield increase) of the model were normally distributed using the SYSTAT Software. Economically optimum N rate was calculated based on the expected profit from the N application, which was derived using the following calculation (McConnell and Dillon 1997):

$$\begin{aligned}\text{Profit } (\$\,\text{ha}^{-1}) = {} & \text{Yield increase due to N} \\ & \text{fertilization } (\text{kg ha}^{-1}) \times \text{Yield value} \\ & (\$\,\text{kg}^{-1}) - [\text{Applied N}(\text{kg ha}^{-1}) \\ & \times \text{ N fertilizer price } (\$\,\text{kg}^{-1})] \end{aligned} \tag{4}$$

The profit from N applications was considered to be optimized when the difference between the extra income due to the yield increase and the cost of the N fertilizer used was at its highest (positive) value. The average value of the yield increase term (Eq. 4) was obtained from the least-squares fits of the Mitscherlich response curves (Eq. 3) and its range was calculated on the basis of the standard error of the variable *a* (maximum yield) of the curves.

Tissue crude protein concentration, in vitro digestible organic matter concentration, and N uptake efficiency data were statistically analyzed using the general linear model (PROC GLM) of the SAS software (SAS Institute 2002). Differences among treatments mean values of the various parameters were separated using Tukey's Honestly Significant Difference test, which corrects for experiment-wise error rate (Littell et al. 1996). The trends of the increasing N rate effects on each of the measured parameters were assessed using polynomial contrasts (Littell et al. 1996). Changes in soil water N concentration over time were analyzed using the regression analysis procedure of the SAS software (SAS Institute 2002). The soil water N concentration data showed great variation (coefficient of variation >40%) about the mean. This variation prompted a test for the normality and homogeneity assumptions of the regression analysis procedure. Normality was tested using the Kolmogorov-Smimov procedure and the normal probability plots, and a homogeneity test was performed using residual plots (Littell et al. 1996). The data were not normally distributed, and the variances were not constant. Therefore, the soil water N concentration data were logarithmically transformed based on the Box-Cox transformation procedure (Box and Cox 1964) to conform to the normality and homogeneity assumptions of the regression analysis procedure. Data were back transformed for all discussions in the manuscript. Treatment differences were considered significant at $P \leq 0.05$.

Results and discussion

Weather conditions during experimental period

The weather conditions, particularly rainfall and temperature, during the experimental period were conducive for 'Tifton 85' production, as indicated by Burton et al. (1993). Total annual rainfall at the study site was 1,044 and 1,222 mm in 2009 and 2010, respectively, which was lower than expected, based on the 50-year average rainfall observed at the site (1,616 mm; Fig. 2). Despite the lower annual rainfall, the overall rainfall distribution pattern in both years followed a pattern similar to the 50-year average rainfall. Inadequate rain in the late spring of the 2009 season affected the initial growth and development of the grass and, consequently, delayed the first harvest, which together with the generally drier season in 2009 (compared to 2010), decreased the total annual forage yield for that year relative to yields in 2010.

Unlike rainfall, temperatures during the experimental period for the two seasons were similar, with no year effects on minimum and maximum temperatures. In 2009, the average minimum temperature during the experimental period ranged from 16°C (October) to 22°C (July), and the maximum temperature ranged from 28°C (October) to 32°C (June). Similarly, in 2010 the average minimum temperature during the experimental period ranged from 18°C (October) to 23°C (July) and the maximum temperature ranged between 27°C (October) and 33°C (June). These temperature ranges were favorable for the growth and development of 'Tifton 85' bermudagrass, which is a warm-season grass (Burton et al. 1993).

Characteristics of soil at the study site

The physical and chemical characteristics of the soil show the soil was an adequate representation of the Entosols, which forms ~80% of the agricultural land use in the Lower Suwannee River Watershed (Soil Survey Staff 2009). The soil had a coarse texture throughout the 1-m sampling depth (Table 1). The coarse soil texture, with small clay (<1.5%) and organic matter (<0.5%) contents up to 1 m depth (Table 1) and low water holding capacity ($\leq$60 g kg^{-1}; Obreza and Means 2006) suggests that the soil could be highly susceptible to nutrient (particularly NO_3) leaching losses, and would

