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Annual Nitrogen Requirement of Bahiagrass Lawns Maintained in Subtropical Climates

Pauric McGroary, Travis W. Shaddox,* John L. Cisar, J. Bryan Unruh, and Laurie E. Trenholm

ABSTRACT

Current best management practices (BMPs) regarding the application of nitrogen (N) to bahiagrass (*Paspalum notatum* Flügge) in southern Florida are 98 to 196 kg ha^{-1} yr^{-1}. This range has not been tested to determine if the range adequately produces quality bahiagrass without adversely contributing to nonpoint source additions of N to ground water. The objectives of this research were to determine the N necessary to support acceptable bahiagrass quality by measuring associated color, growth, and nitrate-N (NO$_3$–N) leaching. Research was conducted from October 2006 to October 2008 in Fort Lauderdale, FL. Nitrogen was applied in 60-d cycles at rates of 49, 98, 196, or 294 kg ha^{-1} yr^{-1} under two irrigation regimes (2.5 mm d^{-1} and 13 mm three times weekly). Bahiagrass quality and color was acceptable under each N rate during each cycle and regression indicated application of N to bahiagrass was not necessary to produce acceptable turfgrass. Nitrate-N leaching was unaffected by N rates during each cycle except during Cycle 3 of 2008 when the 196 and 294 kg ha^{-1} yr^{-1} led to 93 and 94% greater leaching, respectively, than the 49 kg ha^{-1} yr^{-1}. The high-irrigation regime increased NO$_3$–N leaching by as much as eightfold but was not consistent among cycles. If current N recommendations were revised downward (~49 kg ha^{-1} yr^{-1}), bahiagrass quality would remain acceptable and the risk of NO$_3$–N leaching would be reduced.

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Abbreviations: BMP, best management practice.

Bahiagrass is planted on >800,000 ha in Florida (Newman et al., 2014) making it the most abundant turfgrass in Florida. Additionally, bahiagrass is a common turfgrass in Florida home lawns and can be considered a low-maintenance grass requiring less water and N than other warm-season turfgrasses. Furthermore, bahiagrass is well adapted to sandy, acidic soils, which can be common in many parts of Florida. For these reasons, bahiagrass may be a suitable turfgrass for home owners who prefer to reduce water and nutrient applications. Nitrogen recommendations to St. Augustinegrass [*Stenotaphrum secundatum* (Walt.) Kuntze] (Shaddox et al., 2016b) and zoysiagrass (*Zoysia japonica* Steud.) (Trenholm et al., 2012) have been reported to be as high as 165 and <196 kg ha^{-1} yr^{-1}, respectively. Nitrogen requirements of bahiagrass are based on bahiagrass as forage (Newman et al., 2014) rather than maintained as a lawn turf. Nevertheless, recommended N applications to bahiagrass lawns in southern Florida range from 98 to 196 kg ha^{-1} yr^{-1} (Trenholm et al., 2011). This range is intended to produce acceptable bahiagrass across a range of aesthetic preferences. However, the recommended N range is largely based on observational data or results published on other warm-season turfgrasses. Thus, N applications to turfgrasses in Florida have been scrutinized and, in some cases, have been

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severely restricted without consideration given to potential unintended consequences (Hochmuth et al., 2012).

Studies documenting the influence of N rates on bahiagrass lawn quality are limited. However, at appropriate rates, studies have indicated N applications are essential to producing acceptable turfgrass color and quality (Beard, 1973). Snyder and Cisar (2000) applied N at rates of 25, 50, and 100 kg ha^{-1} to 'Tifgreen' bermudagrass [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burtt-Davy] and reported turf quality increased as N rates increased during each 3-mo cycle except one during a 3-yr period. The authors further noted that N applied at 25 kg ha^{-1} yr^{-1} led to unacceptable turf during most cycles and that increasing N applied to 100 kg ha^{-1} yr^{-1} increased turf quality. Similar results were found on St. Augustinegrass. Trenholm and Unruh (2007) applied N at various rates to St. Augustinegrass in central Florida and reported acceptable turf was produced by N applied between 98 and 245 kg ha^{-1} yr^{-1}. This range was approximately twofold greater than the N rate necessary to produce acceptable St. Augustinegrass in northern Florida (Trenholm and Unruh, 2007). Differences were attributed to a longer growing season in central vs. northern Florida.

Previous studies indicate irrigation regime can have a pronounced influence on NO_3–N leaching (Hergert, 1986; Starrett et al., 1995). Applied in excess of evapotranspiration, irrigation may increase NO_3–N leaching and degrade water quality (Barton and Colmer, 2006; Hull and Liu, 2005; Owen and Barraclough, 1983). Snyder et al. (1984) investigated the influence of irrigation on N leaching from turfgrass using a soil tensiometer-controlled irrigation system compared with a traditional daily irrigation regime and reported the sensor-based regime reduced NO_3–N leaching by as much as 96% in one leachate collection cycle. Furthermore, the authors noted turf quality and growth were greater than or equal to the quality and growth resulting from the daily irrigation regime.

