INORGANIC NITROGEN LEACHING AND AGRONOMIC RESPONSE OF ST AUGUSTINEGRASS TO NITROGEN FERTILIZATION STRATEGIES UNDER RESIDENTIAL LAWN CONDITIONS

By

NEIL GRAHAM MILLER YOUNG

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To mum and dad who gave the encouragement and support to go back to school

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NITROGEN LEACHING AND AGRONOMIC RESPONSE OF ST AUGUSTINEGRASS TO NITROGEN FERTILIZATION STRATEGIES UNDER RESIDENTIAL LAWN CONDITIONS

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Neil Graham Miller Young

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In Florida, residential landscape fertilization legislation limits per-application nitrogen (N) rates to 49 kg ha^{-1}, prevent fertilization during the wet season, and control soluble-N to reduce NO_3-N in ground-water. Insufficient data are available to assess the efficacy of N-rate regulation. The performance of controlled-release N sources (CRNS) and their capacity to leach N under abundant seasonal precipitation on St. Augustinegrass [*Stenotaphrum secundatum* Walt. Kuntze] grown on fine sand (Siliceous, hyperthermic Lythic Psammaquent) is unknown. Higher per-application rates of CRNS may sustain agronomic responses (i.e. turf quality, density, growth, and N-uptake) during restrictive seasons. A 24-mo field study compared these agronomic responses and N leaching from polymer-coated urea (PCU), controlled-release liquid (CRL), and biosolid (BSD) applied at 49, 98, and 147 kg N ha^{-1} on 60, 120, and 180-d re-application intervals, respectively. Equal N combinations of PCU and urea, at 49 and 98 kg N ha^{-1} every 60 and 120 d, respectively provided responses equal to urea, which served as the base for comparison at 49 kg N ha^{-1} every 60-d. Residual N carryover from preceding cycles was an important agronomic factor for PCU and BSD at 49 kg N ha^{-1}. Of the CRNS, PCU at 98 kg N ha^{-1} provided the best responses. At 147 kg N ha^{-1} BSD and PCU were capable of sustaining

acceptable turf quality throughout restrictive seasons, with negligible NO_3-N leaching. Initially, urea at 49 kg N ha^{-1} produced maximum leaching losses of 12% of applied N. In subsequent fertilization cycles, N leaching was greatly reduced despite intense hydrological events, indicating N utilization may improve under adequate plant available nitrogen (PAN). Re-application intervals (180-d) in excess of manufacture recommendations for CRL at 147 kg ha^{-1} resulted in progressively lower turf density and increased N leaching. Our findings suggest soluble-N rate restrictions prevent excess N leaching. However, rate regulation of certain CRNS prevents judicious N fertilization throughout restrictive seasons and if St. Augustinegrass density declines during this period due to limited PAN, greater N leaching may result once fertilization resumes.

CHAPTER 1
INTRODUCTION

St. Augustinegrass Land use influenced Demographics

Since 1990, demographic data reports the population in Florida has increased by 31.9% to approximately 18.3 million residents (United States Census Bureau, 2008). Anthropogenic intrusion of this magnitude has shown to drastically alter the nitrogen (N) cycle and more than double the production rate of reactive nitrogen (Galloway and Cowling 2002; Galloway et al. 2004) with detrimental consequences to ecological systems and human health (Wolfe and Patz, 2002). Urban development in the US requires the inclusion of urban and domestic landscapes with St. Augustinegrass sod production increasing dramatically in Florida to support urban expansion (Haydu and Cisar, 1990). Recent land use trends suggest St. Augustinegrass *Stenotaphrum secundatum* (Walt.) Kuntze landscapes encompass an estimated at 810,000 ha in Florida (Trenholm and Unruh, 2007). In recent years, improving water resources in Florida has become a key concern for regulatory bodies and has lead certain factions to implicate fertilization practices on urban landscapes as a potential non-point source contributor to N species degradation of surface and ground water.

Anthropogenic and Ecological Implications from Lawn Fertilization

As human populations escalate so does the demand for safe drinking water that must not exceed the Maximum Contaminant Level (MCL) of 10 mg L^{-1} as NO_3-N set by Environmental Protection Agency (EPA) for human safety. Petrovic (1990) reported that groundwater accounts for 86% of water resources and provides 24% of drinking water for urban areas in the contiguous USA. According to the United States Geological Survey, 1% of public water supplies, 9% of domestic water wells, and 21% of shallow wells in agricultural communities contain nitrate (NO_3-N) in excess of the MCL standard. Serious human health concerns are associated with consumption of excessive NO_3-N in drinking water. High level NO_3-N ingestion is involved in the aetiology of human cancer (Fraser et al. 1980), with increased incidences of gastric cancer (Knight et al., 1989; van Leeuwen et al., 1999) and brain tumors (Mueller et al., 2004). More publicized, however, has been the incidence of methaemoglobinaemia or "blue-baby" syndrome where infants display symptoms of hypoxia (Mansouri, 1985).

Townsend et al. (2003) reported the eutrophication of coastal and marine ecosystems may be an ecological factor that affects human health, due to the increased occurrence of harmful algae blooms (HAB) in coastal water as a result of anthropogenic nutrient loading. On the West coast of Florida the nearly annual occurrence of HAB, commonly known as "Florida Red Tide", is due to the toxic Dinoflagellate *Karenia* brevis or other closely related species, which are linked to marine mortalities and human illness (Van Dolah, et al., 2009).

Sources of NO_3-N contamination of groundwater are diverse and include effluent from septic tanks, animal and human waste, and fertilization of agricultural lands (Keeney, 1986). Flipse et al. (1984) proposed NO_3-N from applied fertilizer N to urban turfgrass landscapes was a primary source of ground-water contamination where these areas were a major land use. In Florida, fertilizer N leaching to groundwater from urban landscapes has been implicated as a potential non-point source contributor to the coastal marine eutrophication and in particular the increasing incidence of "Florida Red Tide" in Sarasota Bay.

Fertilizer Ordinance and Labeling Restrictions

Even though no scientific evidence currently links N loading from urban landscapes with nutrient pollution in the Gulf of Mexico, cities and municipalities have responded with heightened regulatory restriction on urban fertilization practices in efforts to control red tide outbreaks. These local government ordinances and resolutions supersede state-wide fertilizer labeling legislation that was designed to moderate N species degradation of surface and ground water resources. The state fertilizer labeling rule restricts per application N-rates to 49 kg N ha^{-1}, of which, the water-soluble N portion should not exceed 34 kg N ha^{-1} (Department of Agricultural and Consumer services (DACS), No. 4640400, Rule 5E-1.003, 2007).

St. Johns County introduced the first restrictive fertilization ordinance on October 24, 2000; when Guana Marsh Basin was identified as a critical sink for leached N. The enactment limited the portion of soluble N applied from May 15 to October 15 and constrained annual N applied as fertilizer to 196 kg ha^{-1} (Ordinance No. 2000-60), although three years later this enactment was largely repealed with less stringent regulation (Ordinance No. 2003-52). Amidst growing concern over the impact of severe red tide outbreaks on Florida's multi-million dollar tourism and fishing industries the previous year, resolution No. 2006-126 was proposed on May 24, 2006 that called for counties and cities in the Southwest Florida Region to uniformly adopt regulatory urban fertilizer ordinances (Council of the City of Sannibel, Agenda item #4[b], 2006).

On March 6, 2007, the City of Sanibel enacted Ordinance No. 07-003 (Council of the City of Sannibel, Water Resources Department) and later that year Sarasota County adopted the Fertilizer and Landscape Management Code (Board of County Commissioners of Sarasota County, Ordinance No. 2007-63). These legislative codes prohibit N fertilization during the traditional rainy season in South Florida from June 1 through September 30, restrict annual N applied as fertilizer to 196 kg ha^{-1}, and further limit the per-application soluble N portion of fertilizer to 24.5 kg ha^{-1}. The City of Cape Coral passed similar fertilizer legislation with Resolution 72-07 on August 29, 2007 (Commissioner Dolores Bertolin, personnel communication), although seasonal restrictions were not imposed. In 2008, Lee and Charlotte Counties followed suit with Ordinance No. 08-08 and 2008-028, respectively. However, only

Charlotte County chose to follow state Best Management Practices (BMP) guidelines (FDEP, 2008) and limit annual N to between 196 and 294 kg N ha^{-1} for St. Augustinegrass in South Florida.

Fertilizer application limits of 49 kg N ha^{-1} have been imposed unilaterally across all N-sources and may negate the best features of controlled-release nitrogen sources (CRNS) that have been shown to be more effective when applied at infrequent higher per-application rates (Skogley and King, 1968; Hummel and Waddington, 1984; Williams et al., 1997) with reduced potential for N leaching (Rieke and Ellis, 1974; Brown et al., 1977; Nelson et al., 1980; Snyder et al. 1981, 1984; Engelsjord and Singh, 1997; Guillard and Kopp, 2004). These enactments may rule out judicious fertilization with higher rates of CRNS and sustain good turf quality and root growth, before, during, and after restrictive rainy season periods and limit N leaching,.

There is a clear need to evaluate N-loss and agronomic responses of St. Augustinegrass under variable N-source management and application regimes to better understand the efficacy of N-rate regulation. The evaluation of N leaching under CRNS fertilization of St. Augustinegrass may provide valuable information for regulatory bodies to determine if the same stringent rate regulation is applicable to all sources and to ascertain if higher pre-application rates of these N-sources, prior to restrictive seasons can sustain turf vigor for extended periods without environmental consequences. Urban landscape fertilizer ordinances as they are currently written may have damaging agronomic and environmental implications. Ultimately, if the goal is to promote urban landscapes that have aesthetic value, while limiting N-pollution, all factors involved with residential lawn fertilization and N-deposition must be considered.

CHAPTER 2
THE INFLUENCE OF VARIOUS NITROGEN STRATEGIES ON ST. AUGUSTINEGRASS QUALITY, DENSITY, YIELD, AND NITROGEN UPTAKE.

Introduction

Urban landscapes have been implicated as a potential non-point source contributor to nitrogen (N) species degradation of surface and ground water (Petrovic, 1990; King and Balogh, 2008). Recent land use trends suggest an increasing use of St. Augustinegrass [*Stenotaphrum secundatum* (Walt.) Kuntze], in urban landscapes with currently an estimated 810,000 ha in Florida (Trenholm and Unruh, 2007). Statewide fertilizer labeling legislation in conjunction with city and municipality restrictions have been introduced in response to mounting concerns over the impact of urban fertilization practices on Florida's water resources. These enactments were introduced prior to determining N leaching characteristics or agronomic responses of controlled-release N sources (CRNS) on St. Augustinegrass and may have inadvertently constrained optimal CRNS management strategies (i.e. less frequently applied, higher per-application N-rates) that reduce inputs such as labor, time, and energy (Trenkel, 1997). There is a clear need to evaluate the agronomic responses of St. Augustinegrass under varying N sources, application rates, and frequencies to better understand the efficacy of N rate regulation.

Nitrogen Source Categorization and Benefits

Nitrogen-based fertilizers for residential lawns are broadly categorized either as quick or as controlled release, depending on release duration (Turner and Hummel, 1992), although several sub-classes exist within these delineations (Oertli, 1980). The benefits of controlled-release fertilizers have been well documented, the most notable of which include reduced NO_3-N leaching (Rieke and Ellis, 1974; Brown et al., 1977; Nelson et al., 1980; Snyder et al. 1981, 1984; Petrovic, 1990) and lower water use (Subjarit and Trenholm, 2005). While greater N-uptake efficiency in response to quick-release N has been shown in the greenhouse for St. Augustinegrass relative to other warm season grasses (Bowman et al., 2002), little is known about St. Augustinegrass responses under varied CRNS management regimes. Numerous CRNS are commercially available for lawn-care use and stringent fertilizer restrictions exemplify the need to evaluate each N source to determine specific rate and frequency recommendations.

Biosolid N Management under Turfgrass Conditions

Milorganite® (BSD), an activated aerobically digested biosolid (Chinault and O'Connor, 2008), is composed of ~20 % soluble N (Sartain, 1999) and has been evaluated extensively on turfgrass (Turner and Hummel, 1992), although studies pertaining specifically to St. Augustinegrass are limited. Many bio-solid-based fertilizers are marketed. Each has its own set of characteristics. Since Milorganite has been used on turfgrass for over 80 years, it often is used as a standard for biosolid fertilizing and therefore was chosen for this study. Chinault and O'Connor (2008) reported the chemical characteristics of BSD and reported a C/N ratio of 6.0; a ratio that Wolf and Snyder, (2003) maintain should permit relatively rapid microbial decomposition. In contrast, Sartain (1999) reported BSD compared less favorably to mixed component organic N-sources for St. Augustinegrass quality; inferring N-release was too gradual from the unilateral mineralization rate of the organic material. Other studies noted slow initial responses or lower visual quality compared to soluble N sources (Moberg et al., 1970; Volk and Horn 1975; Carrow, 1997).