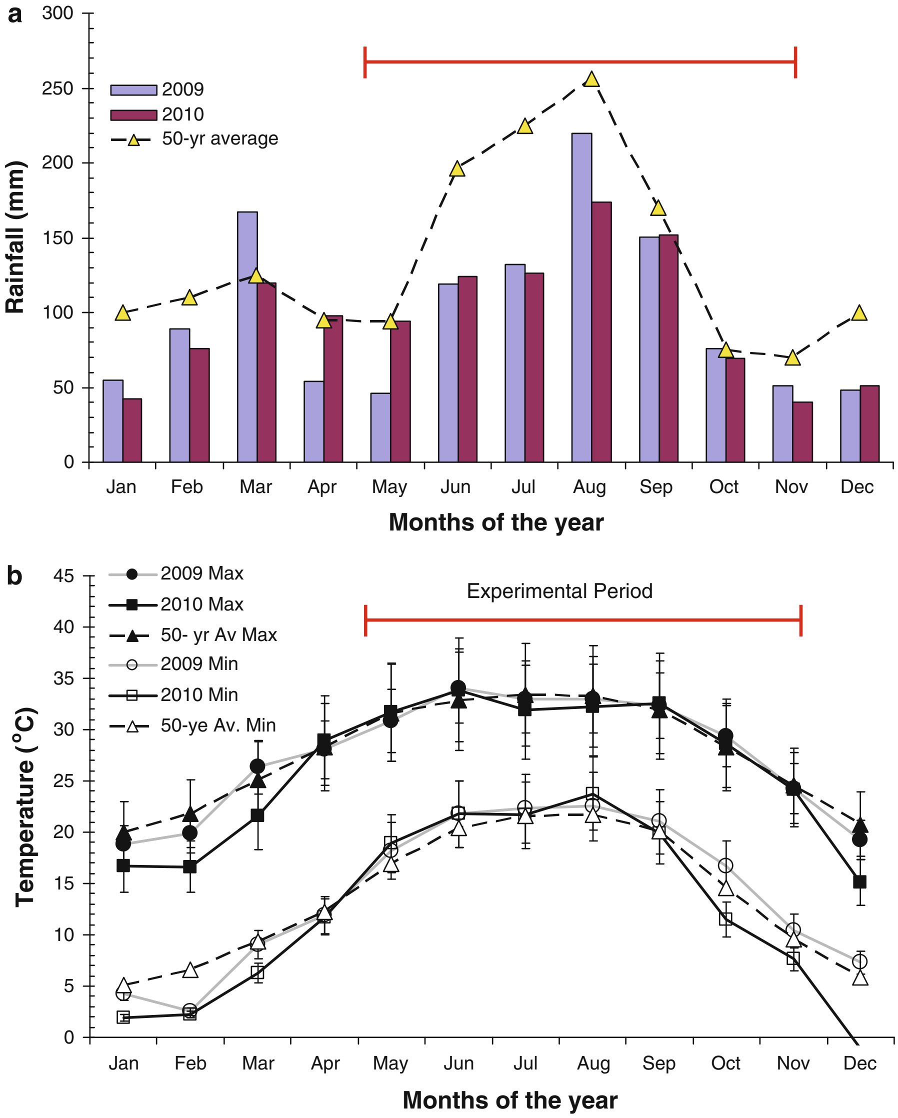

Fig. 2 Monthly rainfall (**a**) and mean monthly minimum and maximum temperatures (**b**) for the study site near Chiefland, FL, in 2009 and 2010 and the 50-year average rainfall and temperatures (*Source*: Southeast Regional Climate Center 2011). *Horizontal bars* indicate data collection period

obviously require intensive nutrient management practices to prevent or at best, reduce nutrient leaching losses. Studies have shown that NO_3 moves with the wetting front and N leaching in sandy soils is intrinsically linked with soil water dynamics. Intense rainfall or excessive irrigation combined with N application on excessively drained sandy soils with low water-holding capacity greatly enhances the potential risk of N leaching (Zotarelli et al. 2007). The surface soil (0–30 cm) was slightly acidic and the level of acidity slightly decreased with soil depth. Nevertheless, the pH of the soil was within the range of pH values (5.5–7.5; Mylavarapu et al. 2007) suitable for bermudagrass production. The total N and Mehlich-3 extractable P concentration of the soil suggest that the soil could be characterized as having "very low" native fertility (Mylavarapu et al. 2007), and thus required the maximum recommended rates of N (90 kg N ha^{-1} after each harvest) and P (45 kg P_2O_5 ha^{-1}) to support normal growth and development of the forage (Mylavarapu et al. 2007). The soil had low organic matter and clay contents and

Table 1 Selected physical and chemical characteristics of the soil used in the study