Prior research conducted on bahiagrass forage species indicates the current Florida BMP recommendations are reasonable (Duncan, 1997). However, bahiagrass maintained under lawn conditions may differ. We are unaware of any research that has investigated the minimum N rate necessary to achieve acceptable bahiagrass as a lawn turf under southern Florida conditions. Therefore, the objectives of this study were to determine the minimum amount of N necessary to produce acceptable quality bahiagrass and to determine the influence of N rate and irrigation regime on color, growth rate, and NO_3–N leaching.

MATERIALS AND METHODS

This study was conducted at the University of Florida Research and Education Center in Fort Lauderdale (26°03′ N, 80°13′ W). Turf was grown on a mined mason sand (Rymatt Golf, Collier County, Florida). Experimental design was a split-plot where main blocks (8 by 4 m) consisted of one of two irrigation regimes: 2.5 mm d^{-1} (low) or 13.0 mm three times weekly (high). When daily precipitation exceeded 6.4 mm, irrigation was halted. Subplots (2 by 4 m) consisted of four N rates: 8.2, 16.3, 32.6, or 49 kg ha^{-1}. Nitrogen rate treatments were applied on 12 Oct., 12 Dec. 2006; 15 Mar., 17 Apr., 18 June, 16 Aug., 11 Oct., 21 Dec. 2007 and 20 Feb., 21 Apr., 23 June, and 3 Sep. 2008. Each application date represented the beginning of a new fertilizer cycle such that Cycle 1 began on 12 Oct. 2006. Nitrogen was applied using solubilized urea (46–0–0) (PCS Sales, Inc.) applied through a CO_2 backpack sprayer to uniformly cover each subplot at a rate of 0.12 L m^{-2} with two flat-fan TeeJet 8010 nozzles (TeeJet Technologies,) spaced ~510 mm apart. Phosphorus and K were applied every 90 d at 49 and 98 kg ha^{-1} yr^{-1}, respectively, using triple superphosphate (0–46–0) and muriate of potash (0–0–60). Additional nutrients were applied as a micronutrient solution (Harrell's Max Minors, Hocking International Laboratories) containing Mg 1%, S 3.5%, B 0.02%, Cu 0.25%, Fe 4%, Mn 1%, Zn 0.6%, and Mo 0.0005% at 15 kg ha^{-1} every 90 d.

Leachate was collected using lysimeters inserted in each subplot. The lysimeters were constructed from 208-L (92 cm height; 59.7 cm diam.; 1.3-cm-thick wall) polyethylene drums with a flat bottom (U.S. Plastic Corp.). Lysimeters were fitted with a 1.9-cm PVC drainage pipe at the bottom to collect drainage. Each lysimeter was then filled with 10-cm layer of 0.6-cm river gravel, a 5-cm layer of coarse sand, and then filled with the fine sand root-zone mix to the same level as the rest of the surrounding plot. Drainage water from each lysimeter was collected in 19-L polyethylene containers. A sand-based bahiagrass sod was planted on 13 Apr. 2006.

Leachate samples were collected for volume determination and acquiring a 20-mL subsample for NO_3–N + NO_2–N analysis from each lysimeter. Leachate samples were collected when leachate exceeded 100 mL, which was ~2 wk^{-1}. Collection cycles began when treatments were applied and continued for ~60 d. Nitrate concentration was measured using a continuous segmented flow analyzer (AutoAnalyzer 3, Seal Analytical) at the University of Florida Analytical Research Laboratory, Gainesville, FL, using USEPA method 353.2 (USEPA, 1983). Concentrations that were lower than the minimum detection limit of 0.05 mg L^{-1} were corrected to the minimum detection limit value.

Perimeter irrigation systems were installed for each of the main plots and consisted of Rainbird 3500 sprinklers spaced at 8 by 8 m adjusted to spray an inward quarter circle. Turf was cut weekly at a height of 7.5 cm using a rotary mower. Harvested tissue was collected, oven-dried at 60°C for 48 h, and then weighed. When turf was cut on the same day as a treatment application, treatments were applied after the harvest.

Turf quality and turf color were recorded fortnightly during the growing season on a scale of 1 to 10, where quality of 1 = dead or brown turf and quality 10 = optimal healthy turf. Quality ratings ≥6.0 were considered acceptable (Krans and Morris, 2007). Meteorological data were collected on 15-min intervals over the duration of the research from an on-site weather network system (http://fawn.ifas.ufl.edu).

Main and subplots were arranged in a randomized complete block design with four replications and type III tests were adjusted for a split-plot design. A linear mixed model was used to account for split-plot design and the Kenward–Roger method was used to estimate the degrees of freedom. Model residuals were analyzed for normality both graphically and numerically with the Shapiro–Wilk *W*-test (Royston, 1982). Data were also checked graphically for homogeneity of variance. These tests determined NO_3–N leaching and growth rate residuals were nonnormal while turf quality and color residuals were normally distributed. Thus, NO_3–N leaching and growth rate data were transformed logarithmically and analysis of variance was conducted on the transformed data, which satisfied assumptions of normality and homogeneity of variance. While statistics were conducted on transformed data, transformed and actual values are reported. Procedure GLIMMIX (SAS Institute, 2010) and SigmaPlot version 12.5 (Systat Software, 2013) were used to analyze data. Mean separations were performed using Tukey–Kramer at $P < 0.05$. Regression of N rate and turf quality, regression equation, and the coefficient of determination (r^2) were determined using SigmaPlot. For regression analysis of N rate and turf quality during Cycle 1 through Cycle 6, data included 72 observations (nine rating events × four replicates × two irrigation rates), 56 observations (seven rating events × four replicates × two irrigation rates), 48 observations (six rating events × four replicates × two irrigation rates), 56 observations (seven rating events × four replicates × two irrigation rates), 72 observations (nine rating events × four replicates × two irrigation rates), and 40 observations (five rating events × four replicates × two irrigation rates), respectively.

