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RESEARCH

Nitrogen Rate Required for Acceptable St. Augustinegrass and Associated Nitrate Leaching

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ABSTRACT

The recommended N rates for St. Augustinegrass (*Stenotaphrum secundatum* [Walt.] Kuntze.) vary in Florida. This research, conducted in Fort Lauderdale, Citra, and Jay, FL, (2006–2008), aimed to determine the minimum N rate necessary for acceptable St. Augustinegrass and to determine the influence of N and irrigation rate on NO_3–N leaching. Urea was applied in Fort Lauderdale, Citra, and Jay at 98, 196, 294, and 588; 49, 196, 343, and 490; and 49, 98, 196, and 294 kg N ha^{-1} yr^{-1}, respectively, based on best management practices. Irrigation was 2.5 mm d^{-1} and 13.0 mm three times weekly in Fort Lauderdale; 13 mm twice weekly and 26 mm wk^{-1} in Citra and Jay. In Fort Lauderdale and Jay, lower than recommended N rates mostly produced acceptable turfgrass. Applications of 196 kg N ha^{-1} (Fort Lauderdale) and 98 kg N ha^{-1} (Jay) were the lowest rates producing acceptable turf. In Citra, 65% more N was required for acceptable turf than the recommended minimum . Leaching from all N rates was similar, except when N rates exceeded recommendations or when turfgrass exhibited herbicide stress. The high irrigation rate doubled NO_3–N leaching compared to the low rate in Fort Lauderdale; irrigation frequency had no influence on leaching in Citra or Jay. The predicted minimum N rate for acceptable turf in Fort Lauderdale was <98 kg N ha^{-1} yr^{-1} (lower than in Citra; more than in Jay). In stressed turf, additional N conferred little benefit to quality and increased leaching.

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Abbreviations: BMP, best management practices; C, fertilizer cycle.

THE PREVALENCE of St. Augustinegrass in Florida landscapes is estimated at 810,000 ha (Trenholm and Unruh, 2007). Fertilization of urban landscapes has been implicated as a nonpoint source contributor to N in surface and ground water (Petrovic, 1990). Commercial turf managers responsible for maintaining these landscapes generally will apply N to enhance turf quality. Applicators who choose to apply N in Florida are required to follow the best management practices (BMPs) for the green industries in Florida (Florida Department of Environmental Protection, 2010) and to possess a state fertilizer license issued by the Florida Department of Agriculture and Consumer Services (Florida Senate, 2015). Current N fertilization recommendations for maintenance of St. Augustinegrass in Florida are categorized geographically into three zones labeled as north, central, and south Florida. Within the north, central, and south zones, recommended N applications rates for St. Augustinegrass are 98 to 196, 98 to 245, and 196 to 294 kg N ha^{-1} yr^{-1}, respectively (Trenholm et al., 2011). The BMP-recommended N application ranges are intended to yield acceptable quality turfgrass encompassing a range of aesthetic preferences while limiting the risk of NO_3–N leaching to ground water. However, concerns have arisen regarding the scientific basis for these N application ranges. Turf quality

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and NO_3–N leaching may vary within the recommended ranges and may be influenced by irrigation rates.

The impact of N application rate on turf quality has been thoroughly documented on warm-season turfgrasses. Most studies define turf quality as a combination of color, density, uniformity, texture, and disease or environmental stress and have used a 1 to 9 scale (1 = dead or brown; 9 = pristine; 6 = minimum acceptable) (Krans and Morris, 2007). Many reports indicate turf quality is acceptable even at low N rates. Rowland et al. (2010) applied a blend of 50% ammonium sulfate and 50% slow-release N at N rates of 12, 24, and 37 kg N ha^{-1} wk^{-1} to 'TifDwarf' and 'TifEagle' bermudagrasses [*Cynodon dactylon* (L.) Pers. × *Cynodon transvaalensis* Burtt Davy], 'SeaDwarf' Seashore paspalum (*Paspalum vaginatum* Sw.), and 'PristineFlora' zoysiagrass (*Zoysia japonica* Stued. × *Zoysia tenuifolia* Willd. ex Thiele) and reported that acceptable turf quality was observed for each turfgrass from each N rate. Trenholm and Unruh (2007) applied a range of N rates to two swards of St. Augustinegrass maintained in north and central Florida and observed that the N required to maintain acceptable St. Augustinegrass in central Florida varied among years with 245 and 98 kg N ha^{-1} yr^{-1} in 2001 and 2002, respectively. These rates were at least twice the amount necessary to produce acceptable quality St. Augustinegrass in north Florida. The authors hypothesized that the greater N requirement may have been caused by the longer growing season in central Florida. Saha et al. (2007) investigated a similar concern in a greenhouse study and that the application of soluble N resulted in greater St. Augustinegrass quality than that produced by slow-release N applied at 294 kg N ha^{-1}. However, all turf quality ratings from each N source were acceptable, with the lowest rating reported to be 0.6 units greater than the minimum for acceptable turfgrass. In general, previous research has investigated turf quality differences among N sources or N rates but was not designed to determine the minimum N rate required to produce acceptable St. Augustinegrass.

Nitrate-N leaching may be strongly influenced by N rate. However, in general, NO_3–N leaching is most often observed when N rates exceed the recommended rates (Brown et al., 1982; Mancino and Troll, 1990; Trenholm et al., 2012) or when high rates of soluble N are applied (Frank et al., 2006). Investigators in California studied NO_3–N leaching as influenced by N source and N rates of 195, 290, and 390 kg N ha^{-1} yr^{-1} applied to tall fescue [*Schedonorus phoenix* (Schreb.) Dumort.] and reported the highest concentration of NO_3–N in leachate resulted from the application of 390 kg N ha^{-1} yr^{-1} using ammonium nitrate (Wu et al., 2010). Furthermore, Wu et al. (2010) noted that an application of 195 kg N ha^{-1} yr^{-1} produced acceptable turf quality and that further additions of N were detrimental. Similarly, Fetter et al. (2012) applied 0, 48, 146, and 292 kg N ha^{-1} yr^{-1} to perennial ryegrass (*Lolium perenne* L.) using soluble N and reported a maximum contamination level of NO_3–N leaching (10 mg L^{-1}) was exceeded only by the 146 and 292 kg N ha^{-1} yr^{-1} rates.

The influence of irrigation on turf quality and nutrient leaching has been well documented. Irrigation regimes that minimize percolation below the rooting zone reduce N leaching. Snyder et al. (1984) investigated soil-sensor based irrigation, which minimized percolation below the turfgrass root zone, and reported that color ratings were enhanced by the use of sensor-based compared to daily irrigation. Furthermore, Snyder et al. (1984) observed a reduction in N leaching under the sensor-based irrigation and noted that the soluble N source leached greater quantities of N than the slow-release source. Irrigation regimes designed to minimize percolation may have less impact on nutrient leaching during periods of increased rainfall. Erickson et al. (2010) investigated nutrient leaching from newly established 'Floratam' St. Augustinegrass in south Florida maintained with 12.7 mm of water applied every other day or applied at sign of visual wilt. The authors observed PO_4–P leaching was reduced using reduced irrigation during the driest trial but the irrigation effect was insignificant during the wettest trial. Irrigation regime had no impact on NO_3–N leaching in any trial regardless of rainfall. It has been proposed that irrigation regimes that decrease irrigation rates per application but increased irrigation events may reduce N leaching by preventing preferential flow (Barton and Colmer, 2006).

Numerous studies have been published indicating that Florida's BMP recommendations are reasonable (Telenko et al., 2015; Trenholm et al., 2012, 2013). However, limited peer-reviewed research has been published establishing the minimum amount of N necessary to achieve acceptable quality St. Augustinegrass in Florida while reporting the influence of these N rates on NO_3–N leaching. Therefore, the objectives of this study were (i) to determine the minimum amount of N necessary to produce acceptable quality St. Augustinegrass in north and south Florida, (ii) to determine if N applied according to the current recommended N application ranges pose a significant risk to NO_3–N leaching, and (iii) to determine if irrigation amounts and frequency influence NO_3–N leaching.