Parameter	Sampling depth		
	0–30 cm	30–60 cm	60–100 cm
Sand (g kg^{-1})	955 ± 25.2	964 ± 30.3	968 ± 28.2
Silt (g kg^{-1})	30.6 ± 5.07	29.6 ± 2.16	27.2 ± 2.09
Clay (g kg^{-1})	15.2 ± 5.05	6.38 ± 0.04	4.36 ± 1.21
pH	6.01 ± 0.22	6.14 ± 0.70	6.21 ± 0.13
Organic matter (g kg^{-1})	4.12 ± 0.72	1.36 ± 0.21	0.02 ± 0.01
Total nitrogen (mg kg^{-1})	12.8 ± 2.72	5.24 ± 0.15	0.31 ± 0.01
Nitrate nitrogen (mg kg^{-1})	8.70 ± 1.56	0.01 ± 0.00	nd[b]
Ammonium nitrogen (mg kg^{-1})	2.92 ± 0.94	0.04 ± 0.01	nd[b]
Mehlich-3 phosphorus (mg kg^{-1})	82.1 ± 8.62	42.2 ± 2.81	51.2 ± 3.14
Mehlich-3 potassium (mg kg^{-1})	45.2 ± 9.24	5.24 ± 1.09	3.24 ± 0.04
Mehlich-3 calcium (mg kg^{-1})	400 ± 39.7	146 ± 21.2	152 ± 12.9
Mehlich-3 magnesium (mg kg^{-1})	65.4 ± 15.9	41.3 ± 3.28	48.2 ± 4.98
CEC[a] (cmol kg^{-1})	3.18 ± 0.07	2.12 ± 1.04	1.64 ± 0.06

Numbers are mean values of 24 replicates ± one standard deviation (values are presented in three significant figures)

[a] Cation exchange capacity

[b] Not detected

consequently low CEC (~3 cmol$_{(+)}$ kg^{-1}), suggesting that the soil possesses small capacity to retain exchangeable cations, including NH_4^+. Thus, the applied NH_4^+ in the fertilizer used may not be retained long enough for plant uptake and could be lost through leaching. Wilklander (1974), and Mancino and Troll (1990) reported that soil retention of ammoniacal fertilizers applied at high rates is dependent on, among others, CEC, and the rate of water percolation through the soil. In a series of column leaching studies, Mackown and Tucker (1985) observed that the amount of NH_4-N leached from a loamy textured soil was linearly related to the CEC of the soil and ranged from 168.4 mg N (CEC = 29 cmol$_{(+)}$ kg^{-1}) to 11.6 mg N (CEC = 102 cmol$_{(+)}$ kg^{-1}).

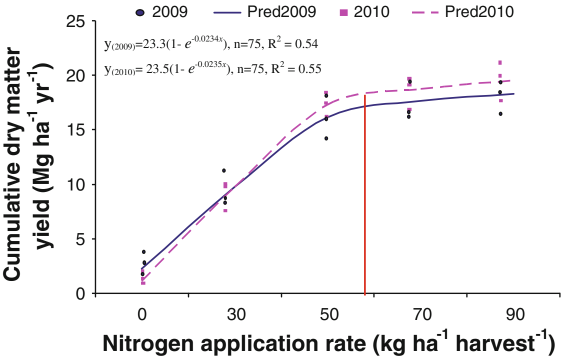

Fig. 3 Yield response curves for dry matter yield of 'Tifton 85' bermudagrass as a function of nitrogen application rates. Each *dot* represent annual dry matter yield for an individual plot. *Vertical line* indicates predicted economically optimum N rate and the corresponding herbage yields for each year

Nitrogen application rates and dry matter yield

According to the Mitscherlich model, N applications explained slightly more than half of the variation in the yield increase ($R^2 = 0.54$; Fig. 3). This suggests a profound effect on yield variation by other factors, such as rainfall, other soil nutrients, soil characteristics, etc. Measured forage yields from the areas receiving no fertilizer were 3.1 and 3.8 Mg ha^{-1} in 2009 and 2010, respectively (Fig. 3). Increasing average yield in 2010 may be attributed to increased precipitation, which lengthened the experimental period for the year resulting in an additional one harvest, compared to 2009. Notwithstanding, the average dry matter yield of the control plots (averaged over the 2 years) was low relative to reported dry matter yield values for 'Tifton 85' bermudagrass growing with adequate N supply (30 ± 5 Mg ha^{-1} year^{-1}; da Fonseca et al. 2007). The low dry matter yield for the control treatment is consistent with the "very low" native fertility designation of the soil at the site (Mylavarapu et al. 2007). Nitrogen fertilization significantly increased forage yields in both years. Applying N at 30 kg ha^{-1} harvest^{-1} increased dry matter yield to 12.9 and 13.1 Mg ha^{-1} year^{-1} for 2009 and 2010, respectively, and increasing the N rate to 50 kg ha^{-1} harvest^{-1} resulted in a further dry matter yield increases to 16.4 and 17.8 Mg ha^{-1} year^{-1} for 2009 and 2010, respectively. A further increase in N rate to 70 kg ha^{-1} harvest^{-1} resulted in only a ~10% increase in dry matter yield over the 50 kg ha^{-1} treatment in both years, and dry matter yield did not differ significantly between the 70 kg ha^{-1} harvest^{-1} treatment (77% of recommended N rate) and the recommended N rate of 90 kg ha^{-1} harvest^{-1} for the 2 years.