Table 1. Historical (10-yr average) and monthly average air and soil temperature from 2007 to 2008 in Ft. Lauderdale, FL.

	Air temperature			Soil temperature		
Month	2007	2008	Historical	2007	2008	Historical
	°C					
January	21.5	19.8	19.0	22.3	21.1	20.8
February	22.1	19.6	20.3	22.4	20.7	22.2
March	22.1	22.4	22.8	22.8	22.7	23.8
April	23.3	23.5	24.8	24.6	25.1	26.3
May	25.1	26.6	25.7	26.0	27.7	28.2
June	26.3	27.2	27.1	26.7	28.3	29.1
July	27.8	27.3	27.7	28.4	28.2	29.8
August	28.5	27.8	28.0	29.2	28.3	30.0
September	27.4	27.5	27.1	28.3	28.0	28.9
October	26.8	24.8	25.5	26.5	25.5	27.1
November	22.5	20.5	22.4	23.4	22.6	23.9
December	22.5	20.5	20.8	23.0	21.2	22.1

RESULTS

Climate

The annual average air and soil temperature was 0.8 and 0.4°C lower, respectively, in 2008 than in 2007 (Table 1). The average monthly air temperature during January and February was 1.7 and 2.5°C lower, respectively, in 2008 than 2007. Similarly, the average monthly soil temperature during January and February was 1.2 and 1.7°C lower, respectively, in 2008 than 2007. Monthly rainfall exceeded the 30-yr normal rainfall during 8 mo (Fig. 1).

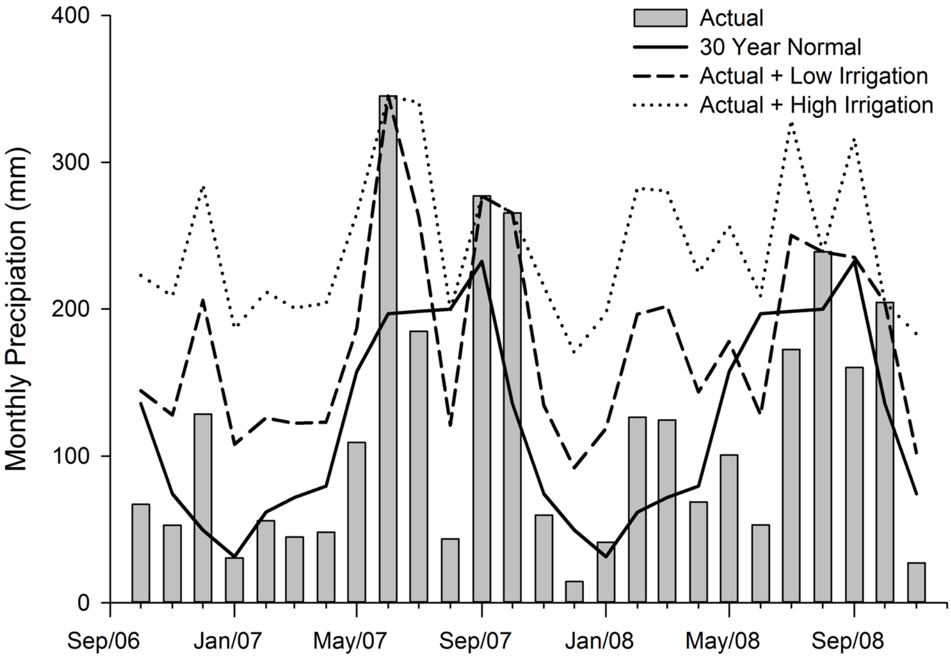

Fig. 1. Actual rainfall, 30-yr normal rainfall, actual rainfall plus low irrigation, and actual rainfall plus high irrigation for each month research conducted over the 2-yr study period in Ft. Lauderdale, FL.

Table 2. Type III tests for fixed effects of turf quality, turf color, growth rate, and NO_3–N leached from bahiagrass (*Paspalum notatum* Flügge) in response to year, N rate, and irrigation from 2007 to 2008 in Ft. Lauderdale.