MATERIALS AND METHODS

This study was conducted at the University of Florida research centers in Fort Lauderdale (26°03′ N, 80°13′ W), Citra (29°24′ N, 82°10′ W), and Jay (30°46′ N, 87°08′ W), FL. Fort Lauderdale is located in south Florida and the recommended N range for St. Augustinegrass is 196 to 294 kg ha^{-1} yr^{-1} (Trenholm et al., 2011). In Fort Lauderdale, turf was grown on a mined mason sand (Rymatt Golf, Collier County, FL) (particle sizes: 1.0–2.0 mm, 0.2%; 0.5–1.0 mm, 5.4%; 0.25–0.50 mm, 29.9%; 0.15–0.25 mm, 62.9%; 0.05–0.15 mm, 1.5%; ≤0.05 mm, 0.1%) with similar textural characteristics to the Hallandale fine sand series (siliceous, hyperthermic Lithic Psammaquent) with a pH of 7.0 and an organic matter content of 2.5%. Experimental design was a split-plot where main blocks (8 by 4 m) consisted of one of two irrigation regimes: 2.5 mm daily (low), except when daily precipitation was >6.4 mm (irrigation turned off), and 13.0 mm three times weekly (high) (Dukes, 2014). Subplots (2 by 4 m) consisted of four N rates: 98, 196, 294, and 588 kg N ha^{-1} yr^{-1}. Nitrogen treatments were applied on 12 Oct. 2006, 12 Dec. 2006, 15 Mar. 2007, 17 Apr. 2007, 18 June 2007, 16 Aug. 2007, 11 Oct. 2007, 21 Dec. 2007, 20 Feb. 2008, 21 Apr. 2008, 23 June 2008, and 3 Sept. 2008. Each application date represented the beginning of a new fertilizer cycle (C). Cycle 1, C2, C3, C4, C5, and C6 were 12 October to 11 December, 12 December to 14 March, 15 March to 16 April, 17 April to 17 June, and 18 June to 11 October, respectively. Spray-grade granular urea (N/P/K 46:0:0) was used as the source of N and was applied with a backpack CO_2–pressurized (206 kPa) sprayer (Weed Systems Inc., Hawthorne, FL) equipped with two flat-fan TeeJet 8010 nozzles (Spraying Systems Co., Glendale Heights, IL) on 510 mm spacing as per the industry standard method of application. Sprayable urea applied at rates above 34.3 kg N ha^{-1} are not recommended according to Florida BMPs but were used as a worst-case scenario. Immediately following N applications, turfgrass plots received 13 mm of irrigation to reduce N loss by volatilization and reduce burn potential (Bowman et al., 1987). In addition to N fertilization, 196 kg P ha^{-1} $yr^{-1}$and 392 kg K ha^{-1} yr^{-1} from triple superphosphate (0:20:0) and muriate of potash (N/P/K 0:0:50) were split equally and applied to all plots every 90 d to maintain soil test values above critical P and K values for St. Augustinegrass (Sartain, 2012, 2013). Additionally, a macro-micronutrient fertilizer (Harrell's Max Minors, Hocking International Laboratories, Sylacauga, AL) containing 1% Mg, 3.5% S, 0.02% B, 0.25% Cu, 4% Fe, 1% Mn, 0.6% Zn, and 0.0005% Mo was applied at a rate of 12 L ha^{-1} every 90 d. Pesticides were applied as needed based on visual identification of a pest. Azoxystrobin [methyl (*E*)-2-(2-[6-(2-cyanophenoxy) pyrimidin-4-yloxy]phenyl)-3-methoxyacrylate] fungicide was applied for control of gray leaf spot (*Pyricularia grisea*).

To measure percolate and N leachate, lysimeters were installed in the center of each subplot. Lysimeters were constructed from plastic drums 920 mm high and 597 mm in diameter, with a 13-mm thick wall, (US Plastics Corporation, Lima, OH). At the bottom of each lysimeter, a polyvinyl chloride drainage pipe (19 mm diameter) was fitted to allow for percolate or leachate collection. At the collection points, each lysimeter was allocated its own 20-L polyethylene container. To stop mined landscape sand migration down into the 20-L polyethylene collection container, a 100-mm layer of filter gravel was placed inside the bottom of each lysimeter and overlaid by a 50-mm layer of choker sand. Each lysimeter was subsequently filled with mined landscape-type sand to a depth of 855 mm. Similarly, a layer of filter gravel, a choker layer, and a mined landscape-type sand layer was installed outside the lysimeter so soil profiles were uniform. Subsequently, mined landscape-type sand was packed around, between, and within each lysimeter to a depth of 855 mm. Although filter gravel and choker layers do not typically exist in Florida home lawns, they were necessary, since prior studies were hampered by sand migration into the leachate collection containers. The choker layer could have resulted in a perched water table, which may have increased atmospheric N loss via denitrification. Although this potential variable could have reduced the amount of NO_3–N leaching, relatively, treatment results were probably unaffected. Perimeter irrigation systems were installed for each main plot and consisted of Rainbird 3500 sprinklers (Rain Bird Inc., Tucson, AZ) spaced at 8 by 8 m, adjusted to spray an inward quarter circle. Following lysimeter installation, Floratam St. Augustinegrass was planted in April 2006.

Citra is located in north Florida and the recommended N range for St. Augustinegrass is 98 to 196 kg ha^{-1} yr^{-1} (Trenholm et al., 2011). In Citra, turf was grown on a Tavares sand (hyperthermic uncoated Typic Quartzipsamments) with a pH of 6.8 and an organic matter content of <4%. The experimental design was similar to that of Fort Lauderdale. However, main plots (8 by 16 m) consisted of one of two irrigation regimes: 13.0 mm applied twice weekly (split) and 26.0 mm applied once weekly (single). When rainfall met or exceeded these amounts, irrigation was suspended. Subplots (4 by 4 m) consisted of four N rates: 49, 196, 343, or 490 kg N ha^{-1} yr^{-1} applied at approximately 60-d intervals. Nitrogen treatments were applied on 3 Apr. 2006, 6 June 2006, 1 Aug. 2006, 30 Sept. 2006, 2 Apr. 2007, 31 May 2007, 8 Aug. 2007, and 3 Oct. 2007. Cycle 1, C2, C3, and C4 were approximately April to May, June to July, August to September, and October to November, respectively. High density polyethylene lysimeters were installed in the center of each subplot, with the top rim of the lysimeter approximately 10 cm below the soil surface. Lysimeters measured 57 cm in diameter and 88 cm in height with a volume of 168 L. Lysimeters were placed on top of a single-piece galvanized steel base unit measuring 25.4 cm in height. A bulkhead fitting was inserted into the base of each unit, to which collection tubing (low-density polyethylene, 0.95 cm in diameter) was attached. Connected tubing ran underground to a central aboveground collection terminal. A leaching bed of washed round river rock (1.9–4.4 cm) covered with nonwoven polyolefin cloth secured with an internal interference fitted hoop of high-density polyethylene tubing (1.3 cm diameter) was placed in the bottom of each lysimeter to minimize soil intrusion into the collection reservoir. Once lowered into bore holes, original soil horizons were recreated in 15-cm sections within the lysimeter, each carefully prepared by dropping a tamping tool (17 kg and 858 cm^2) from a consistent height to approximate the original soil bulk density. Any settling of lysimeters was corrected before plot preparation for sodding using a laser transit-controlled wheeled box blade (GradeMaster FR5, Laser Leveling, Inc., Tampa, FL). Floratam St. Augustinegrass sod was planted in June 2005.

Jay is located in north Florida and the recommended N range for St. Augustinegrass is 98 to 196 kg ha^{-1} yr^{-1} (Trenholm et al., 2011). In Jay, the soil type was Fuquay loamy sand (loamy, kaolinitic, thermic Arenic Plinthic Kandiudults) with a pH of 6.2 and an organic matter content of <4%. A split-plot design was used with irrigation in 15 by 12 m main plots and N rates in 6 by 3 m subplots. Lysimeter design and installation was identical to that in Citra. Treatments included four rates of N and two irrigation regimes. Nitrogen rates were 49, 98, 196, and 294 kg N ha^{-1} yr^{-1}. Nitrogen rate treatments were applied on 14 Apr. 2006, 14 June 2006, 11 Aug. 2006, 16 Apr. 2007, 14 June 2007, and 14 Aug. 2007. Cycle 1, C2, and C3 were approximately mid-April to mid-June, mid-June to mid-August, and mid-August to mid-October, respectively. Irrigation treatments consisted of 13 mm applied twice weekly or 26 mm applied once weekly. Floratam St. Augustinegrass was planted in May 2005.

At each location, main and subplots were arranged in a randomized complete block design with four replications. Type III tests were adjusted for a split-plot design. Irrigation was supplied by four Toro Super 800 rotary irrigation heads (The Toro Company, Bloomington, MN) per plot placed in each corner with four 90° arcs. Turf was cut weekly to a height of 7.5 cm and clippings were allowed to remain on plots. When turf was cut on the same day as a treatment application, treatments were applied after mowing.

Leachate samples were collected by removing all leachate by vacuum extraction (Citra and Jay) or by collecting drained leachate (Fort Lauderdale) for volume determination and acquiring a 20-mL subsample for NO_3–N and NO_2–N analysis from each lysimeter. Leachate subsamples were acidified to 2.0 pH, stored at 4°C, and analyzed within 28 d. Leachate was collected twice weekly during the first year's collection cycles. At the funding agency's request, all subsequent leachate collections occurred weekly. Collection cycles began when fertilizer treatments were applied and continued for approximately 60 d. Nitrate concentration was measured using a continuous segmented flow analyzer (AutoAnalyzer 3, Seal Analytical, Mequon, WI) 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. In Citra and Jay, P and K were applied each March as granular applications of triple superphosphate at 12 kg P ha^{-1} and potassium chloride at 49 kg K ha^{-1}. Ethofumesate (2-ethoxy-2,3-dihydro-3,3-dimethyl-5- benzofuranyl methanesulfonate) (Prograss, Bayer CropScience LP, Research Triangle Park, NC) was applied to St. Augustinegrass plots in Jay on 8 May 2007, for control of torpedograss (*Panicum repens* L.).