The economically optimum N rate derived from the response curves suggest that the field needed N fertilizer rate lower than the recommended N rate of 90 kg ha^{-1} harvest^{-1}. In calculating the economic optimum, the yield level without added N was set to 3.5 Mg ha^{-1}, i.e., the average value for the 2 years. This value was lower than the reported average 'Tifton 85' yield, but within the range of values reported for the grass produced in marginal soils with limited fertility (2.6–5.6 kg ha^{-1}, Mislevy and Martin 1998; Mandebvu et al. 1999; Clavijo et al. 2010; Liu et al. 2011). The most economical N rates were calculated for current prices of N fertilizer at $1.97–2.43 kg^{-1} N (depending on the N content of the fertilizer type) and marketable hay value of $135–152.50 Mg^{-1} for Grade 1 hay (125–150 RFV/RFQ). The resultant economically optimum N rate for both years was ~57 kg N ha^{-1} harvest^{-1} (~60% of the recommended N rate) with a projected average dry matter yield of ~17.3 Mg ha^{-1} year^{-1}, which represents >90% of the observed maximum yield (yield at the recommended N rate of 90 kg ha^{-1} harvest^{-1}). Economically optimum N rate application would have resulted in 33 kg ha^{-1} less N being applied after each harvest than the recommended rate, resulting in a potential economic benefit of ~$325 ha^{-1}.

Effects of nitrogen rates on forage quality

Application of N fertilizer significantly increased crude protein and in vitro digestible organic matter concentrations, relative to the unfertilized (control) treatment (Table 2). Application of a modest N rate of 30 kg ha^{-1} harvest^{-1} resulted in >2-fold increase (50–114 g kg^{-1}) in herbage crude protein concentration relative to the control in 2009, and >3-fold increase in 2010. A further increase in N rate to 50 kg ha^{-1} harvest^{-1} resulted in a further increases to 173 and 181 g kg^{-1} in 2009 and 2010, respectively (Table 2). Johnson et al. (2001) reported a linear increase in bermudagrass crude protein concentration with increasing levels of N fertilization. In that study, herbage crude protein concentrations were 98, 146, and 180 g kg^{-1} for fertilization levels of 0, 78, and 156 kg N ha^{-1} harvest^{-1}, respectively. Contrary to Johnson et al. (2001), no significant increases in tissue crude protein concentration were observed when the N application rate was increased beyond the 50 kg ha^{-1} harvest^{-1} treatment (Table 2). This observation suggests that unlike the other studies, the additional N applied in the present study was not taken up by the crop to increase the tissue N concentration. Minson (1990) observed that crude protein concentrations below 62 g kg^{-1} were not sufficient to meet the requirements of most ruminants, and, thus, herbage

Table 2 Nitrogen uptake efficiency, crude protein concentration, and in vitro digestible organic matter concentration (IVDOM) of 'Tifton 85' bermudagrass fertilized at different nitrogen levels during the 2-year (2009 and 2010) duration of the study

Measurements	Year	Nitrogen application rate (kg ha^{-1} year^{-1})					Standard error
		0	30	50	70	90	
N uptake efficiency (g g^{-1})	2009	NA[a]	0.42 a	0.35 b	0.30 c	0.27 d	0.02
	2010	NA[a]	0.43 a	0.37 b	0.31 c	0.26 d	0.03
crude protein (g kg^{-1})	2009	50.2 c	114 b	173 a	184 a	189 a	22.5
	2010	32.4 c	117 b	181 a	185 a	186 a	23.8
IVDOM (g kg^{-1})	2009	409 b	598 a	592 a	613 a	612 a	61.4
	2010	401 b	601 a	603 a	605 a	614 a	68.7

Numbers are mean values of 15 and 18 samples, respectively, for 2009 and 2010, presented in three significant figures

[a] Not applicable

[b] Treatment means in the same row are not significantly different ($P > 0.05$) if followed by the same letter

with crude protein concentration below this value was considered deficient. In the present study, plants provided with N fertilizer after each harvest exhibited crude protein concentrations above the suggested deficient level (Table 2).