Source of variation	C1†	C2	C3	C4	C5	C6	Average
Quality							
Year (Y)	NS‡	NS	NS	NS	NS	*	NS
N rate (NR)	***	***	***	***	***	***	***
Irrigation (I)	NS	NS	NS	NS	NS	NS	NS
Y × NR	NS	NS	NS	NS	NS	NS	NS
Y × I	NS	NS	NS	NS	NS	*	NS
I × NR	NS	NS	NS	NS	NS	NS	NS
Y × I × NR	NS	NS	NS	NS	NS	NS	NS
Color							
Year (Y)	*	NS	NS	*	NS	*	*
N rate (NR)	***	***	***	***	***	***	***
Irrigation (I)	NS	NS	NS	*	NS	NS	NS
Y × NR	NS	NS	NS	NS	*	NS	NS
Y × I	NS	NS	NS	NS	NS	NS	NS
I × NR	NS	NS	NS	NS	NS	NS	NS
Y × I × NR	NS	NS	NS	NS	NS	NS	NS
Growth Rate							
Year (Y)	*	***	*	**	NS	**	**
N rate (NR)	***	***	***	***	***	***	***
Irrigation (I)	NS	NS	NS	NS	NS	NS	NS
Y × NR	NS	***	NS	NS	NS	NS	NS
Y × I	NS	NS	NS	NS	NS	NS	NS
I × NR	NS	NS	NS	NS	NS	NS	NS
Y × I × NR	NS	NS	NS	NS	NS	NS	NS
Nitrate-N leached							Cumulative§
Year (Y)	NS	*	**	NS	*	*	*
N rate (NR)	NS	NS	*	NS	NS	NS	*
Irrigation (I)	*	NS	NS	**	NS	*	NS
Y × NR	NS	NS	**	NS	NS	NS	*
Y × I	NS	NS	NS	*	NS	NS	NS
I × NR	NS	NS	**	NS	NS	NS	NS
Y × I × NR	NS	NS	NS	NS	NS	NS	NS

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Cycles 1 through 6 were ~60 d beginning on 12 Oct., 12 Dec., 15 Mar., 17 Apr., 18 June, and 16 Aug. 2006; and 12 Oct., 21 Dec., 20 Feb., 21 Apr., 23 June, and 3 Sept. 2007, respectively.

‡ NS, nonsignificant.

§ Annual cumulative.

During June, September, and October of 2007, rainfall totaled 345, 277, and 265 mm and exceeded the 30-yr normal rainfall by 148, 44, and 129 mm, respectively. Additionally, during February and March 2008, rainfall totaled 126 and 124 mm and exceeded the 30-yr normal by 64 and 52 mm, respectively.

Turf Quality and Color

Turf quality was influenced by N rate during each cycle and annual average (Table 2). The influence of all remaining main effects and their interactions on turf quality during each cycle and annual average was insignificant except during Cycle 6 for year (Y) and the Y × irrigation (I) interaction.

Each N rate resulted in acceptable quality during each cycle and annual average. Increasing applied N from 49 to 98 kg ha^{-1} yr^{-1} led to increased turf quality during Cycles 3 and 4, whereas increasing N rate from 49 to 196 and 294 kg ha^{-1} yr^{-1} led to increased turf quality during each cycle and annual average (Table 3). Increasing N rate from 196 to 294 kg ha^{-1} yr^{-1} did not result in greater turf quality except in Cycle 3. The lowest and highest turf quality resulted from N applied at 49 and 294 kg ha^{-1} yr^{-1}, respectively. Turf quality was poorly correlated (r^2 = 0.08 to 0.24) to N rate during each cycle (Fig. 2). The y-intercept of each cycle was greater than the minimum acceptable limit for acceptable bahiagrass (6.0).

Turf color was influenced by N rate during each cycle and annual average whereas irrigation influenced turf color only during Cycle 4 (Table 2). Increasing N applied from 49 to 98 kg ha^{-1} yr^{-1} resulted in greater turf color in Cycles 3, 4, and 5 (Table 3). Whereas, increasing N from 196 to 294 kg ha^{-1} yr^{-1} led to increased turf color in Cycles 3 and 4. Acceptable color was observed from each N rate during each cycle and annual average. The lowest and highest annual average turf color observed was 6.6 and 7.4 from N applied at 49 and 294 kg ha^{-1} yr^{-1}, respectively.

Growth Rate

Year and N rate influenced growth rate during each cycle and annual average except during Cycle 5 when year was insignificant (Table 2). However, during Cycle 2, growth rate was influenced by the Y × N rate interaction, and thus, results are reported accordingly. Growth rate increased by increasing N applied from 49 to 98 kg ha^{-1} during Cycle 3 and Cycle 6 only (Table 3). Annual average growth rate increased by ~1.5-fold by increasing applied N from 49 to 196 kg ha^{-1}. During Cycle 2 of 2008, bahiagrass growth rate was 0.0 g m^{-2} d^{-1} from each N rate, thus, no differences were observed (Table 4). No growth in Cycle 2 of 2008 was followed by the second lowest growth rate of any cycle, which was observed in Cycle 3 of 2008.

Nitrate Leaching

Nitrate-N leaching during Cycle 3 was influenced by the Y × N rate interaction, which was sufficient to produce the same interaction when cumulated annually (Table 2). Thus, the influence of N rate was determined within each year. Irrigation influenced NO_3–N leaching during Cycles 1, 4, and 6. Additionally, NO_3–N leaching during Cycle 4 was influenced by the Y × I interaction.

Nitrate-N leached was unaffected by N rate during 2007 (Table 5). During 2008, NO_3–N leaching was influenced by N rate during Cycle 3 and annual cumulative. During Cycle 3, N applied at 196 and 294 kg ha^{-1} yr^{-1}

Table 3. Bahiagrass (*Paspalum notatum* Flügge) quality, color, and growth rate as influenced by N rate from 2007 to 2008 in Ft. Lauderdale, FL. Values in parenthesis represent backtransformed values.