Several incubation studies have examined N recovery from BSD. Lee and Peacock (2005) found ~60% of applied N was recovered after 70-d, whereas Sartain et al. (2004) reported only ~40% of applied N was recovered following 180-d of aggressive extraction procedures. According to the US EPA Document 40 CFR Part 503 (1999), the annual mineralization rates of the organic-N applied as biosolid are 30, 15, 8, 4, and 3% in years 1, 2, 3, 4, and 5, respectively in EPA region 8. However, these N-release patterns are expected to be accelerated in Florida where higher average annual precipitation and soil temperatures are more conducive of microbial decomposition (Wolf and Snyder, 2003). Correspondingly, Carrow and Johnson (1989) compared CRNS on centipedegrass (*Eremochloa ophiurides*) with ammonium nitrate (AN) and found under periods of active microbial growth, Milorganite generated turf quality ≥ to AN.

Controlled-Release Liquid N Sources in Turfgrass

Liquid CRNS could be beneficial in the lawn care industry which, for convenience, often applies fertilizers as a liquid. The chemical characteristics of these formulations vary, although differential microbial degradation of urea and reacted-N species provides the mechanism for extended N release. Landschoot and Waddington (1987) reported initial turf response decreases relative to urea as the proportion of water-insoluble N (WIN) in the formulation increased, and longer-chained methylene ureas were present. Carrow (1997), evaluated several urea-formaldehyde (UF) products and found Coron® (50% N from urea, remainder polymethylene urea, methylene urea, monomethylol urea) and Nutralene® (13% urea, 51% N from methylene polymers, 36% UF) induced lower average visual quality of bermudagrass (*Cynodon dactylon*) than urea. Splitting the N application into two equal treatments greatly improved long term response but at the expense of initial and intermediate responses. In agreement, Sartain (2004) reported 37% of N applied as Nutralene® was released in the first 7 d. However, in a separate study, Sartain (1992) found no bermudagrass quality, growth rate, or N-uptake differences between urea, Coron®, and N-Sure® (6% methylene diurea and methylol urea by weight, remainder 0.48 to 1.0 ratio triazone to urea) treated turf. Studies indicate reduced NH_3 volatilization and N leaching are associated with urea-triazone products compared with urea and

AN (Clapp and Parham, 1991; Clapp, 2001). With inconsistent performance on warm-season grass, and no published studies documenting the performance of CRNS on St. Augustinegrass, comparative information would be of interest to lawn-care professionals.

Polymer-Coated Urea Fertilization in Turfgrass

Polymer-coated urea (PCU) is a relatively new technology described by Goertz (1991). PCU releases N by osmotic diffusion through the polymeric coating, whereby coating thickness controls the release duration (Christianson, 1988). Field studies have shown PCU provides consistent release patterns within the desired window (Hummel, 1989; Peacock and DiPaola, 1992) and through the alteration of polymer chemistry and coating thickness can offer wide range of flexibility in N-release durations. Initially slow turf response and N-release have been observed compared to soluble-N sources (Carrow, 1997; Hummel, 1989; Sartain et al., 2004). Hence, soluble-N sources are sometimes included in blends as bridging products to provide increased initial responses (Peacock and Dipaola, 1992). Nevertheless, Hummel (1989) and Cisar et al. (2001) both reported increased N-uptake between 14 and 90 d post application relative to soluble N-sources at lower per-application rates applied more frequently.

Research Objectives

Previous studies have observed differences in the performance of CRNS, although these distinctions appear to vary depending on turfgrass species and environment. Even though stringent restrictions have been imposed on lawn-grass fertilization in Florida, few studies have evaluated CRNS on St. Augustinegrass under lawn maintenance regimes. Therefore, the objectives of the experiment were as follows.

- **Objective 1:** Determine if controlled-release N sources applied under current regulatory restrictions can provide acceptable turf quality and density relative to urea.

- **Objective 2:** Evaluate St. Augustinegrass response (i.e. quality, density, and N-uptake) in response to various N management regimes to determine the most effective sources at each N application rate and frequency. Of particular interest was the longevity of turf response from CRNS applied prior to restrictive seasons at rates higher than currently permitted.

- **Objective 3:** Assess fertilizer response based on their broad categorizations by grouping sources across all rates to determine if quick-, controlled-release, or mixed component N sources provided the best St. Augustinegrass responses.

- **Objective 4:** Compare treatment effects on clipping yield under variable N management using yield comparisons with the lawn care industry standard, urea, to determine initial and long term response.

Materials and Methods

The field study was replicated in space, and over two consecutive years at the University of Florida's, Fort Lauderdale Research and Education Center (FLREC) from April 30, 2007 to May 09, 2008 and May 10, 2008 to May 15, 2009 (hereafter each experimental period are denoted as 2007 and 2008, respectively) using St. Augustinegrass [*Stenotaphrum secundatum* Walt. Kuntze] cv. 'Floratam'. The climate in South Florida is subtropical, permitting warm-season grass growth year round, but varies seasonally as shown by data obtained from the Florida Automated Weather Network station located approximately 300 m from the experimental site (Appendix A). Traditionally, two distinct seasons have been demarcated, the wet season (WS) from June to October, and the dry season (DS) from November to May, and our findings have been delineated in a similar manner to reflect climatic variation.

The sand grown sod was established 6-mo prior on mined medium-fine sand (very coarse 0.2%, coarse 5.4 %, medium 29.9%, fine sand 62.9%, very fine sand 1.5%, and silt and clay 0.1%) having similar textural characteristics to the Margate and Hallandale fine sand series (Siliceous, hyperthermic Lythic Psammaquent) found in this coastal plain region. Composite soil samples from each plot were taken throughout the study (n = 4) from the 0 to 10 cm surface layer and analyzed by various procedures (A&L Laboratory, Pompano Beach, FL). Soil chemical characteristics were averaged across the experimental period (Table 2-1). Due to high potassium (K) mobility in sandy soil, muriate of potash at 49 kg K ha^{-1} was applied every 3-mo. Bray P1 and Olsen Bicarbonate phosphorous (P) extraction methods were used to determine soil P status, because of the potential for iron/aluminum-P complexes (under bio-solid fertility) and calcium (Ca)-P complexes under very high Ca inputs from irrigation (data not included). Since additional P was supplied with biosolid (6-2-0) N applications and despite very high soil P status, an additional 24.5 kg P ha^{-1} was applied to all plots except the BSD treatment on October 1, 2007 as triple super phosphate to ensure P was not limiting. Quantifiable visual or growth responses from this supplementary P application were not observed, so no additional P fertilizations were performed thereafter and it was assumed that extraction procedures accurately estimated soil P. Micro-nutrients were applied as Harrell's Max® Minors containing Mg 1%, S 3.5%, B 0.02%, Cu 0.25%, Fe 4%, Mn 1%, Zn 0.6% and Mo 0.0005% at 12.3 L product in 420 L water ha^{-1} every 90-d to ensure adequate tissue concentrations.

The N sources descriptions, application rates, and frequencies are provided in Table 2-2. All treatments totaled 294 kg N ha^{-1} yr^{-1}, which is within best management practice guidelines for St. Augustinegrass N fertilization in South Florida (FDEP, 2008; Sartain, 2007). The controlled-release liquid (CRL) treatments were applied in solution at 181 ml m^{-2} using a CO_2 sprayer, equipped with two flat-fan TeeJet 8010 nozzles at 50 cm spacing. Granular sources were hand sprinkled. The irrigation system configuration (i.e. 2 plots per irrigation zone) permitted all treatments to be irrigated immediately follow application to reduce volatile N losses (Torello and Wehner, 1983). Irrigation was schedule 3 times per week delivering ~0.6 cm at each event, including post-treatment.

Visual Assessments

Fertilizer response was evaluated in terms of visual field assessments of St. Augustinegrass quality, and density. Turf quality is defined as the degree in which turf conforms to an agreed standard, which is composition of uniformity, shoot density, leaf texture, growth habit, smoothness and color (Krans and Morris, 2007). Turf density is a visual estimate of living plants per unit area (Morris, 2001). Visual quality evaluations were conducted approximately every 14-d on a one to nine scale in increments of 0.5; nine was dark green, dense turf, one represented dead, brown turf, and six was deemed minimally acceptable for all components (Carrow, 1997). Turf density was assessed less frequently, but in order to account for seasonal variations, ratings were conducted approximately every 90-d.

St. Augustinegrass Tissue Harvest and Analysis

Harvested clipping tissue provided a basis for quantifying treatment effects on yield and N uptake. Clipping samples were harvested using a commercially available pedestrian rotary mower (Toro, Bloomington, MN) at a 7.5 cm height of cut. Mowing occurred weekly during the WS and bi-weekly during DS in both years. Clippings were removed as part of normal maintenance. Samples removed from the 2.24 m^2 sub-plot units were oven dried at 60^oC for 48 hrs to a constant weight. Yield represented average daily leaf dry matter production above 7.5 cm (Methall et al., 1983). Dried tissue was sub-sampled for analysis of tissue N content using the Kjedahl procedure (Wolf, 1982), with manual colormetric determination (UNIVO 2100, Dayton, NJ) of NH_4-N according to Reardon (1966). Data were obtained according to quality assurance/quality control (QA/QC) protocols set forth by Kennedy et al. (1994) where N-recovery of standard reference materials 1573a and 1547 (National Institute of Standards and Technology) conformed to 89 to 101% of certificated values. Nitrogen uptake, the product of N-content (g N kg^{-1}) and yield (kg dry wt. ha^{-1} d^{-1}), was reported as g N ha^{-1} d^{-1} (Skogley and Sawyer, 1992).

Statistical Design and Analysis

The experiment was conducted according to a randomized complete block design, with 2 x 4 m plots arranged with 3 replicates. All data were tested for their conformity of the assumptions of analysis of variance (ANOVA) using PROC UNIVARIATE with normal plot of residuals and histogram of residuals (Clewer and Scarisbrick, 2001). Yield and relative N uptake data that did not conform were appropriately transformed based on the results of the Box-Cox transformation procedure (Box and Cox, 1964) before statistical analysis.

Because N-sources and rates were not balanced across all treatments, Source x N-rate interactions was investigated separately for yield and N uptake parameters for appropriate sources (i.e. BS, CRL, and PCU at 49, 98, and 147 kg N ha^{-1} rates) and linear regressions were performed using the PROC REG procedure in SAS software (SAS Institute, 1999). All data were subjected to ANOVA using PROC GLM (SAS Institute, 1999) and mean separation was accomplished using single degree contrasts. Two-tailed F tests of error variance for the estimated parameters between years were performed so that means for corresponding cycles could be compared legitimately.

Results and Discussion

Comparisons of N Sources Based on N-Release Categorization

In Florida, much discussion has surrounded residential lawn fertilization practices. County council debates have focused on broad categorizations of N fertilizers based on their N-release mechanism (i.e. quick- or controlled-release). For example, controlled-release N sources have been frequently referred to positively as having less potential to leach N compared to quick-release N fertilizers. However, little consideration is given to the agronomic fertilizer N responses of St. Augustinegrass under these broad N source categorizations. As such, it was considered appropriate to provide comparative information of N-sources based on these broad categorization.

Controlled-release N sources and mixed component N sources (MCNS) (i.e. fertilizer blends containing equal N combinations of quick- and controlled-release N materials) were grouped in appropriate categories, and compared with the quick-release N-source. Turf quality, density, yield, and N-uptake were affected by N-source categorization in 2007 and 2008 (Tables 2-3, 2-4, 2-5, 2-6). Urea, the only treatment composed exclusively from quick-release N produced greater turf quality than CRNS on 11 of 12 cycles through the 24-mo period. Sub-optimal climatic conditions for warm-season grass growth (Moore et al., 2004) during cycle 11 reduced turf quality across most treatments and potentially masked N-source effects. Nitrogen uptake followed a similar pattern. However unlike turf quality; elevated N-uptake from BSD and PCU at 147 kg N ha^{-1} reduced differences between N categories during cycle 1 and 7. Because appreciable improvements in turf quality were not observed in response to greater N-uptake relative to urea during the initial 60-d periods in the WS of 2007 and 2008, the elevated N-release from BSD and PCU at this higher N-rate may have detrimentally influenced the longevity of response from both sources. In both years, it is assumed that excessive initial N-release without correspondingly high improvements in turf quality resulted in lower N-uptake and quality ratings towards the latter stage (cycles 3 and 9) of each 180-d WS release window (Tables 2-3, 2-6).