In vitro digestible organic matter concentration was significantly lower in unfertilized controls than treatments provided with N fertilizer, but did not differ across the different N rates, with values ranging from 598 to 614 g kg^{-1} (Table 2). The in vitro digestible organic matter concentration data are consistent with the observation of Burton et al. (1997) that N rate had no effect on Pensacola bahiagrass forage in vitro digestible organic matter concentration. Adjei et al. (2000) studied the effects of N on warm-season grass yield and nutritive value and reported that N application increased crude protein concentration but in vitro digestible organic matter concentration was generally unaffected. Crude protein and in vitro digestible organic matter concentrations in the present study were consistent with what has been reported for ‘Tifton 85’ bermudagrass (Vendramini et al. 2008; Liu et al. 2011).

Soil solution nitrogen concentration in the root zone

Increased N rates resulted in increased soil solution N concentration within the root zone (0–30 cm depth) in both years (Fig. 4a, b), suggesting that the plants were exposed to larger pools of N. Analysis of the root zone soil water N concentration data across the sampling period for both years showed a highly significant positive correlation ($r^2 \approx 0.97$) between N application rate and soil water N concentration in the root zone, confirming that there was an increased N concentration in the soil solution for plant uptake due to N fertilizer application. Averaged across the sampling period of each year, the root zone soil water N concentration of the control plots (~0.18 mM; Fig. 4a, b) was consistently below a reported low solution N concentration (0.2 mM) levels for proper growth and development of most field-grown crops (Greenwood et al. 1991). Thus, it was not surprising that the control treatment produced not only low yields, but forage of low nutritive quality as well. A modest N application rate of 30 kg ha^{-1} harvest^{-1} significantly increased the mean soil solution N concentration to values (~0.85 and 0.88 mM, respectively for 2009 and 2010) greater than the suggested low soil solution N concentration. Increasing N application rate resulted in further increases in root zone soil solution N concentrations. Because solution N concentration was a point measurement reflecting the soil solution N concentration soil at the time of sampling, the connecting lines in Fig. 4a, b (and also Fig. 5a, b) are for visual representation only.

Effects of nitrogen application rates on nitrogen uptake and use efficiency

As expected, increased N application rates resulted in increased N uptake from the soil, however, N uptake efficiency (as calculated with Eq. 2) decreased with increasing N application rate. In 2009, the greatest N uptake efficiency of 0.42 g g^{-1} was observed at the lowest N application rate (30 kg ha^{-1} harvest^{-1}), and the smallest N uptake efficiency of 0.28 g g^{-1} was observed at the recommended N rate of 90 kg ha^{-1} harvest^{-1}. Similarly, in 2010, the greatest N uptake efficiency of 0.43 g g^{-1} and lowest of 0.26 g g^{-1} occurred in the treatments receiving 30 and 90 kg ha^{-1} harvest^{-1}, respectively. Thus, in both years, a substantial portion (>70%) of the applied N at the recommended rate was not utilized by the crop. This is consistent with the results from the study of Adjei et al. (2000) who observed decreasing N uptake efficiency with increasing N application rate. The authors attributed the trend to the crops’ inability to utilize all applied N at higher rates and consequently resulted in considerable N losses from the treatment receiving higher rates (Adjei et al. 2000). With respect to the N uptake efficiency concept, it was expected that the greatest N accumulation should occur in the plots receiving the recommended N application rate treatment. However, contrary to our expectation, there were no significant differences in N accumulation in the surface soil among the four fertilizer treatment (data not presented). Compared to the control plots, N accumulation in the surface soils were similar, suggesting that N which was not taken up by the plants and should have accumulated in the surface soil did not but was rather lost through leaching (the only possible N loss mechanism likely to occur at the site due to the coarse texture of the soil and the fairly flat morphology of the site).

Consistent with the decreasing trends of N uptake efficiency with N application rate, the greatest