Turf quality was recorded fortnightly during the growing season on a quality scale of 1 to 9, where 1 = dead or brown turf and 9 = optimal healthy turf. Quality ratings ≥6.0 were considered acceptable (Krans and Morris, 2007). Weather and soil temperature data were collected during the duration of the research from an on-site weather network system (http://fawn.ifas.ufl.edu, accessed 30 Sept. 2015), which provided meteorological information in 15-min intervals.

Model residuals were analyzed for normality both graphically and numerically with the Shapiro–Wilk W-test. Data were also checked graphically for homogeneity of variance. These tests determined that NO_3–N leaching data were non-normal and turf quality data were normally distributed. Consequently, NO_3–N leaching data were transformed logarithmically and ANOVA was conducted on the transformed data, which satisfied assumptions of normality and homogeneity of variance. Procedure GLM (SAS Institute, 2010) and SigmaPlot version 12.5 (Systat Software Inc., 2013) were used to analyze the data. Dunnett's LSD values at the 0.05 level are reported for comparisons between N rates and the control (lowest N rate). Regression of N rate and turf quality, regression equations, and the coefficient of determination (R^2) were determined using raw data. In Jay, because of the year × N rate interaction, the regression was conducted within years.

RESULTS

Fort Lauderdale

Nitrate-N leached was influenced by main effects year, N rate, and irrigation. Nitrate-N leached was influenced by the year × N rate interaction in C1 and the year × irrigation interaction during C4 and C6 (Table 1). The highest recommended N rate in south Florida is 294 kg N ha^{-1} yr^{-1}. The resulting NO_3–N leaching from this rate was similar to NO_3–N leaching from 98 kg N ha^{-1} during every cycle and for the cumulative annual total (Table 2). However, increased NO_3–N leaching was observed at the 588 kg N ha^{-1} rate during C1 and C2 and for the cumulative annual total. The 588 kg N ha^{-1} rate led to 3.8-fold greater cumulative annual NO_3–N leaching than the 98 kg N ha^{-1} rate. Nitrate-N leaching was principally linear in response to N rate during C1, C2, and C4 and based on cumulative annual N leaching (Table 1). The high irrigation rate resulted in increased NO_3–N leaching in every cycle and for the cumulative annual total, except for C2 and C6. Cumulated annually, NO_3–N leaching resulting from the high irrigation rate and the low irrigation rate was 4.69 and 2.08 kg ha^{-1}, respectively. In general, monthly rainfall totals followed historical averages with two notable exceptions. Rainfall in June and October of 2007 exceeded the historical average by more than 100 mm (Fig. 1). Additionally, the daily average rainfall exceeded 6.7 mm d^{-1} during June, July, September, and October in 2007 and August and October 2008. Leachate volumes were greater under high irrigation than low irrigation during C2, C4, C5, and C6 and for the cumulative annual total of 2007 and during C1, C2, C3, and C4 and for the cumulative annual total of 2008 (Table 3).

Each N rate resulted in turf quality that met or exceeded the minimum acceptable level during each cycle and annual average except during C2 and C3 under the 98 kg N ha^{-1} rate (Table 4). Furthermore, N applied at 196, 294, and 588 kg ha^{-1} increased turf quality above the 98 kg N ha^{-1} rate during each cycle and the annual average. At each cycle and according to the annual average, turf quality was linear in response to N rate (Table 1). The 98 kg N ha^{-1} rate resulted in the lowest annual average turf quality, whereas the 588 kg N ha^{-1} rate resulted in the highest turf quality: 6.0 and 7.7, respectively. Turf quality during 2008 was lower than 2007 for C3, C4, C5, and C6 and the annual average.

The relationship between N rate and turf quality in Fort Lauderdale is shown in Fig. 2. Regression analysis of N rate and turf quality revealed a linear relationship that was positively correlated (r = 0.78) and was significant (P < 0.001). The model indicates that acceptable turf quality (6.0) may result from applications of 53 kg N ha^{-1} yr^{-1} and higher, which is less than the recommended minimum (98 kg N ha^{-1} yr^{-1}). Furthermore, the linear regression model y-axis intercept estimate for turf quality when 0 kg N ha^{-1} yr^{-1} was applied to St. Augustinegrass in Fort Lauderdale is approximately 5.8.

Table 1. ANOVA for nitrate-N leached and quality of St. Augustinegrass in response to N rate (NR), irrigation (I), and year (Y) from 2006 to 2008 in Fort Lauderdale, Citra, and Jay, FL.

Source of variation	Nitrate-N leached							Turf quality[‡]						
	C1[†]	C2	C3	C4	C5	C6	CuA[§]	C1	C2	C3	C4	C5	C6	Avg.
	kg ha^{-1}							1–9						
Fort Lauderdale														
Y	NS[¶]	NS	***	**	NS	***	**	NS	NS	***	**	**	*	***
NR	***	*	NS	*	NS	NS	**	***	***	***	***	***	***	***
Linear	***	*	NS	*	NS	NS	**	***	***	***	***	***	***	***
Quadratic	*	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS
I	***	NS	*	**	***	NS	*	NS	NS	NS	NS	NS	NS	NS
Y × NR	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Y × I	NS	NS	NS	***	NS	*	NS	NS	NS	NS	NS	NS	NS	NS
I × NR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Y × I × NR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Citra														
Y	***	NS	NS	*	–	–	NS	**	***	NS	*	–	–	**
NR	NS	NS	**	**	–	–	***	***	***	***	***	–	–	***
Linear	NS	NS	NS	**	–	–	***	***	***	***	***	–	–	***
Quadratic	NS	NS	NS	NS	–	–	NS	***	***	***	***	–	–	***
I	NS	NS	NS	NS	–	–	NS	***	**	**	***	–	–	***
Y × NR	NS	NS	NS	**	–	–	NS	*	NS	NS	NS	–	–	NS
Y × I	NS	NS	NS	NS	–	–	NS	NS	NS	NS	NS	–	–	NS
I × NR	NS	NS	NS	NS	–	–	NS	*	NS	NS	*	–	–	NS
Y × I × NR	NS	NS	NS	NS	–	–	NS	NS	NS	NS	NS	–	–	NS
Jay														
Y	*	**	NS	–	–	–	**	**	*	**	–	–	–	**
NR	*	*	NS	–	–	–	*	**	***	***	–	–	–	***
I	NS	NS	NS	–	–	–	NS	NS	NS	NS	–	–	–	NS
Y × NR	*	*	NS	–	–	–	*	***	***	NS	–	–	–	***
2006														
NR linear	NS	NS	NS	–	–	–	NS	***	***	***	–	–	–	***
NR quadratic	NS	NS	NS	–	–	–	NS	NS	*	**	–	–	–	**
2007														
NR linear	**	**	NS	–	–	–	**	**	*	***	–	–	–	**
NR quadratic	NS	NS	*	–	–	–	NS	NS	NS	NS	–	–	–	NS
Y × I	NS	NS	NS	–	–	–	NS	*	NS	NS	–	–	–	NS
I × NR	NS	NS	NS	–	–	–	NS	NS	NS	NS	–	–	–	NS
Y × I × NR	NS	NS	NS	–	–	–	NS	NS	NS	NS	–	–	–	NS

* Significant at $P < 0.05$.

** Significant at $P \leq 0.01$.

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

[†] Cycle. In Fort Lauderdale, C1, C2, C3, C4, C5, and C6 were 12 October to 11 December, 12 December to 14 March, 15 March to 16 April, 17 April to 17 June, and 18 June to 11 October, respectively. In Citra, C1, C2, C3, and C4 were April to May, June to July, August to September, and October to November, respectively. In Jay, C1, C2, and C3 were mid-April to mid-June, mid-June to mid-August, and mid-August to mid-October, respectively.

[‡] Turf quality was based on a scale from 1–9, where 1 = dead or brown turf, 6 = minimally acceptable, and 9 = optimal healthy or green turf.

[§] CuA cumulative annual total.

[¶] NS, nonsignificant.

Citra

Nitrate-N leached was influenced by year and N rate (Table 1). Irrigation and all interactions with irrigation did not influence NO_3–N leaching and are not reported. The only interaction that influenced NO_3–N leaching was year × N rate during C4. No differences in NO_3–N leaching were observed among N rates during C1 or C2 (Table 2). However, during C3, N applied at 343 kg ha^{-1} resulted in a 35% reduction in NO_3–N leaching compared with the 49 kg N ha^{-1} rate; during C4, the 490 kg N ha^{-1} rate led to approximately 18-fold greater NO_3–N leaching than the 49 kg N ha^{-1} rate. Correspondingly, the cumulative annual NO_3–N leaching observed under the 490 kg N ha^{-1} rate exceeded the NO_3–N leaching from N applied at 49 kg ha^{-1} by sevenfold. Cumulative annual NO_3–N leaching was linear in response to N rate (Table 1). Rainfall closely followed the historical average but exceeded the historical average in July 2006 and October 2007 by 85 and 104 mm, respectively (Fig. 1).

Table 2. Nitrate-N leached in response to N rate in St. Augustinegrass from 2007 to 2008 in Fort Lauderdale and 2006 to 2007 in Citra, FL.