These findings indicate that even with advanced N-release technology (i.e. polymer-coating), the delivery of N over extended durations (i.e. 180-d) was less uniform than more frequent, lower per-application N-rates of quick-release urea in South Florida. The inability of CRNS to deliver uniform N release throughout the entire release window may be a contributing cause of lower turf responses when compared to frequent applications of quick-release N fertilizers. Nevertheless, ratings for the granular CRNS at these higher rates were all in the "acceptable" range and generally > 7.

Conversely, when quick and controlled-release were combined as MCNS (i.e. UPCU1 and UPCU2) both turf quality and N-uptake were largely indistinguishable from urea. This indicates that under reduced release durations (i.e. 60 to 120-d windows) the addition of soluble-N largely counteracts problems with inconsistent N-release patterns. Differences were only apparent under cooler conditions in the DS, where quality ratings and N-uptake were greater for urea during cycle 4 (2007). Despite the similarity in terms of quality throughout 2008, N-uptake was lower for MCNS during cycle 12 (DS). Peacock and DiPaola (1992) made similar observations, suggesting polymer coating permeability, dissolution rate, and N-release decrease under lower temperatures. Therefore, in order to optimize N management from MCNS and combat slower N-release from PCU in response to cooler conditions, lawn-care professionals may find it beneficial to increase the proportion of quick-release N in blended fertilizers intended for use under DS conditions in South Florida. However, care should be exercised to ensure increasing the soluble N-fraction of fertilizer blends are in compliance with local fertilizer ordinances. Our study is in agreement with numerous studies (Landschoot and Waddington, 1987; Peacock and DiPaola, 1992; Carrow, 1997) that in most situations, CRNS in combination with quick-release N offer viable alternatives to frequent applications of urea.

Given the propinquity of St. Augustinegrass response under quick-release and MCNS fertilization, it is not surprising that MCNS outperformed CRNS in terms of quality and N-uptake. However, under MCNS fertilization, N-uptake differences were manifested more slowly between categorizes, with CRNS showing comparable levels during cycles 1 and 2 (2007), even with the 50% soluble-N proportion in the blended fertilizers. Therefore, when initiating a MCNS program, initially the proportions of quick- and controlled-release N should be weighted toward the former, in order to induce notable plant response but could be reduced accordingly thereafter.

In the context of this study, direct comparison of quick- versus CRNS may have been confounded by considerably lower measurable parameters in CRL plots over each N-rate and frequency. Nevertheless, turf density assessed on individual rating dates every 3-mo, appeared to be less affected by the N-release mechanism (Table 2-4), demonstrating CRNS were capable of maintaining turf density equal to that of urea on 6 of 9 assessments, despite lower ratings in the CRL treatment. It may be considered unfair to draw broad conclusions of the effectiveness of these N-release categories on St. Augustinegrass based solely on these findings. The author could find no other studies that have made direct agronomic response comparisons between fertilizers based on N-release categorization, but in order to address the subject conclusively a great deal more N-sources in both categories would have been needed.

Comparisons of N Sources Applied at 49 kg ha^{-1} at 60-d Intervals

Fertilizer treatments were divided into six cycles per annum (Table 2-2). During 2007, PCU and BSD were slow to induce satisfactory quality in cycle 1 (Table 2-3). Compared to BSD, lower N-uptake and yield in cycles 1 and 2 for PCU would indicate that the initial release patterns are slower for PCU (Table 2-6). Thereafter, cumulative quality increases suggest residual N-release from preceding applications is sufficient to sustain adequate turf quality (Table 2-3). Examining N-uptake from equivalent WS cycles in 2007 and 2008 provides further evidence that residual N-carryover plays an important role in generating sufficient turf quality for PCU and BSD at this N-rate. Nitrogen uptake increased by 1.3 and 3.8 fold for BSD and

PCU, respectively during cycle 8 (2008) compared to cycle 2, similarly, both sources generated 2- fold increases when cycle 9 was compared to cycle 3.

Current mandates prohibit CRNS being applied at 49 kg N ha^{-1} every 60-d during the WS in certain Florida counties. The supply of residual N from preceding applications appears to be an important aspect for the effectiveness of BSD and PCU at this N-rate and interruption of this process due to restrictive seasons may reduce the effectiveness of this N management approach. It appears improbable that either source would be capable of sustaining acceptable quality (i.e. quality ≥ 6) throughout a 120-d restrictive season with a single 49 kg N ha^{-1} application. Furthermore, because customer satisfaction depends on noticeable turf responses from applied fertilizer, the delayed initial responses particularly from PCU, may limit the wide scale use of this N source and rate, unless PCU was blended with soluble-N.

Quality differences between BSD and PCU were confined to cycles 6 and 7 where PCU delivered superior ratings (Table 2-3). Greater N-uptake for PCU in cycle 5-7 (Table 2-6) also resulted in greater yield, 78 and 116 % relative to urea in cycles 5 and 7, respectively compared to BSD where lower yield, 44 and 70 % were observed relative to urea in the same cycles (Table 2-5).

Despite the 60-d application window corresponding more closely with manufacturer recommendations for CRL (Georgia-Pacific, 2007), this product demonstrated lower turf quality, density, and N-uptake in both years relative to BSD and PCU. In addition, the maximum yield was 55% relative to urea in both years (Table 2-5). These findings indicate this N-reaction product is less effective on St. Augustinegrass. Carrow (1997) reported reduced mowing requirements and visual quality from bermudagrass treated with a similar UF reaction product compared to urea, however differences were less pronounced.

Urea maintained good mean turf quality throughout each cycle and was indistinguishable from the UPCU treatment. Compared with PCU and BSD, UPCU produced greater quality in cycles 2, 4, 6, 10, and 11 (Table 2-3). Elevated N-uptake was observed in cycles 2, 6, and 12, while yield differences were confined to cycles 2 and 4. Increased quality for UPCU without necessarily demonstrating higher average N-uptake or yield may imply that more uniform delivery of applied N from the MCS may benefit turf quality (Table 2-3, 2-5, 2-6).

In contrast, N-source appeared to influence turf density to a lesser degree than quality, with UPCU demonstrating elevated levels on single rating dates in 2007 and 2008 (Table 2-4). Under adequate N fertilization turf density may be expected to fluctuate less than quality, since color improvements (a major component of overall turf quality) are manifested more rapidly in response to available-N (Waddington et al., 1963). During each year, treatments that induced elevated quality also produced denser turf. Consequently, density ratings were generally lower for CRL, consistently below acceptable standards, and less than BSD and PCU on 8 of 9 rating dates (Table 2-4).

For most sources, the annual N rate of 296 kg ha^{-1} yr^{-1} delivered acceptable turf density, as demonstrated by ratings of at least 6.0. However, at this N-rate, which represents the upper annual N limit suggested by best management practice (BMP) guidelines (FDEP, 2008) and exceeds that of most local municipality ordinance restrictions, uniform high density (i.e. density ≥ 7.5) was not achieved, even with urea. While studying the effects of N-rate on bermudagrass density, Carrow et al. (1987) reported similar results indicating that higher annual N-rates were required to achieve maximum turf density, although as was the case in our study, clippings were collected during mowing and turf was grown on a low organic matter sand soil. Johnson et al. (1987) reported that recycling clippings enhanced shoot density and may contribute up to 100 kg

N ha^{-1} yr^{-1}. Under soil conditions similar to that observed in this study, higher N-inputs may be required to achieve maximum St. Augustinegrass density in South Florida. In locations where legislation prohibits such actions, additional stipulations may be needed to enforce the return of clippings to prevent large scale declines in turf density, a factor that has been shown to increase nutrient run-off (Gross et al., 1990; Linde et al., 1995, 1998; Easton and Petrovic, 2004).

Comparisons of N Sources Applied at 98 kg ha-1 at 120-d Intervals

The CRNS evaluated performed best under this 3 cycle per year regime, where cycles covered the WS and DS with a transitional cycle that straddle both periods. The 120-d application interval corresponded more closely with N-release patterns observed from PCU in previous studies (Fry et. al. 1993; Cisar et. al. 2001). Correspondingly, PCU outperformed other CRNS, generating turf quality and yield comparable to urea throughout the 24-mo study (Tables 2-3, 2-5). At this higher pre-application N rate, delayed N-release was less apparent with PCU, demonstrating equivalent levels of N-uptake to quick-release N in the initial 60-d period. Therefore, as a lawn-care product, PCU (8% coating weight) is more suited to this application rate and frequency, because customer satisfaction depends on noticeable turf responses from applied treatments (Spangenberg et al., 1986).

Polymer-coated urea delivered higher average quality ratings in cycles 2, 4, 6, 10, and 12 (Table 2-3) and demonstrated increased yield and N-uptake in cycles, 2, 4, 6, 8, 10, 12 relative to BSD (Table 2-5, 2-6). It has already been stated that responses from PCU decreased under the cooler, DS conditions. Nitrogen release from microbial dependent N-mineralization may be impacted to a greater degree in response to lower temperatures, since quality, density, yield, and N-uptake differences between sources were more apparent during the DS in both years. Stanford et al. (1977) observed the fraction of N mineralized in relation to temperature and reported an ~ 40 % decrease in the rate of mineralization as average monthly air temperature declined from 27 to 22°C; the mean average air temperatures in the WS and DS, respectively (Appendix A). Carrow et al. (1997) evaluated PCU (41-0-0) and Milorganite on bermudagrass at 98 kg N ha^{-1} under temperatures consistent with DS conditions, found reduced shoot growth for Milorganite 72 and 56% that of PCU in year 1 and 2, respectively. In agreement, we observed very similar results when BSD was compared to PCU (42-0-0), with 70 and 53% less yield in 2007 and 2008, respectively. In essence, the bio-available N from BSD may be released more slowly than the N from PCU. Consequently, turf quality, density, yield, and N-uptake were correspondingly lower for BSD, which is in agreement with Sartain et al. (2004) who demonstrated through incubation studies that PCU releases ~80% of applied N in 112-d versus only ~40% from Milorganite during a 180-d incubation period.

The performance of CRL declined under the higher per-application N, reduced frequency regime. Turf quality only marginally exceeded minimally-acceptable standards (i.e. turf quality ≥ 6.0) during the WS in 2007 and thereafter remained consistently below this level. Comparisons of yield during the WS demonstrated inferior growth from this source. For instance, CRL, BSD, and PCU induced average WS yields of 52, 82, and 93% in 2007 and 20, 74, and 132% during 2008, respectively compared to urea (Table 2-5). Moreover, when N-uptake was average over the WS of both years, CRL was the only source to demonstrate lower values in 2008 than 2007 (Table 2-6). Nitrogen uptake was quantified as a function of clipping yield. Minimal yield response following fertilization at 98 kg N ha^{-1} for CRL which corresponded to ~ 40 kg soluble-N ha^{-1} in 2008 may be explained by substantial reductions in turf density (Table 2-4).

In low density warm-season grass canopies, increased assimilation of photosynthates in response to applied N may be channeled preferential towards lateral growth to increase stand density in preference to appreciable biomass yield production for St. Augustinegrass. Low red light (R) to far-red light (FR) ratios caused by FR reflected on green leaves, provide an environmental cue of the presence of neighboring plants (Ballaré et al., 1987). The extent of the reduction correlates with the proximity of surrounding vegetation (Smith et al., 1990) and reduced tillering in bunch growth type C3 grasses (Casal et al., 1986, 1990). In contrast, under high R to FR ratios, as would occur in low density canopies, signals perceived by the phytochrome may induce tillering and through morphological plasticity enable stolon growth to increase turf density. In support, Frank and Hofman (1994) found that through defoliating grass canopies and increasing the R to FR ratio at the canopy base, increased stand density was achieved.