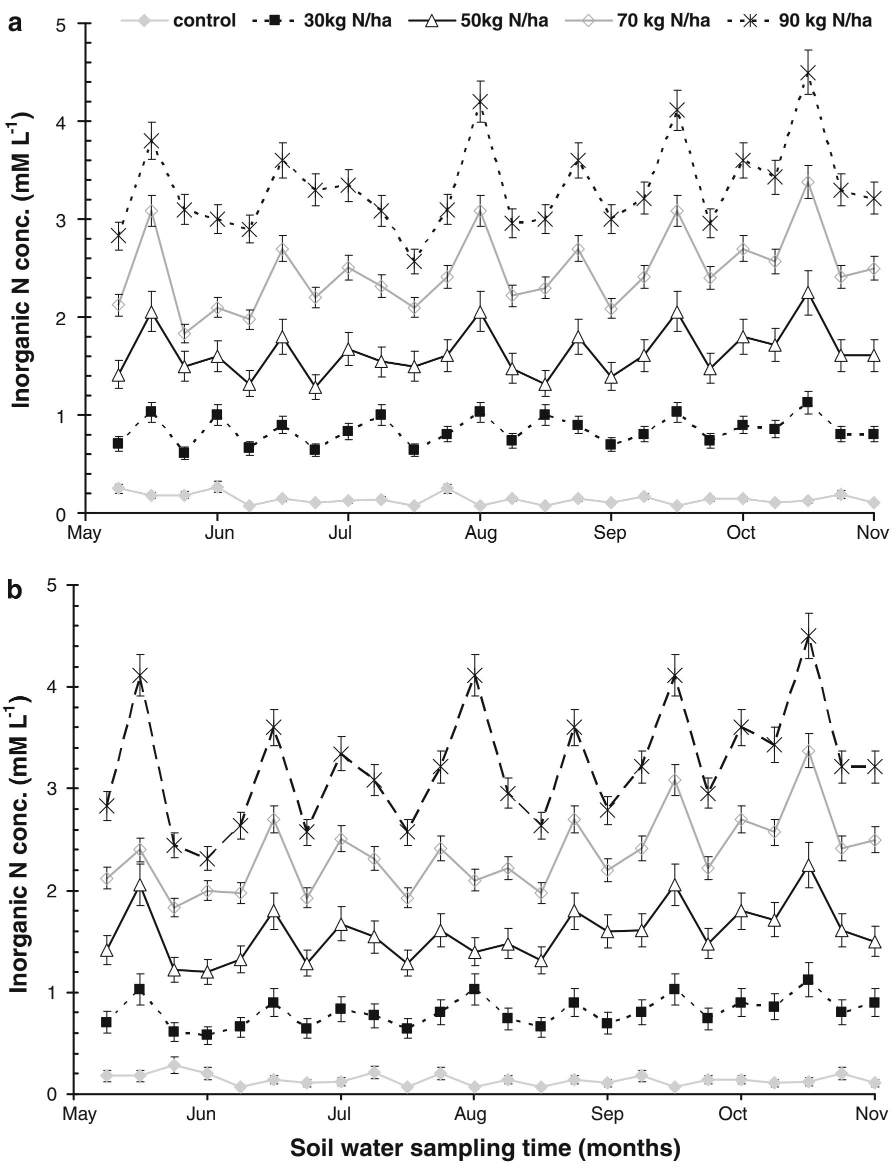

Fig. 4 Average weekly nitrate-N concentration in soil water extracted from 30 cm, representing depths within the root zone of the 'Tifton 85' bermudagrass for **a** 2009 and **b** 2010. *Error bars* denote standard error of the mean. Connecting *lines* between points are for visual purposes only

nitrogen use efficiency (NUE) of 46 and 49 g g^{-1} was observed with the lowest N application rate (30 kg N ha^{-1} harvest^{-1}) in 2009 and 2010, respectively. At the recommended N application (90 kg N ha^{-1} harvest^{-1}), NUE was 24 and 25 g g^{-1}, respectively, in 2009 and 2010. Studies have shown that 'Tifton 85' bermudagrass is one of the forage grasses that use applied N efficiently in terms of biomass production, and NUE values of up to 45 g g^{-1} have been observed (Mandebvu et al. 1999; Brink et al. 2004; Newman et al. 2007). Mislevy and Martin (1998) compared NUE of 'Tifton 85' bermudagrass with 'Florakirk' bermudagrass (*C. dactylon var florakirk*) and 'Florico' stargrass (*C. nlemfuensis Vanderyst var. nlemfuensis*) and observed 'Tifton 85' to be superior in NUE (43, 39, and 37 g g^{-1}, respectively). In separate studies, Newman et al. (2007) compared the productivity three grasses [Argentine bahiagrass, (*Paspalum notatum Flugge*); Common guineagrass, (*Panicum maximum Jacq.*); and 'Tifton 85' bermudagrass] grown at three locations (south Florida, Puerto Rico, and St. Croix) under extended (15 h) and natural daylength for 2 years and showed that 'Tifton 85' bermudagrass consistently had the greatest NUE (up to 45 g g^{-1}). Thus, the low NUE values observed in the treatment