Annual N rate	Nitrate-N leached						
	C1[†]	C2	C3	C4	C5	C6	Annual
kg ha^{-1}	ln (kg ha^{-1})						
Fort Lauderdale							
98	–1.92 (0.18)	–1.48 (0.25)	–2.00 (0.26)	–1.84 (0.19)	–0.73 (0.57)	–1.37 (0.30)	0.49 (1.75)[‡]
196	–1.51 (0.68)	–1.37 (0.31)	–2.32 (0.22)	–1.58 (0.32)	–0.90 (0.45)	–1.49 (0.26)	0.59 (2.25)
294	–1.87 (0.27)	–1.55 (0.23)	–2.06 (1.39)	–2.19 (0.15)	–0.94 (0.48)	–1.55 (0.24)	0.50 (2.78)
588	–0.34 (2.68)	–0.71 (1.78)	–1.68 (1.12)	–2.41 (0.18)	–0.84 (0.70)	–1.52 (0.25)	1.29 (6.75)
$LSD_{0.05}$	0.81	0.70	NS[‡]	NS	NS	NS	0.55
Citra							
49	–1.70 (0.21)	–1.33 (0.29)	–1.65 (0.23)	–1.71 (0.25)	–	–	–0.12 (0.97)
196	–1.68 (0.22)	–1.12 (0.54)	–1.61 (0.24)	–1.34 (0.92)	–	–	0.24 (1.92)
343	–1.29 (1.12)	–1.29 (0.61)	–2.01 (0.15)	–1.31 (0.59)	–	–	0.41 (2.47)
490	–1.33 (1.22)	–0.84 (1.12)	–1.65 (0.29)	–0.43 (4.56)	–	–	1.36 (7.19)
$LSD_{0.05}$	NS	NS	0.28	0.85	–	–	0.8

[†] Cycle. In Fort Lauderdale, C1, C2, C3, C4, C5, and C6 were 12 October to 11 December, 12 December to 14 March, 15 March to 16 April, 17 April to 17 June, and 18 June to 11 October, respectively. In Citra, C1, C2, C3 and C4 were April to May, June to July, August to September, and October to November, respectively.

[‡] Values in parentheses represent backtransformed values.

[§] NS, nonsignificant at $P < 0.05$.

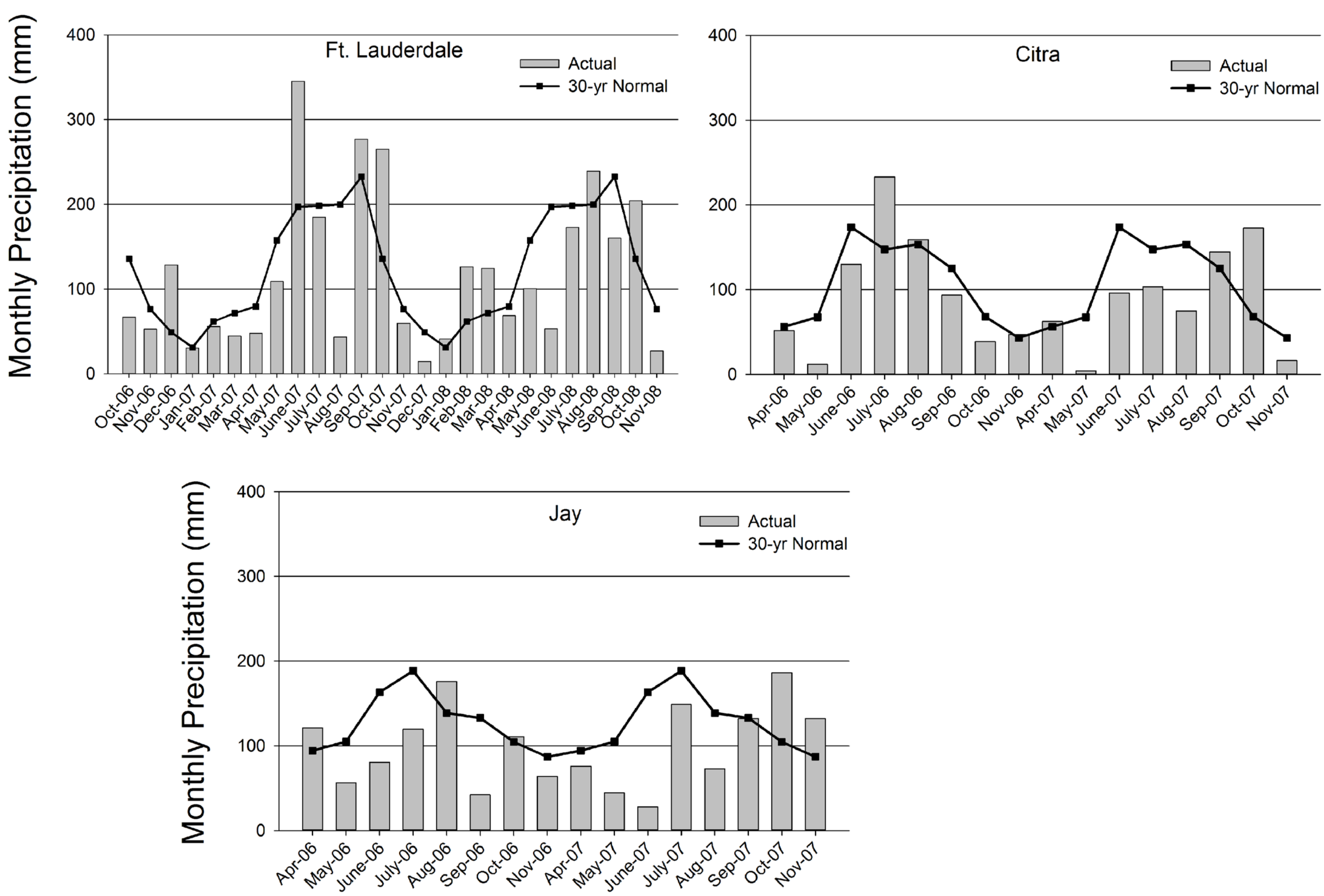

Figure 1. Historical and actual monthly precipitation for the months in which research was conducted over the 2-yr study period in Fort Lauderdale, Citra, and Jay, FL. Note the difference in the *x*-axis scales.

Leachate volumes were similar during each cycle and for the cumulative annual total during both years (Table 3).

The 49 kg N ha^{-1} rate did not yield acceptable turf quality during any cycle or for the annual average, whereas 196, 343, and 490 kg N ha^{-1} each resulted in acceptable turf

Table 3. Leachate volumes as influenced by irrigation from 2007 to 2008 in Fort Lauderdale and from 2006 to 2007 in Citra and Jay, FL.

Location	Irrigation†	Leachate volume C1‡	C2	C3	C4	C5	C6	Annual
		L						
Fort Lauderdale	2007							
	High	60.7	71.8	12.9	76.7	11.7	70.9	404.9
	Low	46.3	45.7	8.9	53.5	88.1	51.6	294.5
	P-value	0.24	0.01	0.08	0.05	0.04	0.01	0.01
	2008							
	High	78.8	54.6	67.1	36.8	90.1	87.3	414.7
	Low	46.6	39.3	46.3	10.7	69.4	80.1	292.6
	P-value	0.02	0.02	0.01	0.01	0.10	0.17	0.02
Citra	2006							
	Single	157.1	136.2	104.3	61.5	–	–	459.2
	Split	102.7	95.4	56.8	28.6	–	–	283.6
	P-value	0.25	0.31	0.35	0.23	–	–	0.29
	2007							
	Single	69.8	144.4	98.5	95.8	–	–	408.5
	Split	38.6	79.3	65.8	73.6	–	–	257.4
	P-value	0.38	0.22	0.31	0.36	–	–	0.29
Jay	2006							
	Single	39.2	41.8	58.6	–	–	–	139.6
	Split	25.7	27.4	33.9	–	–	–	87.2
	P-value	0.11	0.12	0.07	–	–	–	0.08
	2007							
	Single	40.6	72.1	43.3	–	–	–	156.1
	Split	30.2	47.8	28.5	–	–	–	106.6
	P-value	0.28	0.04	0.02	–	–	–	0.02

† High, three applications of 6.4 mm per week; low, 2.5 mm daily; single, one application of 26.0 mm per week; split, two applications of 13.0 mm per week.

‡ Cycle. In Fort Lauderdale, C1, C2, C3, C4, C5, and C6 were 12 October to 11 December, 12 December to 14 March, 15 March to 16 April, 17 April to 17 June, and 18 June to 11 October, respectively. In Citra, C1, C2, C3, and C4 were April to May, June to July, August to September, and October to November, respectively.

Table 4. St. Augustinegrass quality in response to N rate from 2007 to 2008 in Fort Lauderdale and from 2006 to 2007 in Citra, FL.

Annual N rate	Turf quality† C1‡	C2	C3	C4	C5	C6	Average
kg ha^{-1}							
Fort Lauderdale							
98	6.1	5.7	5.8	6.0	6.2	6.0	6.0
196	6.8	6.6	6.4	6.5	6.6	6.6	6.6
294	7.0	6.9	6.8	7.1	7.0	7.0	7.0
588	7.7	8.0	7.7	7.9	7.6	7.6	7.7
$LSD_{0.05}$	0.4	0.5	0.4	0.5	0.4	0.4	0.4
Citra							
49	4.4	4.7	5.2	4.5	–	–	4.7
196	6.0	6.3	6.7	6.3	–	–	6.3
343	6.8	7.1	7.5	7.0	–	–	7.1
490	7.0	7.4	7.7	7.3	–	–	7.4
$LSD_{0.05}$	0.4	0.4	0.4	0.4	–	–	0.3

† Turf quality was based on a scale from 1–9, where 1 = dead or brown turf, 6 = minimally acceptable, and 9 = optimal healthy or green turf.