In 2007, urea plus PCU (UPCU) outperformed CRNS, generating superior turf quality in cycles 1, 3, and 5 relative to PCU and BSD (Table 2-3). However, following an initially-superior quality response from UPCU in 2008, overall quality was more consistent for PCU and BSD and produced combined ratings superior to UPCU in cycles 8 and 10. Clipping yields from UPCU were for the most part undistinguishable from urea and exceeded that of PCU during the 60-d period following fertilization in cycles 1 and 5 (Table 2-5), presumably due to the quick-release portion stimulating more rapid growth. Yield improvements for PCU in 2008 followed a similar pattern to quality with greater yield observed in cycles 7 and 12, where PCU induced yield equal to urea compared to 40% less from UPCU in cycle 12. Our findings suggest that benefits of combining quick and controlled-release sources in 50:50 N proportions (i.e. more rapid initial turf quality responses) are mainly observed during the first 12-mo period. Beyond this time frame, more uniform turf response and greater N-uptake from PCU suggests this source is more effective over a 120-d release interval at 98 kg N ha^{-1} when applied solely in controlled-release formulation. Few studies have monitored the performance of CRNS continuously over extended periods, largely because climatic conditions enforce relatively short growth seasons for warm-season grasses. In this instance, under year-round growth conditions, PCU applied at this N-rate and frequency provided continual improvements in St. Augustinegrass lawn quality and N utilization with continuous use. Our long-term findings are contradictory to numerous studies (Landschoot and Waddington, 1987; Peacock and DiPaola, 1992; Carrow, 1997) whose short-term conclusions indicate PCU sources are more effective when used in conjunction with soluble N. We conclude that under restrictive N legislation, that PCU applied solely as controlled-release fertilizer would be considered more environmental judicious with reduced potential for NO_3-N leaching and improved N-utilization compared to MCNS over the long-term.

Comparisons within N Sources Applied at 147 kg ha^{-1} at 180-d Intervals

The CRNS evaluated differed in their initial and long-term longevity of responses between years. CRL imparted acceptable turf quality for ~120 d and ~43 d, with acceptable turf quality apparent 9 and 20 days after treatments (DAT) for 2007 and 2008, respectively (Fig. 2-1, 2-2). Growth and N-uptake also dropped sharply in the latter year for CRL, with average WS yield relative to urea of 67% in 2007 versus only 15% during 2008. When N-uptake was averaged over both WS periods a 44% reduction was observed (Table 2-5).

In previous studies involving various UF reaction products (Landschoot and Waddingtion, 1987; Carrow 1997), found sources that provided good initial responses were less effective over extended release durations. The 180-d release period far exceeded the 60 to 90-d re-application interval suggested by the manufacturer (Georgia Pacific, 2007), as such, turf density declined appreciable by the end of the each 180-d application period, presumably through insufficient PAN throughout the latter stages of the extended N-release window. These findings highlight the importance of selecting CRNS that closely correspond to the intended use criteria and that St.

Augustinegrass grown on sand soil, low in organic matter, requires continuous inputs of N during summer months in order to sustain adequate turf quality and density.

Conversely, PCU and BSD provided elevated durations of acceptable turf quality in 2008 compared to 2007, although differences in initial and long-term response were observed between sources (Fig. 2-1, 2-2). For instance, BSD produced initial turf quality responses similar to CRL during 2007, although BSD maintained acceptable turf quality far longer (~134 d). Following initial applications, improvements in turf quality were slower from PCU in 2007, ~32-d were required to attain acceptable turf quality following fertilization, although overall response longevity was greater (~152 d) than other CRNS (Fig. 2-1). Yield and N-uptake for PCU averaged over each 60-d cycle reflected this slower initial N-release pattern, with increased N-uptake longevity in the final two cycles of each 180-d period in 2007. (Tables 2-5, 2-6).

For PCU, higher turf quality prior to applications in the WS (2008) was beneficial. This provided a buffer in which to mask latent N-release permitting acceptable turf quality throughout the 180-d interval (Fig. 2-2). In 2008, BSD also delivered acceptable turf quality for the duration of the 180-d release window. When both WS periods were considered, the data indicates that if turf quality is reasonable prior to application, all CRNS evaluated at this N rate were capable of sustaining adequate turf quality for the 120-d restrictive season imposed by certain local legislative bodies. Moreover, both PCU and BSD provided acceptable turf quality for longer durations (i.e > 120-d), particularly in 2008 (Figure 2-2), denoting the potential to reduce application rates to achieve desirable durations of lawn aesthetics.

For BSD, initial responses were largely identical in both years and consistent with urea (Figures 2-1, 2-2), which is in agreement with Sartain (1999) who reported Milorganite is composed of ~20% soluble N and therefore would deliver 29.4 kg ha^{-1} of PAN at this N rate.

Ironically, our findings indicate that in order to obtain noticeable fertilizer responses from St. Augustinegrass, a factor that is important in the lawn-care industry, ~30 kg soluble-N ha^{-1} is required. Although this application rate is currently permitted under state labeling legislation in Florida, certain counties prohibit this per-application rate of soluble N (Board of County Commissioners of Sarasota County, Ordinance No. 2007-63; Board of County Commissioners of Lee County, Ordinance Number 08-08; Board of County Commissioners of Charlotte County, Ordinance Number 2008-028).

Despite lower temperatures, greater improvements in turf quality together with higher average seasonal ratings were observed from BSD during the DS in 2007 and 2008. Quality ratings illustrated more uniform, extended release patterns indicating that N release from BSD (i.e., mineralization) is more tightly coupled to plant demand. In other words, N release from BSD was more biologically driven while PCU was driven by the physical environment. These results suggest BSD applied under this extended regime appears more suited for dry season conditions in South Florida particularly during the initial year of use.

Residual N carry-over from preceding cycles is also possible and may explain extended durations of acceptable turf quality during the WS in 2008. In agriculture, much emphasis is placed on applying biosolids at the agronomic rate to meet crop N requirements. Under Environmental Protection Agency (EPA) guidelines, land managers are directed to adjust application rates in subsequent years of use to account for latent N mineralization from the prior application (United States EPA Document 40 CFR Part 503, 1999). Under field conditions in Florida, He et al. (2000) found that 48% of the total organic N component of biosolids was mineralized in 12-mo and stated that the extent and rate of N mineralization needs to be considered carefully to minimize the risk of NO_3-N leaching. Based on He et al. (2000) and

Sartain et al. (2004) who reported similar mineralization rates, we infer plant available nitrogen (PAN) would increase in response to repeat application of BSD and that measured turf responses should improve correspondingly over time with continual use. Several studies in cool-season turfgrass research with the biosolid Milorganite, have reported these conclusions. Moberg et al. (1970) showed increased yield, color, and N recovery in the second year of evaluations. Waddington et al. (1976) reported total soil-N increased for Milorganite relative to synthetic CRNS, and increased yield resulted from continued use in long-term evaluations. Hummel and Waddington (1981) also showed residual N effects from both synthetic and natural organic fertilizers and hypothesized through continued use, performance of low-recovery N products can be expected to increase. On St. Augustinegrass, BSD compared less favorable to PCU especially under lower pre-application N rates, applied more frequently. Long-term studies, similar to Waddington et al. (1976) and agricultural evaluations by Barbarick et al. (1997) and Barbarick and Ippolito (2007) are required in warm-season turfgrass research to help answer the following questions. How does PAN from BSD change with continuous application? Does N-rate and application frequency influence PAN over time? At what point does cumulative-N increase to the point that exceeds plant uptake and cause detrimental environmental implications?

The Relationship between Controlled-release Nitrogen Rate and St. Augustinegrass Yield

In order to deliver the same total annual N rate, application frequency differed between N rates that preordained two occasions (April 30, 2007 and May 15, 2008) when controlled-release sources were applied in unison at 49, 98, and 147 kg ha^{-1}. N rate x yield interactions were only observed in 2007. Treatment induced differences in turf density prior to fertilizer applications may have influenced interactions in 2008. In the first year, variation in yield can be explained by a linear regression model for each CRNS, with R^2 values of 0.95, 0.98, and 1.00 for BSD, CRL, and PCU, respectively (Fig. 2-3). The data suggests that the maximum yield was not achieved for each CRNS at 147 kg N ha^{-1} and for every 49 kg N ha^{-1} increase in fertilizer N rate you would expect an additional 0.06, 0.04, and 0.02 kg dry weight (DW) ha^{-1} d^{-1} yield increase in St. Augustinegrass under BSD, CRL, and PCU fertilization, respectively.

However, making inferences outside the range of X-values used to find the fitted equations may generate erroneous results. For instance, a maximum yield is expected at a given fertilizer rate in excess of 147 kg N ha^{-1} and above that hypothetical rate, yield is expected to decline. Furthermore, the data only represents the initial 60-d period after fertilization, a factor that was limited due to re-application of sources on the 49 kg N ha^{-1} (60-d frequency). During the relative short period the full extent of N release may not have been realized, because each source was expected to release N for more extended periods and initial response distinctions were noted that undoubtedly influenced the slope, particularly for PCU with slow initial N release characteristics.

Conclusions

This study has shown that acceptable turf quality is possible with high frequency, low application rates of CRNS; however we found that lower frequency, higher application rates of many CRNS produce better quality turf. Thus, limiting application rates reduced optimal controlled-release performance with respect to turf quality, yield, and N-uptake. For instance, at current regulated rates imposed on controlled-release fertilizers in Florida, PCU and BSD provided acceptable quality St. Augustinegrass, albeit after an initial delay in response. The higher per-application rates, which exceeded current regulated rates, over more extended periods, resulted in better turf quality, particularly for PCU at 98 kg N ha^{-1} on a 120-d release interval. Seasonal performance differences were noted, whereby BSD exhibited enhanced responses during the cooler DS at 147 kg N ha^{-1} on the 180-d cycle. Even so, the CRNS evaluated were inadequate in terms of either initial or long term response relative to urea applied at 60-d intervals, although through continuous use, the residual N effect improved initial responses for

PCU and improved longevity for BSD. We found that all CRNS applied at 147 kg N ha^{-1} were capable of delivering acceptable turf quality for the 120-d restrictive season although adequate turf density and quality were required for CRL prior to application. Our findings indicated that controlled-release N in combination with soluble N (i.e. UPCU) offered a viable alternative to frequent applications of urea. The relatively poor performance of several CRNS at high frequency, low rates compared to low frequency, high rates suggest the need for further research to determine the influence of application rate on the fate of applied N from CRNS on St. Augustinegrass.

Table 2-1. Effect of fertilizer treatments on selected soil characteristics averaged over the 24-mo study period.†

TREATMENT	SOIL CHEMICAL CHARACTERISTICS							
	OM	pH	CEC	BRAY1-P§	HCO_3-P¶	K	Mg	Ca
	%		$cmol_c\ kg^{-1}$	---------------- mg kg^{-1}	----------------			
BSD1††	2.2	7.1	5.5	78.8	60.6	92.4	68.5	811.7
PCU1	1.9	7.1	4.5	62.6	45.3	86.1	52.7	694.0
CRL1	1.4	7.2	4.0	67.6	46.4	76.2	46.6	613.8
UPCU1	1.8	7.1	4.7	62.9	45.1	94.6	56.3	698.4
UREA1	2.1	7.1	5.3	63.2	46.0	91.2	63.0	798.9
BSD2	2.1	7.1	5.8	77.9	60.7	96.5	69.8	788.1
PCU2	2.1	7.1	4.8	67.1	50.1	86.4	60.3	712.1
CRL2	1.4	7.2	4.7	67.0	47.8	81.0	58.7	795.8
UPCU2	2.0	7.1	5.4	60.2	44.3	95.9	64.5	805.2
BSD3	2.0	7.1	5.3	80.5	58.5	94.1	67.0	778.2
PCU3	1.9	7.2	4.6	60.1	46.4	88.9	54.1	693.6
CRL3	1.4	7.2	4.7	68.0	45.9	81.3	56.3	798.7
MEAN	1.9	7.1	5.0	68.0	49.8	88.7	59.8	749.0
$LSD_{0.05}$‡	0.4	NS	1.1	4.8	9.9	11.7	12.6	NS
CV%	12.7	0.9	13.0	4.1	11.7	7.8	12.5	15.4

† Average of four sampling instances taken prior to and periodically during study period to a depth of 10 cm.

‡LSD = Soil parameters are significantly different if the difference between column means is greater than Fisher's least significant difference test. NS = Not significant.

§ Bray 1 extractable P (0.03*N* NH_4F + 0.025*N* HCL). ¶ Olsen extractable P (0.5*N* $NaHCO_3$ + 0.025*N* HCL)

†† The numeric demarcation at follows each treatment code indicates N rate and application frequency; 1, 2, and 3 representing 49 kg ha^{-1} (every 60-d), 98 kg ha^{-1}(every 120-d), and 147 kg ha^{-1} (every 180-d), respectively.

Table 2-2. Nitrogen source description and application information.