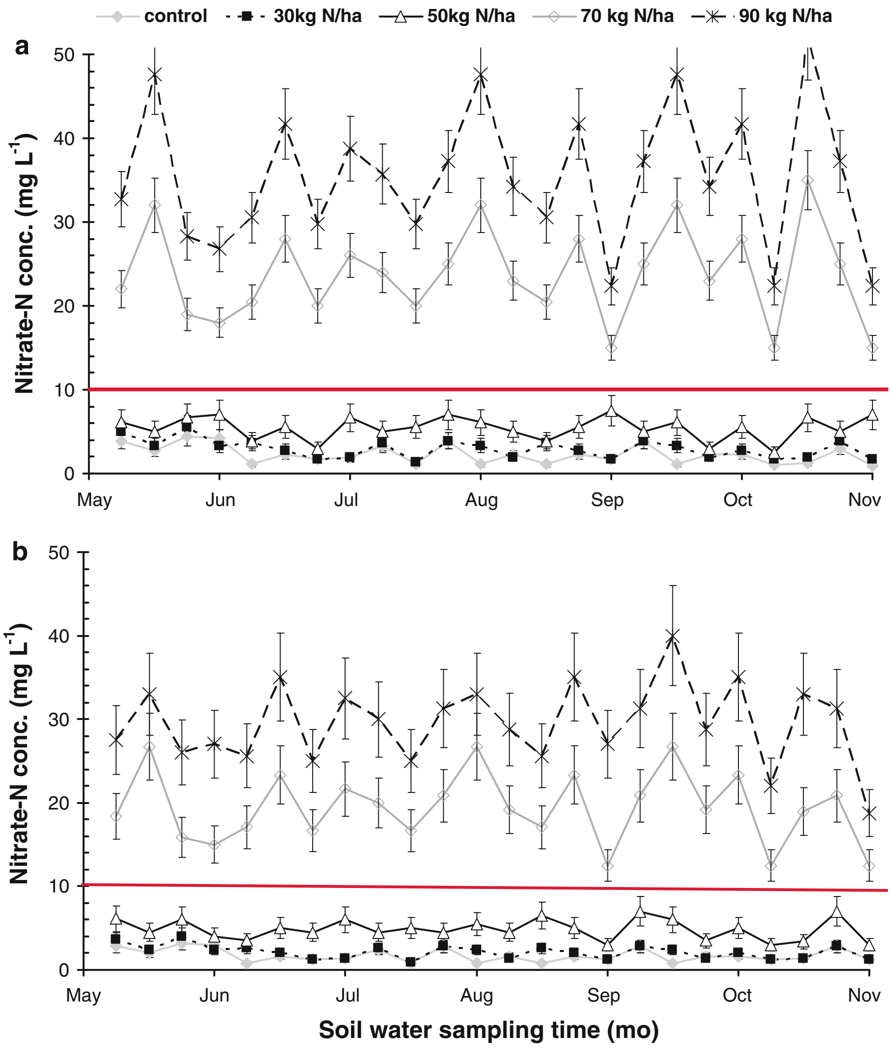

Fig. 5 Average weekly nitrate-N concentration in soil water extracted from 100 cm, representing depths below the root zone of the 'Tifton 85' bermudagrass for **a** 2009 and **b** 2010. *Error bars* denote standard error of the mean. *Horizontal line* within each graph represents the Florida's groundwater nitrate-N standard of 10 mg l^{-1}. Connecting *lines* between points are for visual purposes only

having the recommended N rate was, possibly, a soil limitation factor. The coarse nature of the sandy soil (≥1 m deep), coupled with the low CEC, portends that $NO_3^-$and NH_4^+ could not be retained in the soil long enough for plant uptake resulting in severe N leaching losses, as suggested in the studies of Wilklander (1974), Mackown and Tucker (1985) and Mancino and Troll (1990). Therefore, if the recommended N rate is maintained at the site to target maximum yields, a suggested approach to improve NUE, and consequently improve yields and mitigate the problem of N leaching losses, could be the use of slow release fertilizers. Many studies have shown the benefits of using slow release N fertilizers including efficient N use by plants, reduced leaching losses, and prolonged availability of N throughout the growing season (Alexander and Helm 1990; Catanzaro et al. 1998; Engelsjord and Singh 1997; Fan and Li 2009). Slow release N fertilizers provide a moderate but sustained N supply, which improves N fertilizer use efficiency and reduces N leaching losses (Owens et al. 1999; Fan and Li 2009). Split application of the recommended N rate could also be an alternative N management strategy to consider for production systems in such soils, though the extra labor requirement for this approach should be evaluated in terms of economic returns.