‡ Cycle. In Fort Lauderdale, C1, C2, C3, C4, C5, and C6 were 12 October to 11 December, 12 December to 14 March, 15 March to 16 April, 17 April to 17 June, and 18 June to 11 October, respectively. In Citra, C1, C2, C3, and C4 were April to May, June to July, August to September, and October to November, respectively.

quality during each cycle and for the annual average (Table 4). Unlike turf quality in Fort Lauderdale, turf quality in Citra followed a quadratic trend in response to N, indicating diminishing returns in turf quality with increasing N, especially at the 490 kg N ha^{-1} yr^{-1} rate (Table 1 and Table 4). As such, the gains in turf quality are small and statistically nonsignificant (Table 4) but the potential risk for N leaching is high (Table 2) in Citra at the 490 kg N ha^{-1} yr^{-1} rate. The annual average turf quality was increased by the application of 196, 343, and 490 kg N ha^{-1} compared with the 49 kg N ha^{-1} by 25, 34, and 37%, respectively. Turf quality scores under the split irrigation schedule during C1, C2, C3, and C4 and for the annual average were 5.7, 6.1, 6.4, 5.9 and 6.0, respectively. Turf quality increased under the single irrigation schedule for each cycle and the annual average. Turf quality under the single irrigation schedule during was 6.4, 6.6, 7.1, 6.6 and 6.7 for C1, C2, C3, C4 and the annual average, respectively.

The relationship between N rate and turf quality in Citra is shown in Fig. 2. The model predicts acceptable turf quality (6.0) may be observed with N applied at a rate of 165 kg N ha^{-1} and higher. The relationship was well described (R^2 = 0.62) by the quadratic model and was significant (*P*

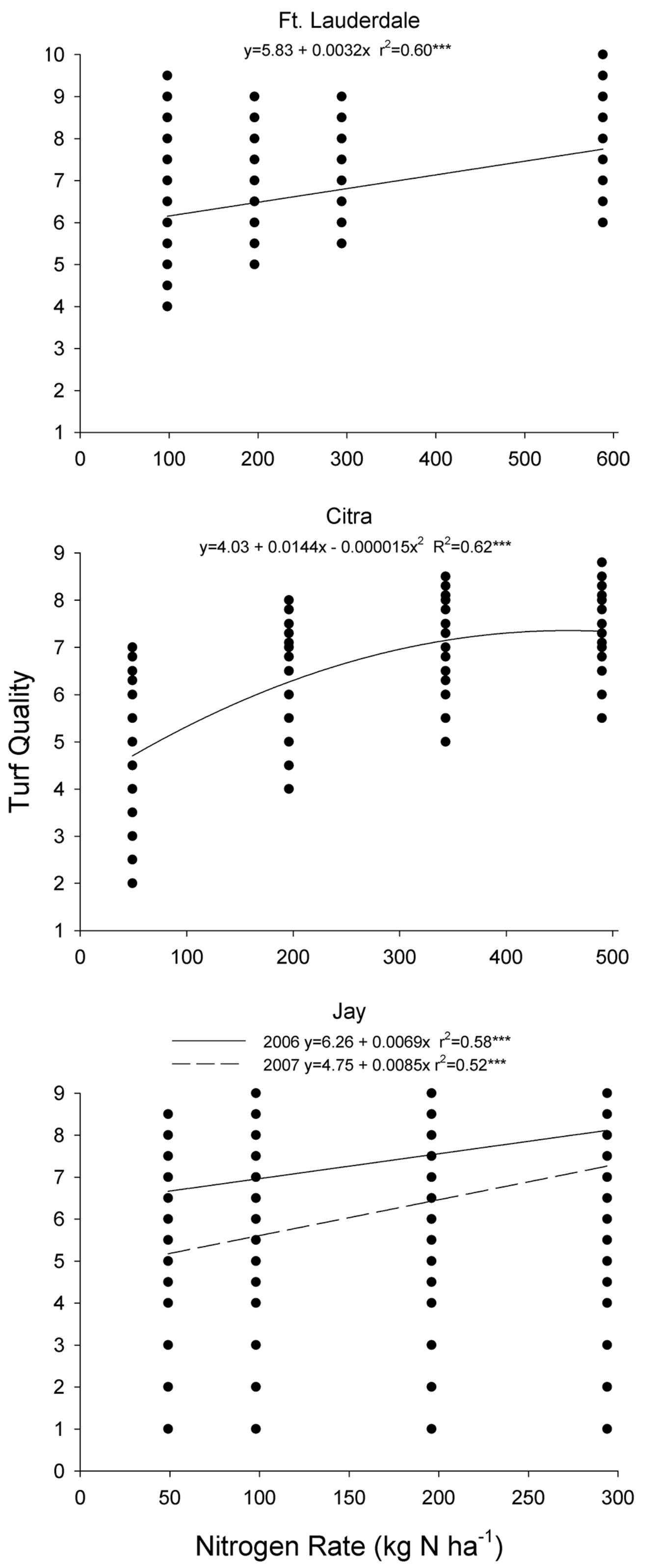

Figure 2. Relationship between Nrate and St. Augustinegrass quality in Fort Lauderdale, Citra, and Jay, FL. In Fort Lauderdale, Citra, and Jay, data include 832 observations (52 ratings per year × 2 yr × 2 irrigation rates × 4 replicates), 544 observations (34 ratings per year × 2 yr × 2 irrigation rates × 4 replicates), and 208 observations (26 ratings per year × 2 irrigation rates × 4 replicates), respectively. Note the difference in the *x*-axis scales. ***, regression was significant at $P < 0.001$.

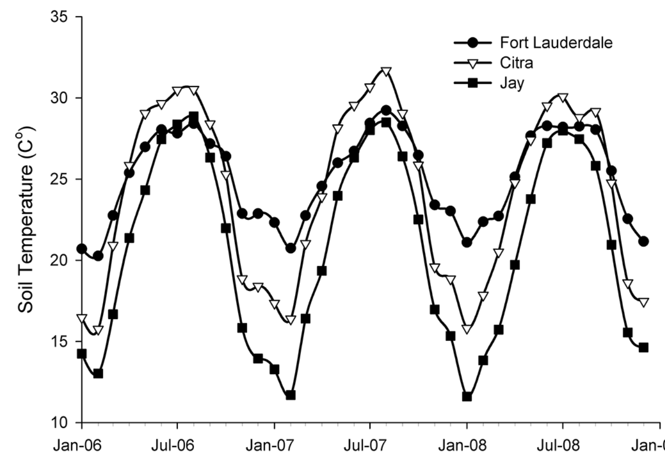

Figure 3. Average monthly soil temperature in Fort Lauderdale, Citra, and Jay, FL, from 2006 to 2008.

< 0.001). The predicted annual average turf qualities and the 95% confidence intervals for the recommended minimum (98 kg ha^{-1} yr^{-1}) and maximum (196 kg ha^{-1} yr^{-1}) N rates were 5.3 ± 0.14 and 6.3 ± 0.14, respectively. According to the quadratic model for Citra, the *y*-axis intercept estimate for the turf quality of unfertilized St. Augustinegrass (Fig. 2., i.e., when 0 kg N ha^{-1} yr^{-1} was applied) is approximately 4.0. This turf quality rating of 4.0 is well below the minimum accepted standard for quality of 6.0, especially compared with unfertilized St. Augustinegrass in Fort Lauderdale discussed above. Soil temperatures in Citra remained above those in Jay during each month and exceeded soil temperatures in Fort Lauderdale during June, July, August, and September of each year (Fig. 3).

Jay

Nitrate-N leached was significantly influence by the year × N rate interaction but no other interaction of main effects was observed (Table 1). Consequently, NO_3–N leaching results are reported for the year × N rate interaction. Nitrate-N leaching from St. Augustinegrass as influenced by irrigation and all interactions with irrigation (i.e., irrigation × year, irrigation × N rate) was found to be insignificant and is not reported. Rainfall was generally below the historical average except in October and November 2007 (Fig. 1).

In 2006, N rates did not influence NO_3–N leaching during any collection cycle nor for the annual total (Table 5). However, during C1 and C2 of 2007, NO_3–N leaching was found to be approximately 30-fold higher than in 2006 and differences between N rates were observed. During C1, NO_3–N leaching from the 294 kg N ha^{-1} treatment exceeded NO_3–N leaching from the 49 kg N ha^{-1} rate by 5.68 kg N ha^{-1}. Nitrate-N leaching during C2 was similar, with the 294 kg N ha^{-1} N rate resulting in 8.79 kg ha^{-1} more N leaching than the 49 kg N ha^{-1} rate. Nitrate-N leaching in response to N rate in 2007 was linear at C1 and C2 (Table 1 and Table 5). Differences among N rates during C3 of 2007 were not observed, although a significant curvilinear (quadratic) trend in N leaching was detected during C3 in response to N rate (Table 1 and Table 5). However, the 294 kg N ha^{-1} N rate resulted in 14.52 kg N ha^{-1} more annual cumulative N leaching than the 49 kg N ha^{-1} rate and NO_3–N leaching was linear in response to N rate.