TRT†	PRODUCT DESCRIPTION	N-P-K ANALYSIS	N APPLIED	APP. ‡ INTERVAL	MANUFACTURER
			kg ha^{-1}	days	
BSD1§	Lawn grade sewage sludge biosolid	6-2-0	49	60	Milorganite, Miliwaukee, WI
PCU1	Polymer-coated urea	42-0-0	49	60	Pursell Inc., Sylacauga, AL
CRL1	12% Urea + 18% methylene urea + triazone	30-0-0	49	60	Georgia-Pacific, Decatur, GA
UPCU1	50:50 N (urea:polymer-coated urea)	44-0-0	49	60	Pursell Inc. & PCS Sales, Inc
Urea	Granular	46-0-0	49	60	PCS Sales, Northbrook, IL
BSD2	Lawn grade sewage sludge biosolid	6-2-0	98	120	Milorganite, Miliwaukee, WI
PCU2	Polymer-coated urea	42-0-0	98	120	Pursell Inc., Sylacauga, AL
CRL2	12% Urea + 18% methylene urea + triazone	30-0-0	98	120	Georgia-Pacific, Decatur, GA
UPCU2	50:50 N (urea:polymer-coated urea)	44-0-0	98	120	Pursell Inc. & PCS Sales, Inc
BS3	Lawn grade sewage sludge biosolid	6-2-0	147	180	Milorganite, Miliwaukee, WI
PCU3	Polymer-coated urea	42-0-0	147	180	Pursell Inc., Sylacauga, AL
CRL3	12% Urea + 18% methylene urea + triazone	30-0-0	147	180	Georgia-Pacific, Decatur, GA

† TRT = Treatment code: CRL = Control release liquid; PCU = Polymer-coated urea; BS = Activated sewage sludge biosolid; UPCU = Urea in equal N combination with polymer-coated urea. ‡ N source release window, sources reapplied following interval (days).
§ The numeric demarcation at follows each treatment code indicates N rate and application frequency; 1, 2, and 3 representing 49 kg ha^{-1} (every 60-d), 98 kg ha^{-1}(every 120-d), and 147 kg ha^{-1} (every 180-d), respectively.

Table 2-3. The influence of N source, application rate, and frequency on average visual quality over 60-d cycles across 2007 and 2008.

TREATMENT†	ST. AUGUSTINEGRASS QUALITY											
	2007						2008					
	WET SEASON			DRY SEASON			WET SEASON			DRY SEASON		
	C1‡	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
	------------------------- RATINGS [1-9 SCALE] -------------------------											
BSD1§	6.0	7.1	7.0	6.7	6.7	6.8	6.8	7.7	6.9	7.1	6.3	7.3
PCU1	5.7	7.5	7.3	6.9	6.8	7.7	.3	7.7	7.2	7.0	6.4	7.7
CRL1	5.4	6.4	5.7	5.7	5.0	5.7	5.6	6.5	5.7	6.0	5.6	6.1
UPCU1	6.8	7.6	7.4	7.3	7.5	7.7	7.5	7.6	7.1	7.9	6.9	7.6
UREA1	6.0	7.8	7.4	7.6	7.8	7.6	7.8	7.5	7.1	7.8	6.7	7.3
BSD2	6.3	6.8	7.4	6.3	6.9	6.5	7.4	7.2	7.5	7.2	6.0	6.6
PCU2	6.2	7.5	7.7	7.1	7.0	7.6	7.7	7.5	7.5	7.9	6.2	7.6
CRL2	6.3	6.6	6.5	5.4	5.7	5.4	5.9	5.6	5.9	5.3	5.2	5.6
UPCU2	6.9	7.4	8.0	6.7	7.6	7.3	8.0	6.9	7.7	7.0	6.4	6.7
BSD3	7.0	7.1	6.0	7.7	7.2	6.3	7.8	7.2	6.4	8.0	7.3	6.9
PCU3	6.5	7.8	6.6	6.7	8.0	7.3	7.9	7.4	6.2	6.6	8.0	7.7
CRL3	6.7	6.8	6.6	6.3	5.0	4.9	6.2	5.5	5.2	6.6	5.3	5.5
CONTRAST¶												
UREA vs. CRNS#	*	***	***	***	***	***	***	**	***	***	NS	**
UREA vs. MIXED††	NS	NS	NS	**	NS	NS	NS	NS	NS	NS	NS	NS
MIXED vs. CRNS	NS	**	***	***	***	***	***	*	***	***	*	*
PCU1 vs. BSD1	NS	NS	NS	NS	NS	**	*	NS	NS	NS	NS	NS
CRL1 vs. BSD1 & PCU1	NS	***	***	***	***	***	***	***	***	***	**	***
UPCU1 vs. PCU1 & BSD1	NS	*	NS	***	NS	*	NS	NS	NS	***	*	NS
PCU2 vs. BS2	NS	**	NS	***	NS	**	NS	NS	NS	**	NS	**
CRL2 vs. BSD2 & PCU2	NS	*	***	***	***	***	***	***	***	***	**	***
UPCU2 vs. PCU2 & BSD2	*	NS	*	NS	*	NS	*	*	NS	*	NS	NS
PCU3 vs. BSD3	NS	**	**	***	*	**	NS	NS	NS	***	*	*
CRL3 vs. BSD3 & PCU3	NS	**	***	***	***	***	***	***	***	***	***	***

NS, *, **, ***, = P>0.05, P<0.05, P<0.01, P<0.001

† Treatment code: CRL = Control release liquid; PCU = Polymer-coated urea; BSD = Activated sewage sludge biosolid; and UPCU = Urea in equal N combination with polymer-coated urea.

‡C = Means of 3 replications, averaged over each 60-d cycle.

§ The numeric demarcation that follows each treatment code indicates N rate and application frequency; 1, 2, and 3 representing 49 kg ha^{-1} (every 60-d), 98 kg ha^{-1}(every 120-d), and 147 kg ha^{-1} (every 180-d), respectively.

¶ Single degree contrasts performed at the alpha level 0.05.

CRNS: Controlled-release N sources (BSD, CRL, and PCU) grouped across all rates and frequencies.

†† MIXED: Mixed component N sources (UPCU) grouped over both rates.

Table 2-4. The influence of N source, application rate, and frequency on visual density evaluated ~ every 3-mo across 2007 and 2008.

TREATMENT†	ST. AUGUSTINEGRASS DENSITY								
	2007				2008				
	WET SEASON		DRY SEASON		WET SEASON		DRY SEASON		
	04/29	07/31	10/30	01/29	05/09	08/08	11/07	02/20	05/15
	------------------------- RATINGS [1-9 SCALE] -------------------------								
BSD1§	4.7‡	7.0	5.0‡	6.7	7.0‡	7.3	6.3‡	5.0	6.5
PCU1	4.8‡	7.5	6.3‡	6.2	8.0‡	7.2	6.5‡	5.2	7.2
CRL1	5.0‡	6.5	4.0‡	4.8	6.0‡	6.5	5.2‡	4.2	4.2
UPCU1	4.8‡	7.5	6.3‡	6.7	7.5‡	7.3	7.3‡	5.7	7.2
UREA1	5.2‡	7.3	6.2‡	8.0	7.2‡	7.3	7.0‡	5.7	6.2
BSD2	4.8‡	6.7	6.0	6.5	6.3‡	6.5	7.0	5.0	5.3
PCU2	4.8‡	7.5	7.5	5.8	7.5‡	7.0	9.0	4.8	7.0
CRL2	4.8‡	6.5	5.0	5.3	5.5‡	5.3	4.8	4.0	3.8
UPCU2	4.8‡	7.2	7.5	7.2	6.8‡	6.5	7.0	5.2	5.7
BSD3	5.2‡	7.0	4.7‡	7.0	6.2‡	6.8	5.7‡	6.0	5.0
PCU3	4.8‡	7.7	5.7‡	7.3	7.2‡	7.0	4.8‡	8.2	6.7
CRL3	5.0‡	6.7	4.2‡	4.7	5.2‡	5.3	4.5‡	4.2	3.2
CV (%)	6.0	3.7	11.0	8.3	9.7	5.6	6.2	11.4	12.2
CONTRAST¶									
UREA vs. CRNS#	NS	NS	*	***	NS	**	NS	NS	NS
UREA vs. MIXED††	NS	NS	NS	**	NS	NS	**	NS	NS
MIXED vs. CRNS	NS	*	***	**	*	*	***	NS	**
PCU1 vs. BSD1	NS	*	*	NS	NS	NS	NS	NS	NS
CRL1 vs. BSD1 & PCU1	NS	***	**	***	**	**	***	*	***
UPCU1 vs. PCU1 & BSD1	NS	*	NS	NS	NS	NS	*	NS	NS
PCU2 vs. BSD2	NS	***	**	NS	*	NS	*	NS	***
CRL2 vs. BSD2 & PCU2	NS	**	***	*	**	***	***	*	***
UPCU2 vs. PCU2 & BSD2	NS	NS	NS	*	NS	NS	NS	NS	NS
PCU3 vs. BSD3	NS	**	NS	NS	NS	NS	NS	***	**
CRL3 vs. BSD3 & PCU3	NS	**	*	***	**	***	**	***	***

NS, *, **, ***, = P>0.05, P<0.05, P<0.01, P<0.001

† Treatment code: CRL = Control release liquid; PCU = Polymer-coated urea; BSD = Activated sewage sludge biosolid; and UPCU = Urea in equal N combination with polymer-coated urea. ‡C = Fertilization events followed visual assessment. § The numeric demarcation that follows each treatment code indicates N rate and application frequency; 1, 2, and 3 representing 49 kg ha^{-1} (every 60-d), 98 kg ha^{-1}(every 120-d), and 147 kg ha^{-1} (every 180-d), respectively. ¶ Single degree contrasts performed at the alpha level 0.05.

CRNS: Controlled-release N sources (BSD, CRL, and PCU) grouped across all rates and frequencies.

†† MIXED: Mixed component N sources (UPCU) grouped over both rates.

Table 2-5. The influence of N source, application rate, and frequency on dry weight yield over each 60-d cycle across 2007 and 2008.

TREATMENT	ST. AUGUSTINEGRASS DRY WEIGHT YIELD											
	2007						2008					
	WET SEASON			DRY SEASON			WET SEASON			DRY SEASON		
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
	---------- kg DW ha^{-1} d^{-1} ----------											
BSD1	2.8	9.2	3.9	0.5	0.4	0.9	8.3	12.2	7.8	0.5	0.3	2.2
PCU1	1.6	4.8	4.4	0.6	0.8	1.6	13.6	15.5	8.6	0.5	0.3	2.6
CRL1	1.4	3.9	1.1	0.2	0.5	0.2	1.1	3.5	3.0	0.3	0.2	0.6
UPCU1	2.1	9.1	6.2	1.0	0.8	1.9	12.6	14.6	9.0	0.6	0.3	2.5
UREA1	3.4	11.9	6.7	1.4	1.0	2.0	11.7	12.1	9.3	0.9	0.3	2.5
BSD2	3.5	5.7	6.3	0.7	0.7	0.5	10.2	6.3	7.7	0.5	0.2	1.1
PCU2	2.9	11.2	6.8	1.2	0.7	1.5	25.7	12.6	7.0	0.9	0.2	2.5
CRL2	2.7	4.9	2.4	0.3	0.3	0.2	1.6	2.1	2.8	0.2	0.2	0.3
UPCU2	5.4	8.8	9.1	1.3	1.4	1.3	16.6	7.3	8.2	0.7	0.3	1.1
BSD3	6.4	9.5	1.7	1.0	0.7	0.6	22.4	10.7	4.3	1.1	0.4	0.8
PCU3	4.8	20.0	4.3	0.4	1.8	2.2	39.4	16.7	5.1	0.5	0.5	2.6
CRL3	4.5	6.2	1.2	0.4	0.2	0.3	1.6	1.9	1.5	0.5	0.2	0.3
CV (%)	19.0	14.4	17.2	18.4	17.9	24.5	16.7	16.8	7.9	15.3	11.3	13.0
CONTRAST¶												
UREA vs. 49 Kg RATE#	*	**	**	***	*	*	NS	NS	**	**	*	*
PCU1 vs. BSD1	NS	NS	NS	NS	*	NS	*	NS	NS	NS	NS	NS
CRL1 vs. BSD1 & PCU1	NS	NS	***	NS	NS	**	***	***	***	NS	NS	***
PCU1 vs. UPCU1	NS	*	NS	*	NS	NS	NS	NS	NS	NS	NS	NS
UREA vs. 98 Kg RATE††	NS	*	NS	**	NS	**	NS	**	***	*	*	***
PCU2 vs. BSD2	NS	**	NS	*	NS	*	***	*	NS	*	NS	***
CRL2 vs. BSD2 & PCU2	NS	*	***	**	*	*	***	***	***	***	NS	***
PCU2 vs. UPCU2	*	NS	NS	NS	*	NS	*	NS	NS	NS	NS	***
UREA vs. 147 Kg RATE	*	NS	***	***	NS	**	NS	NS	***	NS	NS	***
PCU3 vs. BSD3	NS	**	*	**	***	***	**	NS	NS	**	*	***
CRL3 vs. BSD3 & PCU3	NS	***	*	NS	***	**	***	***	***	*	***	***

NS, *, **, ***, = P>0.05, P<0.05, P<0.01, P<0.001

† Treatment code: CRL = Control release liquid; PCU = Polymer-coated urea; BSD = Activated sewage sludge biosolid; and UPCU = Urea in equal N combination with polymer-coated urea. ‡C = Means of 3 replications, averaged over each 60-d cycle. § The numeric demarcation that follows each treatment code indicates N rate and application frequency; 1, 2, and 3 representing 49 kg ha^{-1} (every 60-d), 98 kg ha^{-1}(every 120-d), and 147 kg ha^{-1} (every 180-d), respectively. ¶ Single degree contrasts performed at the alpha level 0.05. # 49 kg RATE: Single degree contrast of urea vs. all sources applied at 49 kg N ha^{-1}. †† 98 kg RATE: Single degree contrast of urea (49 kg N ha^{-1}) vs. all sources applied at 98 kg N ha^{-1}. ‡‡ 147 kg RATE: Single degree contrast of urea (49 kg N ha^{-1}) vs. all sources applied at 147 kg N ha^{-1}.