Nitrogen rate	C1†	C2	C3	C4	C5	C6	Average
kg ha^{-1} yr^{-1}							
				Turf quality			
				1–10			
49	6.7b‡	6.5c	6.3c	6.7c	6.7b	6.4b	6.5c
98	7.0ab	6.8bc	6.6b	7.0b	6.9ab	6.7ab	6.8b
196	7.2a	7.1ab	6.8b	7.2ab	7.1a	7.0a	7.1ab
294	7.2a	7.3a	7.2a	7.4a	7.2a	7.1a	7.2a
				Turf color			
				1–10			
49	6.8b	6.5c	6.5c	6.8c	6.7c	6.6b	6.6c
98	7.2ab	6.9bc	6.8b	7.2b	7.0b	6.9b	6.9b
196	7.4a	7.2ab	7.1b	7.3b	7.2ab	7.3a	7.2a
294	7.4a	7.4a	7.5a	7.7a	7.4a	7.3a	7.4a
				Growth rate			
				ln (g m^{-2} d^{-1})			
49	−0.74 (0.5)b	−1.39 (0.3)c	−1.70 (0.2)c	−0.10 (1.1)c	1.03 (2.9)c	0.74 (2.2)c	0.28 (1.4)b
98	−0.69 (0.5)b	−1.30 (0.3)bc	−1.26 (0.3)b	0.11 (1.3)bc	1.22 (3.5)bc	0.94 (2.7)b	0.47 (1.7)b
196	−0.39 (0.7)a	−0.98 (0.4)ab	−0.80 (0.5)a	0.45 (1.8)ab	1.42 (4.3)ab	1.12 (3.3)ab	0.71 (2.1)a
294	−0.35 (0.7)a	−0.88 (0.4)a	−0.75 (0.5)a	0.58 (1.9)a	1.49 (4.5)a	1.20 (3.5)a	0.78 (2.2)a

† Cycles 1 through 6 were ~60 d beginning on 12 Oct., 12 Dec., 15 Mar., 17 Apr., 18 June, and 16 Aug. 2006; and 12 Oct., 21 Dec., 20 Feb., 21 Apr., 23 June, and 3 Sept. 2007, respectively.

‡ Within columns, values followed by the same letter are not different according to Tukey-Kramer at the 0.05 probability level.

resulted in ~16-fold greater NO_3–N leaching than the 49 kg ha^{-1} yr^{-1}. When NO_3–N leaching was cumulated annually, NO_3–N leaching produced by N applied at 294 kg ha^{-1} yr^{-1} was increased by eightfold compared with 49 kg ha^{-1} yr^{-1}. In Cycle 3 and annual cumulative of 2007, leachate volumes did not differ in response to N rate (data not shown).

Nitrate-N leaching was affected by irrigation during Cycles 1, 4, and 6. During Cycle 1 and Cycle 6, the high-irrigation regime led to 1.5- and threefold greater leaching, respectively, than the low-irrigation regime (Table 6). Nitrate-N leaching during Cycle 4 as influenced by irrigation differed between years (Table 6). During 2007, NO_3–N leaching was unaffected by irrigation, while in 2008 the high-irrigation regime led to an eightfold increase in NO_3–N leached compared with the low regime. During each cycle, the high irrigation resulted in greater leachate volumes than the low irrigation, leading to a 66% increase in total leachate (data not shown).

DISCUSSION

Turf Quality and Color

Bahiagrass quality and color was influenced by N rate during each cycle with little or no influence from irrigation (Table 1). Increases in turf quality (Skogley and Ledeboer, 1968; Snyder and Cisar, 2000; Wu et al., 2010) and color (McGroary et al., 2009; Trenholm and Unruh, 2007) observed from increasing N rates have been noted in prior studies. The observed increase in quality is generally attributed to increased N uptake, which, in turn, leads to increased production of amino acids, proteins, chlorophyll, and hormones (Carrow et al., 2001). We observed a weak ($r^2 < 0.24$) yet significant relationship ($P < 0.001$) between turf quality and N rate. Other investigators have reported a stronger correlation between turf quality and N rate (Shaddox et al., 2016b; Trenholm and Unruh, 2007). However, prior studies have not investigated bahiagrass under lawn conditions in southern Florida. The high temperature and rainfall typically observed in southern Florida may result in N mineralization rates higher than those observed in prior studies. Additionally, the low N requirements typically associated with bahiagrass may be sufficed by atmospheric N deposition, which can exceed 3.0 kg ha^{-1} yr^{-1} of inorganic N in Ft. Lauderdale (National Atmospheric Deposition Program, 2015). Therefore, we postulate that the low N requirements of bahiagrass combined with N mineralization and atmospheric N deposition resulted in conditions that supplied sufficient N to meet the needs of the turfgrass. Thus, additional N applications were unnecessary, and a weak correlation between turf quality and N rate was observed.