The year × N rate interaction influenced St. Augustinegrass quality during the majority of cycles and for the annual average (Table 1). St. Augustinegrass turf quality is reported by the year × N rate interaction. In 2006, N rates of 98, 196, and 294 kg ha^{-1} led to greater turf quality than the 49 kg N ha^{-1} rate during each cycle and for the annual average (Table 5). Each N rate resulted in acceptable St. Augustinegrass quality during each cycle except C1, in which quality was 5.8 in response to the 49 kg N ha^{-1} rate. The turf quality of St. Augustinegrass during all cycles (C1, C2, and C3) and for the annual averages were principally linear in response to N rate; however, statistically significant quadratic components were detected in 2006 (Table 1 and Table 5).

In 2007, increasing N rates resulted in a reduction of St. Augustinegrass quality during C1, did not influence turf quality during C2, and increased turf quality during C3 (Table 5). However, during all cycles, including C2, turf quality in response to N rate was linear (Table 1). St. Augustinegrass quality remained below acceptable levels until C2 under the 196 kg N ha^{-1} rate. By C3, N applied at each rate except 49 kg ha^{-1} resulted in acceptable quality St. Augustinegrass. The average annual St. Augustinegrass quality remained below acceptable levels under each N rate. However, increasing N rates did increase the annual turf quality average for St. Augustinegrass, with quality following a significant linear trend increasing from 5.0 to 5.5 at the 49 and 294 kg N ha^{-1} yr^{-1} rates, respectively (Table 1 and Table 5).

Because St. Augustinegrass quality in Jay was influenced by the year × N rate interaction, a regression analysis of N rate and quality was determined within years (Fig. 2). Linear regression analysis indicated that the turf quality response to N rate during 2006 and 2007 was well described (r^2 = 0.58 and 0.52, respectively) and was significant ($P < 0.001$). According to the linear regression model for 2006, an acceptable turf quality of 6.6 was achieved with only 49 kg N ha^{-1} yr^{-1} in Jay, FL. Furthermore, turf quality according to the *y*-axis intercept (0 kg N ha^{-1} yr^{-1}) was predicted to be approximately 6.3 for unfertilized St. Augustinegrass in Jay. Alternatively in 2007, 147 kg N ha^{-1} yr^{-1} was required to achieve minimal acceptable St. Augustinegrass quality (6.0), whereas unfertilized turf quality in Jay according to the *y*-axis intercept (Fig. 2) was only 4.8. As discussed previously, the regression analysis *y*-axis intercepts for unfertilized St. Augustinegrass in Citra (and Jay) were generally below 5 in turf quality, whereas turf quality was closer to 6.0 for unfertilized St. Augustinegrass in Fort Lauderdale.

DISCUSSION

Nitrate Leaching

Fort Lauderdale

Typical N applications to established warm-season turfgrasses range from 58 to 350 kg N ha^{-1} yr^{-1} (Carrow et al., 2001) and N leaching from turfgrasses maintained under these N rates tends to be low and similar to that of unfertilized turf plots (Petrovic, 1990; Turner and Hummel, 1992). The annual cumulative NO_3–N leaching observed between 98 and 294 kg N ha^{-1} rates in our study was similar. Cumulated annually, our NO_3–N leaching values are consistent with those reported by Morton et al. (1988). Morton el al. (1988) investigated N leaching from the application of urea at rates ranging from 0 to 244 kg N ha^{-1} yr^{-1} to Kentucky bluegrass (*Poa pratensis* L.) in Rhode Island maintained with water applied to minimize percolation (water applied when soil-water potential attained −0.05 MPa tension) or water applied to simulate overwatering (three applications per week of 1.25 cm per applications). These authors determined that under the overwatering irrigation regime, 3.04 and 4.87 kg N ha^{-1} leached from the 98 and 244 kg N ha^{-1} treatments, respectively. Most prior studies have investigated NO_3–N leaching using N rates below 300 kg N ha^{-1} yr^{-1}. To confirm the potential NO_3–N leaching risk associated with exceeding University of Florida recommendations for nutrient applications to established turf, we included a 588 kg N ha^{-1} rate (double the recommended maximum rate). This rate resulted in greater NO_3–N leaching than the 98 kg N ha^{-1} rate. This indicates that the current recommended N rates for south Florida do not pose an increased risk of NO_3–N leaching. However, exceeding 294 kg N ha^{-1} yr^{-1} may increase NO_3–N leaching and is not recommended.

The high irrigation regime in four of the six cycles led to greater NO_3–N leaching than the low regime. This was probably a result of the greater leachate volumes collected under the high compared with the low irrigation schedule during most cycles and for the annual totals for both years (Table 3). The influence of moisture management on NO_3–N leaching is well documented (Hergert, 1986; Morton et al., 1988; Snyder et al., 1984). Our findings reinforce those of Morton et al. (1988), who reported that 3.04 and 13.65 kg N ha^{-1} leaching was caused by irrigating based on scheduled (no percolation) or overwatering with 3.75 cm of water per week in addition to rainfall, respectively. In terms of magnitude, our differences between irrigation regimes are lower than those of Morton et al. (1988), who observed an approximately fourfold increase in N leaching under the high irrigation regime, whereas

Table 5. Nitrate-N leached and St. Augustinegrass quality in response to the interaction of year and N rate in 2006 and 2007 in Jay, FL.

Annual N rate	Nitrate-N leached				Turf quality†			
	C1‡	C2	C3	Annual	C1	C2	C3	Average
$kg\ N\ ha^{-1}$	ln ($kg\ ha^{-1}$)				1–9			
2006								
49	−1.65 (0.21)§	−1.62 (0.21)	−1.85 (0.17)	−0.60 (0.59)	5.8	6.5	7.3	6.5
98	−1.97 (0.16)	−1.95 (0.16)	−2.23 (0.11)	−0.93 (0.44)	6.3	7.3	7.9	7.2
196	−1.82 (0.23)	−1.87 (0.20)	−1.77 (0.20)	−0.69 (0.65)	6.8	8.1	8.5	7.8
294	−1.77 (0.18)	−1.79 (0.17)	−2.77 (0.62)	−0.58 (0.95)	7.1	8.5	8.6	8.1
$LSD_{0.05}$	NS¶	NS	NS	NS	0.3	0.3	0.3	0.3
2007								
49	−0.59 (4.20)	−0.71 (3.69)	−1.55 (0.22)	0.46 (8.12)	4.1	5.2	5.8	5.0
98	0.01 (3.28)	−0.28 (4.39)	−1.93 (0.17)	0.90 (7.84)	3.8	5.5	6.4	5.3
196	1.00 (6.98)	1.38 (10.22)	−1.82 (0.18)	2.08 (17.40)	3.7	6.0	7.1	5.6
294	1.43 (9.88)	1.41 (12.48)	−1.43 (0.26)	2.33 (22.64)	3.5	5.8	7.2	5.5
$LSD_{0.05}$	1.83	2.10	NS	1.73	0.5	NS	0.6	0.5

† Turf quality was based on a scale from 1–9, where 1 = dead or brown turf, 6 = minimally acceptable, and 9 = optimal healthy or green turf.

‡ Cycle. C1, C2, and C3 were mid-April to mid-June, mid-June to mid-August, and mid-August to mid-September, respectively.

§ Values in parentheses represent backtransformed values.

¶ NS = nonsignificant at $P < 0.05$.

we observed only a twofold increase. Clearly, irrigating using schedules and amounts similar to our high rate (39 mm wk^{-1}) rather than our low rate (17.5 mm wk^{-1}) may pose an increased risk to groundwater contamination, at least under similar environmental conditions.

Citra

Citra is located north of the boundary separating north and central Florida and is subject to nutrient application recommendations for north Florida (Florida Department of Environmental Protection, 2010). The only N rate that increased NO_3–N leaching above the 49 kg N ha^{-1} rate was the 490 kg N ha^{-1} rate (2.5-fold the recommended highest rate of 196 kg N ha^{-1}) during C4 and for the cumulative annual total . Precipitation during October (2006 and 2007) was 30 mm below and 104 mm above the historical average, respectively (Fig. 1). The influence of greater rainfall during C4 is also correlated with the additional 2.17 kg N ha^{-1} leaching observed during 2007 compared with 2006. Precipitation has been reported by others to influence N leaching, as previously discussed (Balkcom et al., 2003; Barton and Colmer, 2006; Erickson et al., 2010).

Unlike the results in Fort Lauderdale, irrigation rate in Citra did not influence NO_3–N leaching. Although a direct comparison between locations was beyond the scope of this investigation, weekly irrigation schedules and amounts in Citra provided the same quantity of water (26 mm) applied either as a single application or split in two weekly applications. This led to equal quantities of leachate during each cycle and for the cumulative annual total during both years (Table 3). In Fort Lauderdale, weekly irrigation supplied different quantities of water (either 17.5 or 39 mm). We believe that the difference between irrigation regimes in Citra was not sufficient to induce NO_3–N leaching differences.