Table 2-6. The influence of N source, application rate, and frequency on nitrogen uptake over each 60-d cycle across 2007 and 2008.

TREATMENT†	ST. AUGUSTINEGRASS NITROGEN UPTAKE											
	2007						2008					
	WET SEASON			DRY SEASON			WET SEASON			DRY SEASON		
	C1‡	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
	$g\ N\ ha^{-1}\ d^{-1}$											
BSD1	47	204	81	10	9	21	172	269	163	11	5	41
PCU1	25	85	86	14	18	32	265	324	176	12	5	49
CRL1	19	69	17	4	8	4	18	67	52	6	3	10
UPCU1	32	177	117	19	18	40	244	292	193	14	6	47
UREA1	55	249	121	33	20	27	216	256	195	19	6	46
BSD2	59	103	133	12	14	9	206	116	172	10	4	19
PCU2	57	231	145	24	15	33	601	257	151	19	4	47
CRL2	40	81	41	5	6	4	25	33	52	4.1	4	5
UPCU2	103	156	193	24	32	27	337	128	193	16	5	18
BSD3	125	182	26	24	13	10	496	201	71	28	8	14
PCU3	109	497	72	8	42	47	958	356	90	13	12	44
CRL3	76	92	18	8	3	3	27	301	24	10	3	4
CV (%)	19.4	7.3	9.8	20.7	18.7	18.6	9.2	7.0	3.8	12.1	18.1	9.1
CONTRAST¶												
UREA vs. CRNS#	NS	**	**	***	*	***	NS	**	***	**	NS	***
UREA vs. MIXED††	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	*
MIXED vs. CRNS	NS	NS	***	***	***	***	**	*	***	*	NS	***
PCU1 vs. BSD1	NS	*	NS	NS	*	*	*	NS	NS	NS	NS	NS
CRL1 vs. BSD1 & PCU1	NS	NS	***	*	NS	***	***	***	***	**	NS	***
UPCU1 vs. BSD1 & PCU1	NS	*	NS	NS	NS	**	NS	NS	NS	NS	NS	*
PCU2 vs. BSD2	NS	*	NS	*	NS	**	*	*	NS	*	NS	***
CRL2 vs. BSD2 & PCU2	NS	*	***	**	*	***	***	***	***	***	NS	***
UPCU2 vs. PCU2 & BSD2	*	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	*
PCU3 vs. BSD3	NS	**	**	**	**	***	NS	NS	NS	**	NS	***
CRL3 vs. BSD3 & PCU3	*	***	**	NS	***	***	***	***	***	**	***	***

NS, *, **, ***, = $P>0.05$, $P<0.05$, $P<0.01$, $P<0.001$

† Treatment code: CRL = Control release liquid; PCU = Polymer-coated urea; BSD = Activated sewage sludge biosolid; and UPCU = Urea in equal N combination with polymer-coated urea. ‡C = Means of 3 replications, averaged over each 60-d cycle. § The numeric demarcation that follows each treatment code indicates N rate and application frequency; 1, 2, and 3 representing 49 kg ha^{-1} (every 60-d), 98 kg ha^{-1}(every 120-d), and 147 kg ha^{-1} (every 180-d), respectively. ¶ Single degree contrasts performed at the alpha level 0.05. # CRNS: Controlled-release N sources (BSD, CRL, and PCU) grouped across all rates and frequencies. †† MIXED: Mixed component N sources (UPCU) grouped over both rates.

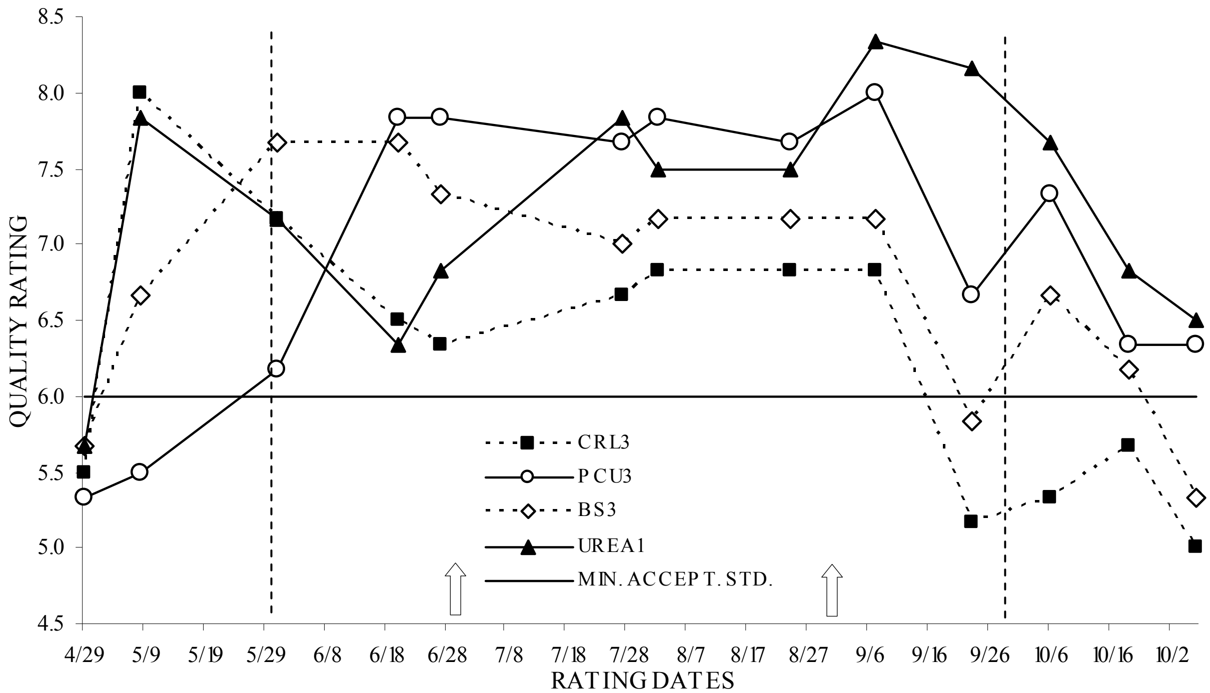

Fig. 2-1. The duration of acceptable St. Augustinegrass quality (i.e ratings ≥ 6) provided by CRNS applied at 147 kg N ha^{-1} prior to the 4-mo rainy season fertilization on April 30, 2007. Vertical dashed lines indicate restrictive season parameters. Urea at high frequency, low per-application N provided a quality benchmark to assess initial and the long term response from CRNS. Arrows indicate urea fertilization events.

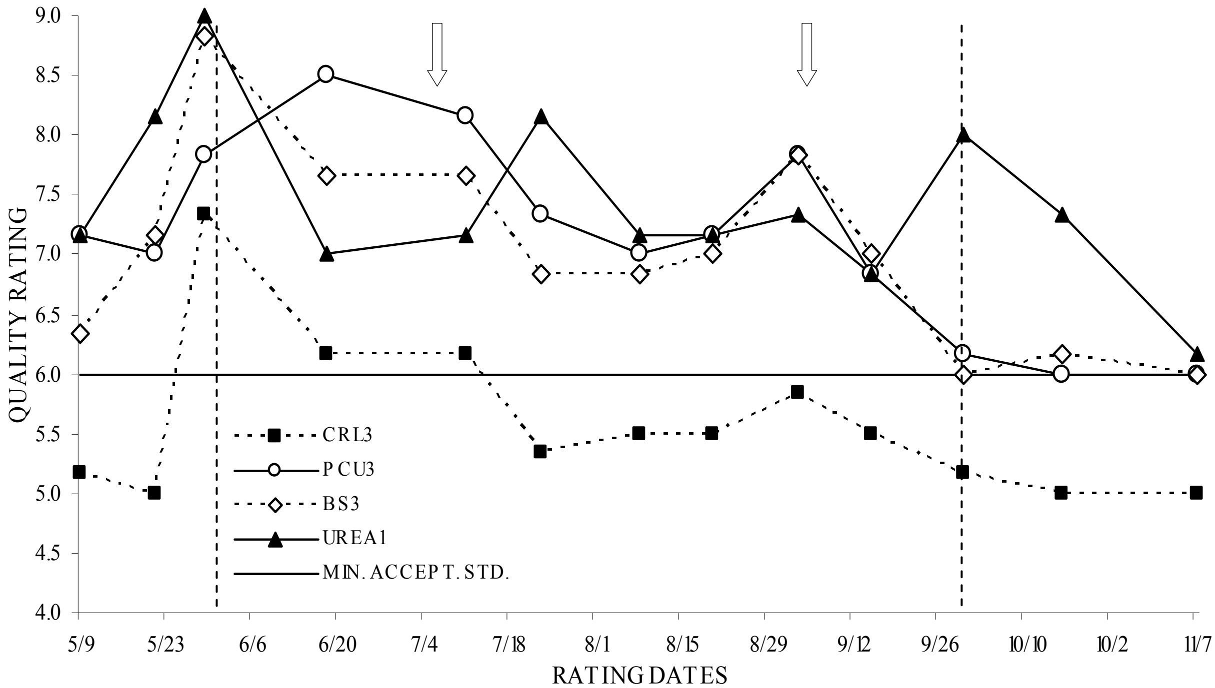

Fig. 2-2. The duration of acceptable St. Augustinegrass quality (i.e ratings ≥ 6) provided by CRNS applied at 147 kg N ha^{-1} prior to the 4-mo rainy season fertilization on May 15, 2008. Vertical dashed lines indicate restrictive season parameters. Urea at high frequency, low per-application N provided a quality benchmark to assess initial and the long term response from CRNS. Arrows indicate urea fertilization events.

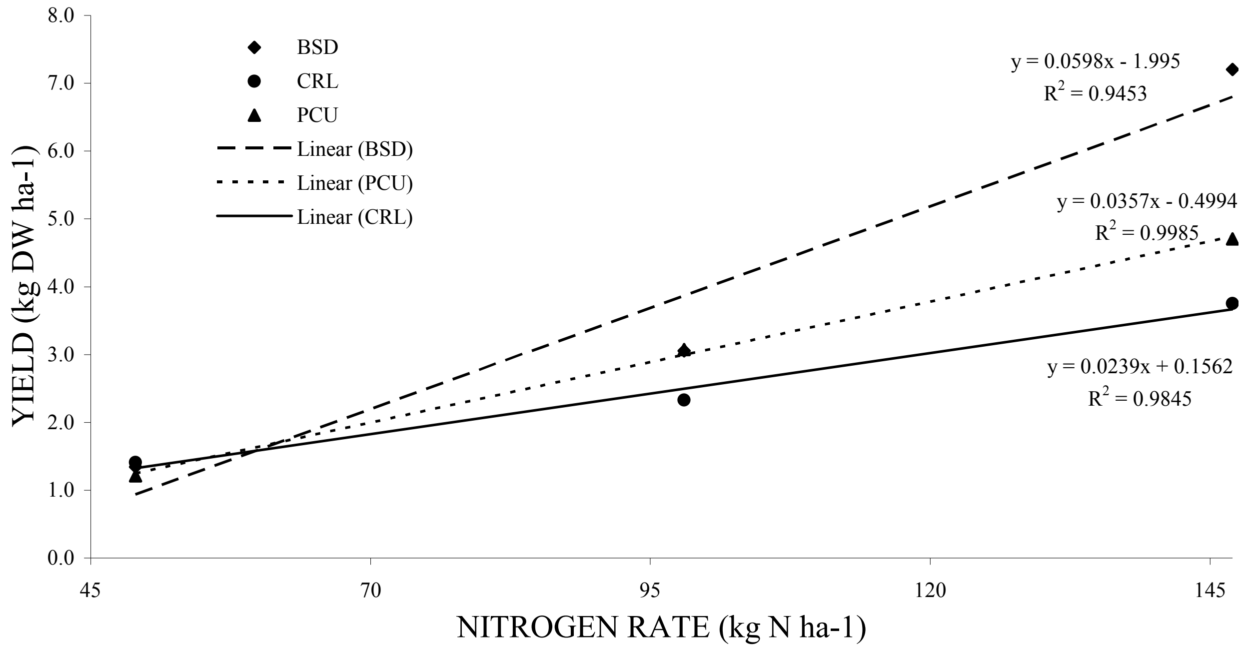

Fig. 2-3. The relationship between CRNS rate (i.e. 49, 98, 147 kg N ha^{-1}) and average St. Augustinegrass yield during the 60-d period following initial fertilization in 2007.