Growth Rate

Irrigation did not influence growth rate during any cycle (Table 1). Previous researchers have reported irrigation to influence bahiagrass growth; however, many of these studies have included unirrigated bahiagrass (Beaty et al., 1974). Ashley et al. (1965) investigated 'Pensacola' bahiagrass yield as influenced by N rates and irrigation and reported

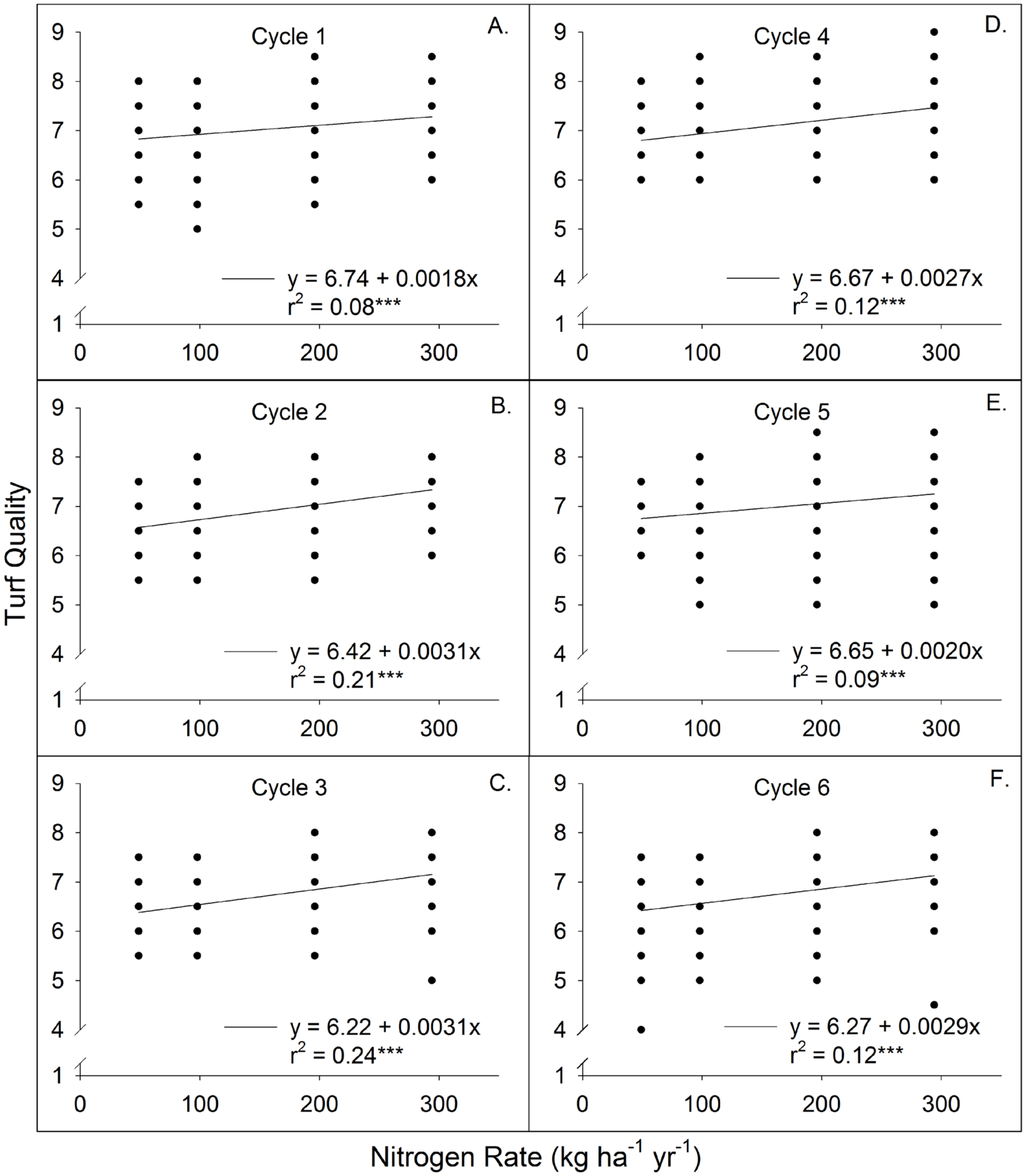

Fig. 2. Relationship between N rate and bahiagrass (*Paspalum notatum* Flügge) visual quality from 2007 to 2008 in Ft. Lauderdale, FL. (A) Cycle 1. Mid-October through mid-December. $n = 72$. (B) Cycle 2. Mid-December through Mid-March. $n = 56$. (C) Cycle 3. Mid-March through mid-April. $n = 48$. (D) Cycle 4. Mid-March through mid-June. $n = 56$. (E) Cycle 5. Mid-June through mid-August. $n = 72$. (F) Cycle 6. Mid-August through mid-October. $n = 56$. r^2 values marked with *** are significant at $P < 0.001$.

irrigation increased yields only during periods of limited rainfall. The authors conducted their study in Alabama where limited rainfall existed during the study. Conversely, our study was conducted in southern Florida where rainfall is generally not a limiting factor as a result of the subtropical climate. Thus, our findings seem reasonable, particularly since we compared low and high irrigation in a high precipitation environment rather than irrigated or nonirrigated.