Jay

Nitrogen rates did not influence NO_3–N leaching in 2006 (Table 1 and Table 5). Similarly, Easton and Petrovic (2004) investigated N leaching from soluble N applied to Kentucky bluegrass under two N rates and noted that the 50 and 100 kg N ha^{-1} rates leached similar quantities of NO_3–N (18.2 and 22.0 kg N ha^{-1}, respectively) once the turf was fully established. A more recent study by Trenholm et al. (2012) investigated the influence of increasing N rates on ‘Empire’ zoysiagrass in central Florida and found no NO_3–N leaching differences among N rates between 49 and 343 kg N ha^{-1}. However, greater NO_3–N leaching occurred once N rates reached 490 kg N ha^{-1}. Our high N rate was 294 kg N ha^{-1}, well below the 490 kg N ha^{-1} rate used by Trenholm et al. (2012). Although our high N rate of 294 kg N ha^{-1} exceeded the rate recommended by the Florida BMPs by 98 kg N ha^{-1}, apparently differences between NO_3–N leaching among N rates would require an N rate greater than 294 kg N ha^{-1}.

Although research exists that indicates N rates do not influence N leaching, numerous studies indicate a potential risk. In 2007, the 294 kg N ha^{-1} rate led to 5.68 kg N ha^{-1} more NO_3–N leaching than the 49 kg N ha^{-1} rate during C1, 8.79 kg N ha^{-1} more NO_3–N during C2, and 14.52 kg N ha^{-1} more NO_3–N as cumulative annual totals. Increased N leaching associated with increasing N rates has been documented (Frank et al., 2006; Wu et al., 2010). Frank et al. (2006) investigated N leaching from 10-yr old Kentucky bluegrass in Michigan and at 637 d after treatment, 0.3 and 5.0 kg N ha^{-1} leached under the 49 and 98 kg N ha^{-1} rates, respectively.

Generally, N applied to St. Augustinegrass leaches less readily than N applied to other warm-season turfgrasses (Bowman et al., 2002). We postulate that St. Augustinegrass was capable of assimilating sufficient applied N to effectively reduce N leaching to the point that no differences between the low and high N rates were observed in 2006. In 2007, N leaching was approximately 30-fold greater than in 2006. During this period of elevated N leaching, NO_3–N leaching differences were observed between the 49 kg N ha^{-1} and the 294 kg N ha^{-1} rates. This observation was noted in C1 and C2 and for the cumulative annual total and was caused by an herbicide application (ethofumesate) that severely injured the turf reducing turf quality, which we will discuss in the following section. Other researchers have reported increases in N leaching following a sudden reduction in turf quality and growth (Bushoven et al., 2000).

Since rainfall remained below the historical average during the majority of the months (Fig. 1), we would expect irrigation rates to influence NO_3–N leaching. This was not the case. Since irrigation regimes differed in application frequency and not quantity, NO_3–N leaching differences were not observed, as previously discussed.

Turf Quality

Fort Lauderdale

Turf quality was acceptable under each N rate during each cycle and for the annual average, except under the 98 kg N ha^{-1} rate during C2 and C3 (Table 4). The regression results indicate that reducing the current N recommendations to 98 kg ha^{-1} would result in acceptable turf on an annual average basis (Table 4, Fig. 2). However, this study was conducted for 2 yr. Prolonged exposure to low N rates can lead to unacceptable turf, which may only be evident after the first 2 yr (Telenko et al., 2015). As observed in C2 and C3, the 98 kg N ha^{-1} rate did not yield acceptable quality turf. Moreover, turf quality was reduced in the second year (Table 1), primarily as result of turf under the 98 kg N ha^{-1} treatment failing to achieve acceptable levels (data not shown). This may pose a potential concern for commercial turf managers whose customers cannot accept seasonal fluctuations in quality below acceptable levels. Alternatively, the current lowest recommended N rate for south Florida (196 kg N ha^{-1}) resulted in acceptable quality turf during each cycle. It is possible that a rate between 98 and 196 kg N ha^{-1} would supply sufficient N, yield acceptable turf, and avoid any objectionable seasonal reductions in turf quality. However, further research would be necessary to justify a reduction of the current recommended rate.

Citra

Similar to Fort Lauderdale, each increase in applied N increased turf quality above the 49 kg N ha^{-1} rate. However, only turf supplied with 196 kg N ha^{-1} and higher resulted in acceptable quality turf. The unacceptable turf observed under the 49 kg N ha^{-1} rate during each cycle indicates that 49 kg N ha^{-1} yr^{-1} supplied insufficient N to meet minimum turf quality expectations. The quadratic regression model indicates that an N rate of 165 kg N ha^{-1} would be necessary to yield acceptable quality turf (Fig. 2). This represents an increase of 67 kg N ha^{-1} yr^{-1} above the current minimum recommended annual N rate of 98 kg N ha^{-1} yr^{-1}. The separation of Florida into north, central, and south regions and their associated nutrient application recommendations provides each region with suitable management practices that encompass the majority of turf management scenarios. However, differences in environmental factors that influence plant growth do exist within each region. During our experimental period, average soil temperatures in Citra remained above those of Jay during each month and actually exceeded the soil temperatures in Fort Lauderdale during most summer months (Fig. 3). Apparently, because the soil temperatures in Citra exceeded the soil temperatures in Jay, St. Augustinegrass demand for N exceeded the minimum N currently recommended to yield minimum acceptable turf.

Reduced growth in warm-season turfgrass subjected to cooler temperatures has been documented. Stanford et al. (2005) compared the shoot weight of TifDwarf bermudagrass subjected to night air temperatures of 19 and 11°C and reported a 71% reduction in shoot weight under 11°C. Similar results were observed by Newman et al. (2001) when investigating the influence of temperature on the yield of 'Pensacola' bahiagrass (*Paspalum notatum* Flügge). When temperature was increased from ambient to ambient + 4.5°C, dry matter yield increased by 11, 12, and 26% in three consecutive years. Clearly, temperature can have a pronounced effect on warm-season growth and associated N uptake. Our results indicate that St. Augustinegrass managed using the minimum N recommendations (98 kg ha^{-1} yr^{-1}) for north Florida may fall below acceptable turf quality levels in areas subject to elevated soil temperatures.

Jay

In 2006, under normal growth conditions, the results indicate that minimum acceptable turf quality (6.0) would be produced by an N rate below 49 kg N ha^{-1} (Table 5, Fig. 2). The current University of Florida annual N application recommendation for St. Augustinegrass in north Florida is 98 to 196 kg ha^{-1}. In terms of NO_3–N leaching, these ranges pose little increased risk and are justified by our finding that NO_3–N leaching from rates below and above the current recommended rates was similar (Table 5). However, since the 49 kg N ha^{-1} rate resulted in acceptable turf quality, the lower recommended range (98 kg N ha^{-1}) may need to be adjusted down to reflect our findings more closely.

In 2007, the regression results indicate that acceptable turf quality would be achieved by an N rate of 147 kg N ha^{-1} (Table 5, Fig. 2). During 2007, turfgrass was subjected to an herbicide application (ethofumesate) and did not recover until C3. Current University of Florida nutrient application recommendations are predicated on the assumption that the turfgrass is healthy and growing under normal environmental conditions. This was not the case in 2007 and, as such, the current minimum recommended N rate (98 kg ha^{-1} yr^{-1}) did not result in acceptable turf. We observed a decrease in quality as N rates increased during C1, the initial cycle following the ethofumesate application. This apparent detrimental interaction between N and ethofumesate on turf quality has not been well documented and the exact cause of quality reduction caused by increasing N rates remains unclear. However, the reduction in turf quality is most likely to be responsible for the highest leaching rates observed in this study (Table 5) and underscores the need to maintain healthy turf to reduce the risk of N leaching.

CONCLUSIONS

These results indicate that N applied according to the recommendations for Jay and Fort Lauderdale produced acceptable quality turf at the low and high N range when turf was not exhibiting stress symptoms during most cycles. For Jay, the regression analysis predicted that the N rate to promote minimum acceptable turf quality in all cycles was below the current recommended minimum (98 kg ha^{-1} yr^{-1}). Based on regression analysis, the minimum N required to yield acceptable turf in Citra was predicted to be 165 kg N ha^{-1} yr^{-1}, which represents an increase in 67 kg N ha^{-1} yr^{-1} from the current recommended minimum (98 kg N ha^{-1} yr^{-1}). This may be a result of the increased temperatures observed in Citra compared to Jay during each month. In Fort Lauderdale, the 98 kg N ha^{-1} rate failed to produce acceptable turf quality in some cycles, whereas the 196 kg N ha^{-1} rate led to acceptable turf quality during each cycle of each year. Therefore, the current recommendation of 196 kg N ha^{-1} is valid. In Jay, when turf exhibited stress because of the ethofumesate application, increasing the N rate did not result in an immediate increase in turf quality but increased NO_3–N leaching. Fertility recommendations to enhance recovery from turf stress while minimizing risk of NO_3–N leaching have not been investigated and warrant further investigation.