CHAPTER 3
INORGANIC NITROGEN LEACHING FROM ST AUGUSTINEGRASS IN RESPONSE TO NITROGEN FERTILIZATION STRATEGIES UNDER RESIDENTIAL LAWN CONDITIONS

Introduction

Anthropogenic intrusion to the magnitude experienced in Florida in recent years has the potential to drastically alter the nitrogen (N) cycle and more than double the production rate of reactive N (Galloway and Cowling 2002; Galloway et al. 2004). For example, increasing human population densities in various watersheds have been correlated with nitrate (NO_3-N) degradation of groundwater (Vitousek et al., 1997; Peierls et al., 1991), with detrimental consequences to ecological systems (Wolfe and Patz, 2002). Human health may also be impacted due the reliance on groundwater for drinking supplies, must not exceed the Maximum Contaminant Level (MCL) of 10 mg L^{-1} as N set by Environmental Protection Agency (EPA). Residential landscapes have increased dramatically in Florida in unison with urban development to support population expansion (Haydu and Cisar, 1990). St. Augustinegrass [*Stenotaphrum secundatum* (Walt.) Kuntze] is the predominant vegetation in Florida residential landscapes (Erickson et al., 2005) with an estimated land use of 810,000 ha (Trenholm and Unruh, 2007). Routine fertilization practices of residential turfgrass have been implicated as a major source of NO_3-N contamination of groundwater in these locations (Flipse et al., 1984). Urban fertilizer usage has increased in tandem with residential landscape expansion in Florida (Erickson et al., 2005) and detailed evaluations of N fertilization strategies on St. Augustinegrass are needed, particularly in South Florida where the most populated areas are located throughout coastal regions where fine sand soils are subjected to frequent and intense seasonal precipitation (McCollum et al, 1978; McCollum and Cruz, 1981; Pendleton et al. 1984; Hurt et al., 1995).

Environmental precursors in southern Florida are highly conducive of rapid N leaching (i.e. coarse textured soil with high soil-water percolation) under conditions of excessive N fertilization coupled with abundant precipitation or irrigation (Reike and Ellis, 1974; Snyder et al., 1984; Morton et al., 1988; Barton et al., 2006). In efforts to address concerns over N loss from residential landscape N fertilization and to more effectively manage urban coastal watersheds influenced by non-point source pollutants, state-wide fertilizer labeling legislation was introduced. Directed specifically at residential and urban landscapes, this legislation limits per-application N rates to 49 kg ha^{-1} and restricts the water-soluble N portion to 34 kg N ha^{-1} (Department of Agricultural and Consumer services, No. 4640400, Rule 5E-1.003, 2007).

In addition, certain coastal counties and municipalities imposed further prohibitive measures by restricting N fertilization during the traditional rainy season in Florida from June 1 through September 30; constrains annual fertilizer N to 196 kg ha^{-1}, and controls the soluble-N fraction to 24.5 kg N ha^{-1} per-application (Council of the City of Sannibel, Water Resources Department, Ordinance No. 07-003; Board of County Commissioners of Sarasota County, Ordinance No. 2007-63; Board of County Commissioners of Lee County, Ordinance No. 08-08).

The scientific literature suggests that minimal N leaching or run-off occurs from judicious fertilization of established turfgrass with quick-release N-sources (Easton and Petrovic, 2004; Gross et al., 1990, 1991; Linde et al., 1995, 1998; Miltner et al., 1996; Mosdell and Schmidt, 1985; Petrovic et al., 1986; Starr and Deroo, 1981; Snyder et al., 1981, 1984), although appreciable N leaching has been observed when excess N fertilization on coarse textured soils is coupled with high irrigation or precipitation (Barton et al., 2006; Nelson et al., 1980; Reike and Ellis, 1974; Snyder et al., 1984). Several studies have indicated that NO_3-N leaching is significantly reduced under controlled- versus quick-release N fertilization strategies (Brown et al., 1977; Nelson et al., 1980; Snyder et al. 1981, 1984; Petrovic et al., 1986; Geron et al., 1993; Engelsjord and Singh, 1997; Guillard and Kopp, 2004). Of these, only Petrovic et al. (1986), Geron et al. (1993), and Guillard and Kopp, (2004) conducted their studies to address residential lawn fertilization under the cool-season grass conditions. In fact, no prior study to date has examined the influence of quick- and controlled-release N-sources on N leaching from a conventional St. Augustinegrass lawn environment.

Imposing stringent N application rate restrictions unilaterally across all N-sources may negate the best features of controlled-release nitrogen sources (CRNS). They are more effective when applied at infrequent higher per-application rates (Skogley and King, 1968; Hummel and Waddington, 1984; Williams et al., 1997), which decreases water use in St. Augustinegrass (Subhrajit and Trenholm, 2005), and reduced N-species leaching (Brown et al., 1977; Nelson et al., 1980; Snyder et al. 1981, 1984; Petrovic et al., 1986; Engelsjord and Singh, 1997; Guillard and Kopp, 2004). Current legislation prohibits higher per-application rates of CRNS prior to the 120-d restrictive seasons, although these sources may provide sustained growth and vigor due to extended N-release patterns. There is considerable interest in determining whether higher pre-application rates of CRNS fertilizers induce appreciable N leaching under St. Augustinegrass lawn conditions. Consequently, research to investigate N-leaching under varying N sources, application rates, and frequencies on St. Augustinegrass is of primary importance to better understand the efficacy of N rate regulation and provide legislative bodies with valuable information so that future enactments advocate sound agronomic and environmental principles.

Research Objectives

Numerous studies that evaluated N-leaching under cool-season residential turfgrass conditions have reported that environmental impacts of N fertilization are reduced when CRNS strategies are compared to quick-release soluble N approaches. However, to date no published studies are available under St. Augustinegrass lawn conditions. Therefore, the objectives of this experiment were as follows.

- **Objective 1:** to determine if controlled-release N sources can be applied at higher rates than currently permitted prior to restrictive seasons without negatively contributing to groundwater N degradation.
- **Objective 2:** to evaluate whether N leaching losses are escalated when the soluble portion of applied N is increased from currently mandated levels of 24.5 kg N ha^{-1} to 49 kg N ha^{-1}.
- **Objective 3:** to ascertain if variable N management approaches result in differences in N species leached.
- **Objective 4:** to establish if total N recovery was influenced by N management regime, using a N budget approach.

Materials and Methods

The experimental design, treatments, and statistical analysis were described in the materials and methods section in chapter two (p 20), this section will focus on methodology pertaining to inorganic N leaching determinations. For a statistical standpoint, the only distinction between chapters was the occurrence of outliers. On two occasions, for urea and CRL 3 outliers were identified as datum that exceeded three standard deviations from the mean and were subsequently removed from analysis.

Unfortunately, an appreciable amount of water samples were inadvertently discarded while awaiting analysis at FLREC. This constituted samples from November 7, 2007 to January 6, 2008, and in terms of application cycles corresponded to the beginning of the dry season (DS) sampling period when 49 and 147 kg N ha^{-1} treatments were initially applied in cycle 4 and 2, respectively. Furthermore, this impacted half of the third cycle for 98 kg N ha^{-1} treatments. As such, leaching data for these full cycles are not presented.

Construction Specifications of the Field-Based N Leaching Facility

A pre-existing elevated facility to permit gravity-fed water percolate collection was used for this experiment and since this facility has not been previously described a detailed account of construction specifications are provided. In November 2004, ~ 400 m^3 cubic meters of native soil was extracted allowing the installation of underlying hard fractured limestone fill base for structural support. The foundation was laser-graded to provide a uniform base on which to construct an artificial soil profile throughout the 27.5 x 14 m site that corresponded to the constructed profile in each lysimeter; designed to facilitate quantifiable water percolation with minimal risk of flow restriction due to sand migration.

Each lysimeter was constructed from a high density polyethylene drum that was 86 cm long, an interior of 55 cm, a 1.3 cm thick wall, (US Plastic Corp., Lima, OH) and the flat bottom was removed. When installed the lysimeter was inverted so that the manufactured threaded aperture (to allow attachment of a liquid extraction device) was situated at the base. Polyvinyl chloride (PVC) drainage pipes (schedule 40, 1.9 cm diameter) were individually installed into the foundation with sufficient gradient to permit gravity-fed flow to the percolate collection sites located at the periphery of the facility. Drainage PVC pipe was connected to each lysimeter with a screw in PVC fitting, attached to a 90^o elbow.

A stainless steel screen (1 mm mesh) was inserted into each lysimeter drainage outlet to retain the gravel (>14 mm 1%, 12-14 mm 7.5%, 9-12 mm 10.5%, 6.73-9 mm 28%, 6-6.73 mm 41%, 4-6 mm 7%, 2-4 mm 3.5%, <2mm 1.5%), which was back-filled to a depth of 10 cm. Medium sand (>2 mm 0.1%, 1-2 mm, 7.6%, 0.5-1.0 mm 26%, 0.25-0.5 mm 45.6%, 0.15-0.25 mm 19.1%, 0.053-0.15 1.2%, <0.053 0.6%) was uniformly positioned to a depth of 5 cm between the gravel layer and the finer root zone sand to act as a “choker layer” to prevent particle migration. Mason sand (very coarse 0.2%, coarse 5.4 %, medium 29.9%, fine sand

62.9%, very fine sand 1.5%, and silt and clay 0.1%) that closely matched the particle size distribution of the Margate and Hallandale fine sand soil series (Siliceous, hyperthermic Lythic Psammaquent) found in this coastal plain region was back-filled, and uniformly compacted at ~15 cm depth increments.

The soil profile at the experimental site was constructed to conform exactly to lysimeter specifications before an additional 5 cm of mason sand was installed above the upper rim of each lysimeter to provide a final mason sand depth of 76 cm. The elevated rectangular platform was re-leveled and the sloping sides were gently graded to facilitate grass mowing maintenance. Sampling stations with sufficient capacity to contain three 20 L percolate collection containers were excavated and supported with timber framing. An automatic irrigation system was configured to provide watering flexibility with individual irrigation zones covering 4 x 4 m unit areas (i.e. 2 treatment plots per irrigation zone). Each zone was fitted with landscape 1800 series pop-up sprinklers with 12 Series VAN, 15° Trajectory, 90^{o} arc nozzles (Rain Bird Corp. Azusa, Ca) at each corner.

In November 2006, 6-mo prior to the initiation of our experiment, the existing sod was removed and mason sand matching the original specifications was used to re-construct the initial soil profile specification, before St Augustinegrass cv. ‘Floratam’ sod, harvested from sand grown soil was installed. Establishment fertilization included 49 kg P ha^{-1} from triple super phosphate and 49 kg K ha^{-1} from muriate of potash on January 12 and April 20, 2007. No N fertilizer was applied until treatment initiation on April 30, 2007.

Percolate Sampling and Field Quality Assurance

Percolate drainage samples were collected ~every 7-d or following precipitation events exceeding 0.64 cm in accordance with Florida Department of Environmental Protection (FDEP) quality assurance/quality control (QA/QC) protocol that stipulate appropriate collection of blanks, duplicates and standards during field sampling. Sampling occurred more frequently for the 21-d periods following N fertilization when precipitation of ≥ 0.25 cm prompted sampling. Percolate water volume was recorded on each occasion. Sub-samples were collected in polyethylene scintillation vials, stored on ice at $4^{o}C$ during the sampling procedure, and stored in a frozen matrix until analysis. The N concentration of irrigation water was determined at each sampling event and precipitation N was periodically assessed throughout the study period.