We found N rates to positively influence growth rate during each cycle, which corroborates previous studies. Ebdon et al. (2013) investigated the influence of N applied at 49, 147, 245, 343, and 441 kg ha^{-1} yr^{-1} to perennial ryegrass (*Lolium perenne* L. 'Brightstar') and reported growth rate increased as N rate increased. The author's lowest and highest N rates were 49 and 441 kg ha^{-1} yr^{-1}, which led to growth rates of 1.6 and 7.1 g m^{-2} d^{-1}, respectively. Similarly, Snyder and Cisar (2000) investigated N applied at 25, 50, and 100 kg ha^{-1} yr^{-1} to bermudagrass and observed clipping yields increased with each increase in N during each year of their 3-yr study. Our growth rate differences were also consistent among cycles except during Cycle 2 of 2008 when N rates resulted in no increase in growth. This was a result of lower air and soil temperatures experienced in January and February 2008 than in 2007, which led to bahiagrass entering a state of quiescence in late winter.

Table 4. Bahiagrass (*Paspalum notatum* Flügge) growth rate in response to the interaction of year and N rate from 2007 and 2008 in Ft. Lauderdale, FL. Values in parenthesis represent backtransformed values.

	Growth rate						
Nitrogen rate	C1†	C2	C3	C4	C5	C6	Average
kg ha^{-1} yr^{-1}	ln (g m^{-2} d^{-1})						
				2007			
49	−0.76 (0.47)a‡	−1.39 (0.26)c	−1.12 (0.36)b	0.46 (1.68)b	1.16 (3.23)b	1.01 (2.85)b	0.52 (1.72)b
98	−0.88 (0.43)a	−1.30 (0.29)bc	−0.74 (0.52)ab	0.57 (1.91)ab	1.32 (3.88)ab	1.24 (3.56)ab	0.69 (2.06)ab
196	−0.59 (0.55)a	−0.98 (0.39)ab	−0.61 (0.59)a	0.80 (2.44)ab	1.45 (4.36)a	1.40 (4.20)a	0.85 (2.43)a
294	−0.53 (0.59)a	−0.88 (0.44)a	−0.40 (0.68)a	0.96 (2.69)a	1.53 (4.64)a	1.46 (4.40)a	0.95 (2.60)a
				2008			
49	−0.73 (0.50)b	UD§ (0.00)	−2.29 (0.12)c	−0.68 (0.59)b	0.90 (2.56)b	0.46 (1.63)c	0.04 (1.08)c
98	−0.50 (0.63)ab	UD (0.00)	−1.78 (0.18)bc	−0.34 (0.77)ab	1.12 (3.18)ab	0.64 (1.91)bc	0.26 (1.33)bc
196	−0.11 (0.90)a	UD (0.00)	−1.11 (0.39)a	0.10 (1.26)a	1.40 (4.18)a	0.83 (2.37)ab	0.56 (1.82)ab
294	−0.24 (0.79)a	UD (0.00)	−1.03 (0.33)ab	0.21 (1.28)a	1.45 (4.36)a	0.94 (2.59)a	0.61 (1.87)a

† Cycles 1 through 6 were ~60 d beginning on 12 Oct., 12 Dec., 15 Mar., 17 Apr., 18 June, and 16 Aug. 2006; and 12 Oct., 21 Dec., 20 Feb., 21 Apr., 23 June, and 3 Sept. 2007, respectively.

‡ Within columns, values followed by the same letter are not different according to Tukey–Kramer at the 0.05 probability level.

§ UD, the natural log of zero is undetermined.

Table 5. Nitrate-N leached in response to the interaction year and N rate from bahiagrass (*Paspalum notatum* Flügge) from 2007 to 2008 in Ft. Lauderdale, FL. Values in parenthesis represent backtransformed values.

	NO_3–N leached						
Nitrogen rate	C1†	C2	C3	C4	C5	C6	Cumulative‡
kg ha^{-1} yr^{-1}	ln (kg ha^{-1})						
				2007			
49	−2.64 (0.07)a§	−1.86 (0.18)a	−3.90 (0.02)a	−2.10 (0.12)a	−1.39 (0.25)a	−1.79 (0.22)a	−0.16 (0.88)a
98	−2.43 (0.14)a	−1.85 (0.18)a	−4.60 (0.01)a	−1.81 (0.25)a	−1.23 (0.31)a	−2.03 (0.16)a	−0.03 (1.05)a
196	−2.27 (0.15)a	−1.86 (0.16)a	−4.17 (0.02)a	−1.90 (0.16)a	−1.41 (0.24)a	−1.65 (0.39)a	−0.03 (1.13)a
294	−2.10 (0.19)a	−2.09 (0.12)a	−4.47 (0.01)a	−2.18 (0.11)a	−1.38 (0.25)a	−2.03 (0.13)a	−0.20 (0.85)a
				2008			
49	−1.90 (0.16)a	−1.24 (0.33)a	−0.92 (0.41)b	−1.91 (0.24)a	−0.74 (0.50)a	−0.92 (0.43)a	0.66 (2.10)b
98	−1.52 (0.25)a	−1.19 (0.35)a	−0.46 (1.41)ab	−2.62 (0.12)a	−0.78 (0.46)a	−0.94 (0.39)a	0.90 (3.00)ab
196	−1.36 (0.46)a	−0.80 (0.72)a	0.51 (6.06)a	−2.82 (0.10)a	−0.82 (0.50)a	−0.98 (0.37)a	1.44 (8.24)ab
294	−1.63 (0.41)a	−0.82 (1.33)a	0.67 (6.70)a	−2.40 (0.44)a	−0.09 (6.06)a	−0.60 (2.06)a	1.65 (17.03)a

† Cycles 1 through 6 were ~60 d beginning on 12 Oct., 12 Dec., 15 Mar., 17 Apr., 18 June, and 16 Aug. 2006; and 12 Oct., 21 Dec., 20 Feb., 21 Apr., 23 June, and 3 Sept. 2007, respectively.