Nitrogen applications to healthy St. Augustinegrass managed according to current University of Florida recommendations do not pose an increased risk to NO_3–N leaching. However, N applications within the current recommended ranges may increase NO_3–N leaching if applied to stressed or unacceptable turf. Defining 'stressed' turf is currently subject to opinion and should be further clarified before inclusion in BMPs.

High irrigation rates led to a twofold increase in NO_3–N leaching in Fort Lauderdale, where irrigation regimes differed in the quantity of water applied. In Jay and Citra, irrigation regimes provided equal quantities of water and thus the irrigation rates did not influence NO_3–N leaching.

References

Balkcom, K.S., A.M. Blackmer, D.J. Hansen, T.F. Morris, and A.P. Mallarino. 2003. Testing soils and cornstalks to evaluate nitrogen management on the watershed scale. J. Environ. Qual. 32:1015–1024. doi:10.2134/jeq2003.1015

Barton, L., and T.D. Colmer. 2006. Irrigation and fertiliser strategies for minimising nitrogen leaching from turfgrass. Agr. Water Manage. 80:160–175. doi:10.1016/j.agwat.2005.07.011

Bowman, D.C., C.T. Cherney, and T.W. Rufty. 2002. Fate and transport of nitrogen applied to six warm-season turfgrasses. Crop Sci. 42:833–841. doi:10.2135/cropsci2002.0833

Bowman, D.C., J.L. Paul, W.B. Davis, and S.H. Nelson. 1987. Reducing ammonia volatilization from Kentucky bluegrass turf by irrigation. HortScience 22:84–87.

Brown, K.W., J.C. Thomas, and R.L. Duble. 1982. Nitrogen-source effect on nitrate and ammonium leaching and runoff losses from greens. Agron. J. 74:947–950. doi:10.2134/agronj1982.00021962007400060005x

Bushoven, J.T., Z.C. Jiang, H.J. Ford, C.D. Sawyer, R.J. Hull, and J.A. Amador. 2000. Stabilization of soil nitrate by reseeding with perennial ryegrass following sudden turf death. J. Environ. Qual. 29:1657–1661. doi:10.2134/jeq2000.00472425002900050037x

Carrow, R.N., D.V. Waddington, and P.E. Rieke. 2001. Developing fertilizer programs. In: Turfgrass soil fertility and chemical problems: Assessment and management. Ann Arbor Press, Chelsea, MI. p. 339–366.

Dukes, M.D. 2014. Summary of IFAS turf and landscape irrigation recommendations. AE436. Univ. Florida IFAS Extension. http://edis.ifas.ufl.edu/ae436 (accessed 1 Oct. 2015).

Easton, Z.M., and A.M. Petrovic. 2004. Fertilizer source effect on ground and surface water quality in drainage from turfgrass. J. Environ. Qual. 33:645–655. doi:10.2134/jeq2004.6450

Erickson, J.E., D.M. Park, J.L. Cisar, G.H. Snyder, and A.L. Wright. 2010. Effects of sod type, irrigation, and fertilization on nitrate-nitrogen and orthophosphate-phosphorus leaching from newly established St. Augustinegrass sod. Crop Sci. 50:1030–1036. doi:10.2135/cropsci2009.07.0411

Fetter, J.C., R.N. Brown, J.H. Gorres, C. Lee, and J.A. Amador. 2012. Nitrate and phosphate leaching under turfgrass fertilized with a squid-based organic fertilizer. Water Air Soil Pollut. 223:1531–1541. doi:10.1007/s11270-011-0962-y

Florida Department of Environmental Protection. 2010. Florida friendly best management practices for protection of water resources by the green industries. Florida Department of Environmental Protection, Tallahassee, FL.

Florida Senate. 2015. Agricultural fertilizers: registration and licensing. Florida State. http://www.flsenate.gov/Laws/Statutes/2015/576.021 (accessed 6 Oct. 2015).

Frank, K.W., K.M. O'Reilly, J.R. Crum, and R.N. Calhoun. 2006. The fate of nitrogen applied to a mature Kentucky bluegrass turf. Crop Sci. 46:209–215. doi:10.2135/cropsci2005.04-0039

Hergert, G.W. 1986. Nitrate leaching through sandy soil as affected by sprinkler irrigation management. J. Environ. Qual. 15:272–278. doi:10.2134/jeq1986.00472425001500030013x

Krans, J.V., and K. Morris. 2007. Determining a profile of protocols and standards used in the visual field assessment of turfgrasses: A survey of National Turfgrass Evaluation Program-sponsored university scientists. Appl. Turf. Sci. doi:10.1094/ATS-2007-1130-01-TT.

Mancino, C.F., and J. Troll. 1990. Nitrate and ammonium leaching losses from N-fertilizers applied to 'Penncross' creeping bentgrass. HortScience 25:194–196.

Morton, T.G., A.J. Gold, and W.M. Sullivan. 1988. Influence of overwatering and fertilization on nitrogen losses from home lawns. J. Environ. Qual. 17:124–130. doi:10.2134/jeq1988.00472425001700010019x

Newman, Y.C., L.E. Sollenberger, K.J. Boote, L.H. Allen, and R.C. Littell. 2001. Carbon dioxide and temperature effects on forage dry matter production. Crop Sci. 41:399–406. doi:10.2135/cropsci2001.412399x

Petrovic, A.M. 1990. The fate of nitrogenous fertilizers applied to turfgrass. J. Environ. Qual. 19:1–14. doi:10.2134/jeq1990.00472425001900010001x

Rowland, J.H., J.L. Cisar, G.H. Snyder, J.B. Sartain, A.L. Wright, and J.E. Erickson. 2010. Optimal nitrogen and potassium fertilization rates for establishment of warm-season putting greens. Agron. J. 102:1601–1605. doi:10.2134/agronj2010.0184

Saha, S.K., L.E. Trenholm, and J.B. Unruh. 2007. Effect of fertilizer source on nitrate leaching and St. Augustinegrass turfgrass quality. HortScience 42:1478–1481.

Sartain, J.B. 2012. Soil and tissue testing and interpretation for Florida turfgrasses. SL 181. Univ. Florida IFAS Extension. https://edis.ifas.ufl.edu/ss317 (accessed 1 Oct. 2015).

Sartain, J.B. 2013. General recommendations for fertilization of turfgrasses in Florida soils. SL 21. Univ. Florida IFAS Extenstion. https://edis.ifas.ufl.edu/pdffiles/LH/LH01400.pdf (accessed 1 Oct. 2015).

SAS Institute. 2010. SAS/STAT user's guide. SAS Inst., Cary, NC.

Snyder, G.H., B.J. Augustin, and J.M. Davidson. 1984. Moisture sensor-controlled irrigation for reducing N leaching in bermudagrass turf. Agron. J. 76:964–969. doi:10.2134/agronj1984.00021962007600060023x

Stanford, R.L., R.H. White, J.P. Krausz, J.C. Thomas, P. Colbaugh, and S.D. Abernathy. 2005. Temperature, nitrogen and light effects on hybrid bermudagrass growth and development. Crop Sci. 45:2491–2496. doi:10.2135/cropsci2005.0070

Systat Software Inc. 2013. SigmaPlot 12.5: User's guide. Systat Software, Inc., Chicago, IL.

Telenko, D.E.P., T.W. Shaddox, J.B. Unruh, and L.E. Trenholm. 2015. Nitrate leaching, turf quality, and growth rate of 'Floratam' St. Augustinegrass and common centipedegrass. Crop Sci. 55:1320–1328. doi:10.2135/cropsci2014.09.0639

Trenholm, L.E., J.L. Cisar, and J.B. Sartain. 2011. St. Augustinegrass for Florida lawns. ENH 5. Univ. florida IFAS Extension. http://edis.ifas.ufl.edu/lh010 (accessed 1 Oct. 2015).

Trenholm, L.E., and J.B. Unruh. 2007. St. Augustinegrass fertilizer trials. J. Plant Nutr. 30:453–461. doi:10.1080/01904160601172007

Trenholm, L.E., J.B. Unruh, and J.B. Sartain. 2012. Nitrate leaching and turf quality in established 'Floratam' St. Augustinegrass and 'Empire' zoysiagrass. J. Environ. Qual. 41:793–799. doi:10.2134/jeq2011.0183

Trenholm, L.E., J.B. Unruh, and J.B. Sartain. 2013. Nitrate leaching and turf quality in newly sodded St. Augustinegrass. J. Plant Nutr. 36:1935–1943. doi:10.1080/01904167.2013.819893

Turner, T.R., and N.W. Hummel. 1992. Nutritional requirements and fertilization. In: D.V. Waddington, R.R. Carrow, and R.C. Shearman, editors, Turfgrass. ASA, CSSA,and SSSA, Madison, WI. p. 385–440.

USEPA. 1983. Nitrogen, nitrate-nitrite. Method 353.2 (colorimetric, automated, cadmium reduction). Methods for chemical analysis of water and wastes, EPA-600/4–79–020. USEPA, Cincinnati, OH.

Wu, L.S., R. Green, G. Klein, J.S. Hartin, and D.W. Burger. 2010. Nitrogen source and rate influence on tall fescue quality and nitrate leaching in a southern California lawn. Agron. J. 102:31–38. doi:10.2134/agronj2009.0209