Effects of nitrogen application on nitrate leaching

Studies have shown that soil water NO_3-N concentration likely to pose ecological problems is primarily the

NO_3-N that escapes plant uptake and moves past the root zone (Woodard et al. 2002, 2003). Despite the differences in the total annual precipitation in 2009 and 2010 (1,044 and 1,222 mm, respectively; Fig. 2), the average NO_3-N concentration (averaged across entire sampling period for each year) were similar. Thus, there was no year effect on the leachate NO_3-N concentrations. The measured NO_3-N concentrations below the root zone varied over the sampling period, showing "peaks and valleys" in both years. This could be attributed to the rainfall intensity that occurred prior to soil water sampling. Generally, the greater the amount of rainfall immediately before sampling, the smaller the NO_3-N concentration measured which, possibly, could be a dilution of the leached N. Unfortunately, the actual volume of water that percolated through the soil at each rainfall event could not be measured, and empirical calculations based on basic meteorological data introduced numerous unjustified assumptions so the actual mass of leached N could not be quantified. However, despite this shortcoming of the study, treatment effects on leached NO_3-N below the root zone was still obvious. The 90 kg ha^{-1} $harvest^{-1}$ treated plots had the greatest groundwater NO_3-N concentrations followed by the 70 kg ha^{-1} $harvest^{-1}$ treated plots (Fig. 5a, b). Consistent with the high N uptake efficiency at 30 kg ha^{-1} $harvest^{-1}$, the lowest leachate N concentration (~5 mg l^{-1}) was observed at this treatment in both years (Fig. 5a, b). Across the sampling period in each year, the water samples collected from the depths below the root zone from this treatment had NO_3-N concentrations similar to that of the control plots. Since N uptake efficiency from this treatment was ~42%, the data suggest that ~58% of the applied N escaped plant uptake, but considering the N application rate it is unlikely that the amount of leached N would significantly contaminate the percolating water.

Studies have shown that NO_3-N leaching is a common occurrence in the sandy soils of southeastern United States, particularly in intensive forage production systems where high N fertilization are used (Woodard et al. 2002, 2003; Zotarelli et al. 2007; Fan and Li 2009). Fruh (1967) showed that N is one of the most limiting nutrients that causes eutrophication and, consequently, freshwater quality deterioration. Further, it is reported that high N concentrations (>10 mg l^{-1}) in drinking water could lead to methemoglobinemia, or "blue baby" syndrome (USEPA 1992). Thus, USEPA and US Public Health Service (USPHS) have established NO_3-N level of 10 mg l^{-1} as the maximum contaminant limit in drinking water for humans and domesticated animals (USEPA 1992). Consequently, in 1996, the Florida Department of Environmental Protection (FLDEP) set its portable water and groundwater NO_3-N standard at 10 mg l^{-1} (FLDEP 1996).

Based on the FLDEP groundwater NO_3-N standard, plots receiving N application rate of ≥70 kg ha^{-1} $harvest^{-1}$ (≥77% of the recommended N rate) could negatively impact groundwater quality, if such rates are applied to soils with coarse (sand) textures having limited water and nutrient holding capacity. Additionally, our results indicate that for plots receiving N application at the recommended rate of 90 kg ha^{-1} $harvest^{-1}$ at this site, an average NO_3-N concentration of 35 mg l^{-1} (averaged across sampling period for both years) occurred in leachate, and 20 mg l^{-1} for the 70 kg ha^{-1} $harvest^{-1}$ treatment (Fig. 5a and b). These NO_3-N concentrations were 3.5X and 2X the FLDEP groundwater NO_3-N standard, and should be of environmental concern to stake holders. Applying N at rates ≤50 kg ha^{-1} $harvest^{-1}$ resulted in leachate NO_3-N concentrations below the groundwater NO_3-N standard of 10 mg l^{-1} under the site's soil and microclimate conditions. Thus, for environmental sustainability, a critical look into site-specific N fertilizer rate recommendation is imperative. Such recommendations should not only focus on maximum forage production, but mainly on the economically optimum N rate, having full cognizance of potential N leaching losses.

Conclusions

When considering production only, N rate of 90 kg ha^{-1} $harvest^{-1}$ produced the greatest yield but also resulted in significant NO_3-N leaching, with leachate NO_3-N concentration exceeding the groundwater NO_3-N standard. To obtain potential forage yields of adequate nutritive value in such leaching-sensitive soils, the recommended N rate, if it has to be applied, should be done in split doses, and the use of new N fertilizer products, e.g. slow release N fertilizers, should be considered for utilization in the production systems in such soils. Nonetheless, the study showed a modeled economically optimum N rate of ∼57 kg N ha^{-1} $harvest^{-1}$ (∼60% of the recommended N rate), which projected an average dry matter yield of >90% of the maximum yield at the site without sacrificing the forage quality. For growers, the optimum N rate cannot be a fixed percentage of that required for maximum yield response because the optimum depends on the price combination of N fertilizer and the value of the marketable yield, which fluctuates but still a better option. We conclude that, potential economic and environmental benefits could be attained when N application rate recommendations are based on site-specific economically optimum N rate.

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