‡ Annual cumulative.

§ Within columns, values followed by the same letter are not different according to Tukey-Kramer at the 0.05 probability level.

Nitrate-N Leached

Nitrate-N leaching was influenced by N rate only during Cycle 3 of 2008. This was likely caused by decreased turf growth in Cycle 2. During Cycle 2 of 2008, bahiagrass was quiescent and produced no growth because of below average temperatures. Reductions in turfgrass growth have been associated with increases in NO_3–N leaching (Shaddox et al., 2016b; Trenholm et al., 2012). Presumably, the reduction in growth leads to a reduction in transpiration, which directly influences water and nutrient uptake. With plant uptake of N limited, applied N remained in the soil available to be leached. Generally, NO_3–N leaching has been correlated with rainfall events (Brown et al., 1977; Erickson et al., 2010). However, rainfall events during the majority of the study were less than or equal to the 30-yr average (Fig. 1). This resulted in similar leaching volumes among N rates during each cycle of 2008, which further reduces the probability that rainfall was the

Table 6. Nitrate-N leached as influenced by irrigation of bahiagrass (*Paspalum notatum* Flügge) during Cycles 1 and 6 and in response to the interaction year × irrigation during Cycle 4 from 2007 to 2008 in Ft. Lauderdale, FL. Values in parenthesis represent backtransformed values.

	NO_3–N leached	
Irrigation	Cycle 1†	Cycle 6
	ln (kg ha^{-1})	
High‡	−1.66 (0.28)	−1.06 (0.81)
Low§	−2.30 (0.18)	−1.68 (0.22)
P-value	0.04	0.01
	Cycle 4	
	2007	2008
High	−1.80 (0.21)	−1.53 (0.41)
Low	−2.19 (0.11)	−3.35 (0.05)
P-value	0.11	0.01

† Cycles 1 through 6 were ~60 d beginning on 12 Oct., 12 Dec., 15 Mar., 17 Apr., 18 June, and 16 Aug. 2006; and 12 Oct., 21 Dec., 20 Feb., 21 Apr., 23 June, and 3 Sept. 2007, respectively.

‡ High is 13.0 mm three times weekly.

§ Low is 2.5 mm d^{-1}.

causal factor influencing NO_3–N leaching differences among N rates. Having eliminated other plausible explanations, we postulate that N applied at 196 and 294 kg ha^{-1} yr^{-1} exceeded the turf demand when the turfgrass was quiescent leading to increased NO_3–N leaching. While these results suggest N applications may increase the risk of NO_3–N leaching, we used foliar-applied urea, which may substantially differ from granular N sources, particularly slowly available N forms.

The high-irrigation regime led to increased NO_3–N leaching than the low-irrigation regime during three of the six fertilization cycles. This observation reinforces those reported by Barton and Colmer (2006). The authors investigated N leaching from various N sources under irrigation supplied at 70 and 140% daily pan evaporation and observed that increasing irrigation to 140% led to increased N leaching from each fertilizer source by up to fourfold. Other researchers have also reported irrigation management to have a pronounced influence on NO_3–N leaching (Hergert, 1986; Petrovic, 1990; Snyder et al., 1984). Under our environmental and rainfall conditions, the high-irrigation regime provided more water than was necessary to maintain turf quality. The excess water increased soil percolation resulting in increased NO_3–N leaching. This underscores the importance of managing water according to the soil's capacity to retain it against gravitational flow. Additional water may enhance downward water movement and increase the potential risk of nutrient contamination of ground water.

CONCLUSIONS

Our results indicate that current University of Florida N application recommendations to bahiagrass in southern Florida are higher than necessary to produce an acceptable bahiagrass lawn. Nitrogen applied at 49 kg ha^{-1} yr^{-1} led to acceptable turf quality during each cycle. Whereas, the regression model indicated that acceptable quality could be achieved without applying N. Therefore, an N rate of 49 kg ha^{-1} yr^{-1} appears to be more advantageous than the current low rate of 98 kg ha^{-1} yr^{-1} in terms of reducing inputs and reducing the potential for NO_3–N leaching without adversely influencing quality or color. It is recommended that the currently recommended high N rate (196 kg ha^{-1} yr^{-1}) be lowered to 98 kg ha^{-1} yr^{-1} to reduce the risk of NO_3–N leaching from seasonal fluctuations in growth rate and rainfall. Under southern Florida conditions, lowering the high recommended N rate to 98 kg ha^{-1} yr^{-1} would not result in a reduction of turf quality below acceptable levels. Irrigating bahiagrass according to our high-irrigation regime provided no benefit in terms of turf quality, color, or growth rate. Instead, the high-irrigation regime increased NO_3–N leaching during some cycles, and thus, irrigation regimes similar to our low regime should be implemented when possible.

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