Percolate Water Sample Analysis and Laboratory Quality Assurance

Leachate samples were analyzed at FLREC for NO_3-N and NH_4-N using colorimetric methods G-200-97 Rev.3 and G-171-96 Rev. 8, respectively (Seal Analytical, Norderstedt, Germany). Leachate data were subjected to strict QA/QC protocols. Colorimetric NO_3-N and NH_4-N calibration curves achieved $r^2 \geq 0.9995$, while blanks, spikes, duplicates, and certified standards were ± 5% of expected values. In order to achieve consistent spike recoveries, the minimal detection limit (MDL) was increased to 0.05 mg l^{-1} and 0.03mg l^{-1} for NO_3-N and NH_4-N, respectively and sample concentrations determined below these levels were reported as MDL values, therefore, N leaching data are considered to be worst case scenario.

The dual channel instrument permitted simultaneous analysis of NO_3-N and NH_4-N, however, the significant amount of time saved came at the expense of accurately determining NO_3-N. The G-200-97 method relies on the reduction of NO_3-N to nitrite (NO_2-N) for colorimetric detection. Since NO_2-N concentrations should be established under a system devoid of cadmium reduction capacity and would be subtracted from NO_3-N to accurately depict the concentration of NO_3-N, this study reported inorganic-N leaching as NO_x-N and NH_4-N.

Mean cycle flow-weighted NO_x-N concentrations data, calculated as the total NO_x-N leached divided by total percolate volume were presented by fertilization cycle. To demonstrate the influence hydrological factors may contribute to increased instances of groundwater pollution through excessive N leaching, individual NO_x-N leaching events were plotted with precipitation data (summed over each sampling period) during periods when peak NOx-N concentrations were observed. Mean N loading data, calculated as the inorganic-N concentration divided by the surface area of the lysimeter, were summed over each fertilization cycle to convey the potential for fertilizer N strategies' to contribute to specific water body impairment. In coastal watersheds, where residential land-use has been estimated, this information may prove particularly pertinent since ground water delivers the majority of non-point source, land derived-N pollutants to estuaries and coastal ecosystem where N is often the limiting nutrient for growth (King and Balogh, 2008). In addition, the inorganic N inputs were summarized in budget format and aligned with N recovered in leachates and St. Augustinegrass tissue over each fertilization cycle to illustrate the efficacy of fertilizer N-strategies and to divulge potential N losses or sinks not measured in this study.

Results and Discussion

Flow-Weighted NO_x-N Concentrations Influenced by N Source and Hydrology

During this study, N source influenced mean cycle flow-weighted NO_x-N concentrations with highest concentrations occurring under urea fertilization, applied solely or in combination with polymer-coated urea (PCU) (i.e. urea plus PCU at 98 kg N ha^{-1} [UPCU2]) at soluble N rates of 49 kg ha^{-1} during the wet season (WS), 2007. When averaged per fertilization cycle maximum NO_x-N concentrations for urea were 6.4 and 3.1 mg L^{-1} in cycle 1 and 2, respectively (Table 3-1). For UPCU2, greatest concentrations occurred during the same period with NO_x-N concentrations of 10.5 mg L^{-1} (Table 3-2). In subsequent cycles, NO_x-N concentrations from soluble-N sources were greatly reduced and despite a similar trend, whereby elevated concentrations from urea and UPCU2 occurred during the initial 60-d period following fertilization during the WS of 2008, no differences between soluble-N and CRNS were observed.

In 2007, NO_x-N leaching was closely coupled with hydrological factors. Two intense precipitation events occurred shortly after fertilizations and appeared to coincide with peak NO_x-N concentrations. The first produced 60 mm and resulted in high initial NO_x-N concentrations from urea (82.4 mg L^{-1}) and UPCU2 (237.0 mg L^{-1}), 17 days after fertilization (DAF) (Fig. 3-1). The second 85 mm precipitation event occurred 6 DAF of 49 kg N ha^{-1} sources, produced no additional losses from UPCU2, but induced further NO_x-N concentrations of 28.6 mg L^{-1} from the urea treatment (constituting a 3-fold reduction in leachate NO_x-N concentrations compare to cycle 1). The lower NO_x-N concentrations from urea under greater precipitation-induced leaching conditions may indicate increased capacity for St. Augustinegrass to capture and utilize applied N as the summer progressed. On the other hand, it may indicate that insufficient time had elapsed for complete transformation of urea to NH_4-N, through enzymatic urease induced hydrolysis (Conrad, 1942) and subsequent nitrification of NH_4-N to NO_3-N (Harper and Boatman, 1926).

Sarigumba and Fiskell (1976) conducted urea transformation studies under sandy soil conditions in Florida and reported the majority of urea hydrolysis occurred within 3-d under Blichton fine sand soil conditions, whereas Eriksen and Kjeldby (1987) reported that 85% urea hydrolysis rate after 4-d. Sabey et al. (1956) illustrated through temperature based incubation studies that nitrification increases linearly with temperature and that the bulk of ammonium sulfate was nitrified within 7-d at soil temperatures of 25^{o}C (lower soil temperatures than observed in our study, Appendix A). Sartain et al. (2004) reported the presence of NO_3-N in leachate from incubated isobutylidene diurea (IBDU) after 7-d; a source that depends on an additional stage of water hydrolysis for urea release.

Noticeably higher NO_x-N levels were collected in the leachate, 28.6 mg NO_x L^{-1} compared to 7.8 mg NH_4 L^{-1} (data not included) over this 6-d period in 2007 and the cation exchange capacity (CEC) of the soils was low (~3.2 $cmol_c$ kg^{-1}). Therefore, we conclude that appreciable nitrification had occurred and that St. Augustinegrass was better able to recover applied N, even though climatic conditions were more conducive of rapid N-leaching following the second 49 kg N ha^{-1} urea application. These findings, together with leachate data from successive cycles demonstrating negligible losses of NO_x-N despite substantial precipitation events in close proximity to fertilization (Tables 3-1, 3-2), suggests the capture and utilization of applied N increases towards the latter stages of the summer growing season.

Considering that the St. Augustinegrass stand was established 180-d prior to treatment initiation during the dry season (DS), in which lower temperatures and photoperiods were less conducive of growth, together with no N inputs during the establishment period, we believe the root system had not fully developed during the initial stages of the experiment. DiPaola et al. (1982) described distinct seasonal rooting patterns for St. Augustinegrass, noting that aggressive root initiation and growth during summer months was greatly reduced under cooler winter soil temperatures. Enhanced root growth is associated with increased plant available nitrogen (PAN), namely in the form of root length. Although the root to shoot dry weight ratio declines with elevated N supply, the more highly branched, finer root structure increases surface area and nutrient acquisition (Marschner, 2002). Bowman et al (1998) reported that greater N accumulation and lower N leaching resulted from deeper rooted creeping bentgrass genotypes. In greenhouse studies, Bowman et al. (2002) demonstrated that compared to six warm-season grass varieties, St. Augustinegrass possesses inherently greater root length density (RLD) and theorized that this morphological characteristic resulted in lower NO_3-N leaching. In essence, under N deprived conditions during establishment, RLD progressively increased for St. Augustinegrass under adequate PAN during summer months. The pulse of NO_x-N remained in contact with the deeper root system for longer durations and resulted in reduced NO_x-N leaching as the WS progressed.

Consequently, given the relationship between N fertility and root growth it appears plausible that restrictive fertilizer ordinances (June - October), may negatively impact root development during WS months, when optimal root growth has been observed for St. Augustinegrass systems. For example, during early summer 2007, when the root system of St. Augustinegrass may not have fully developed, we observed NO_x-N in concentrations in excess of MCL standards (~13 mg L^{-1}) in leachates following a UPCU1 application (i.e. 24.5 kg soluble N ha^{-1}), which corresponds to currently mandated N fertility guidelines for residential lawns (Fig. 3-3). It appears that N losses that exceed MCL standards are possible, even under stringent soluble N level control, if significant precipitation events are encountered shortly after fertilization. Ironically, the unintended consequences of fertilizer legislation may result in greater NO_3-N leaching, once fertilization resumes, if RLD is adversely affected by 120-d periods when N inputs are constrained. More research is required to better understand the physiological and morphological changes that occur in St. Augustinegrass in response to intervals of severe N limitation in order to better understand the efficacy of restrictive season legislation.

Our findings indicating NO_x-N losses in excess of MCL standards are possible with soluble N fertilization in conjunction with intense precipitation. However, these losses tend to decline over time, possibly indicating that N uptake efficiency improves concomitantly with successive fertilization. Conversely, judicious use of CRNS prior to restrictive seasons presented no such risk, which is consistent with numerous other studies (Petrovic et al. 1986, Geron et al. 1993;

Guillard and Kopp, 2004), and would provide N for extended durations (Carrow, 1997; Hummel, 1989; Landschoot and Waddington, 1987; Moberg et al., 1970; Peacock and DiPaola, 1992; Volk and Horn 1975), to supplement root growth.

Under CRNS fertilization, minimal NO_x-N was leached and average cycle flow-weighted NO_x-N losses were for the most part were ≤ 1.0 mg L^{-1} per cycle (Tables 3-1, 3-2, 3-3). Leachate NO_x-N concentrations in excess of MCL were not observed from biosolid (BSD) or PCU applied at 147 kg N ha^{-1} throughout the 24-mo study period and were largely restricted to MDL values (Fig. 3-4, 3-5). These findings are consistent with numerous studies whose conclusions were drawn from diverse locations and grass varieties. Barton et al. (2006) investigated the influence of N source fertilization and irrigation during a 22-mo turfgrass production study with four warm-season grass varieties, reporting NO_3-N concentration in percolate from polymer-coated N or biosolid treatments never exceeded MCL standards, even when applied at 400 kg N ha^{-1} under high irrigation (i.e. 140% evapo-transpiration). Brown et al., (1977) under similar study parameters, showed that FWNC of < 3 mg l^{-1} resulted from what was considered high N rates (146-244 kg ha^{-1}) of Milorganite on bermudagrass turf grown on sandy soil under high irrigation regimes. Guillard and Kopp (2004) demonstrated that a mixed species cool-season lawn turf fertilized with either polymer-coated sulfur-coated urea (PCSCU) or an organic N source at 147 kg N ha^{-1} yr^{-1} produced no NO_3-N leaching above MCL standards throughout a 36-mo residential lawn leaching study. Petrovic et. al. (1986) reported similar conclusions with anion exchange resin NO_3-N detection techniques employed to a 30 cm depth under a Kentucky bluegrass lawn environment fertilized with PCU and Milorganite treatments at 98 kg N ha^{-1}.

Several studies have documented higher levels of NO_3-N leaching from certain CRNS, which include sulfur-coated urea (SCU), IBDU, and methylene urea (Petrovic et al., 1986; Snyder et al.

1981, 1984). In the present study, there was a tendency for controlled-release liquid (CRL) treatments to leach higher concentrations of NO_x-N compared to BSD or PCU, particularly at 147 kg N ha^{-1} (Table 3-3). Over each 30-d period after fertilization with the highest N rate of CRL (147 kg ha^{-1}), peak NO_x-N concentrations of 25.2, 63.5, and 32.4 mg NO_x-N L^{-1} were detected in leachates shortly after fertilization during cycle 1, 3, and 4, respectively (Fig. 3-4, 3-5). According to manufacturer labeling, this N rate should deliver ~59 kg soluble N ha^{-1} per-application and subsequently NO_x-N leaching was consistent with initial losses recorded from urea N at 49 kg ha^{-1}. However, the potential for urea to leach applied N, diminished under repeat fertilization. In contrast, 2.5-fold increases in NO_x-N were observed from CRL in the subsequent cycle (Fig. 3-4, 3-5). This result could be explained by progressively lower turf density in CRL plots due to insufficient N release over the latter stages of each application interval (Tables 2-4).

The relationship between turf density and the potential to leach NO_3-N has not been well studied on established grass stands. Research is required to address this concern, particularly in Florida where residential lawns may experience a decline in turfgrass density due to inadequate PAN during the peak growing season under fertilization restrictions, a factor that may exacerbate NO_3-N leaching through reduced N uptake under higher soil infiltration rates (Petrovic, 1990). Current data indicates a close correlation between increasing turf coverage and reduced NO_3-N leaching (Easton and Petrovic, 2008; Rosenthal and Hipp, 1993; Snyder and Cisar, 2000), however these studies have focused on turf establishment situations where low plant densities are cognately associated with immaturely rooted turf. Conversely, increased potential for NO_3-N run-off losses due to low plant density has received attention and several studies have noted that run-off losses decline as turf density increases. These authors attributed lower nutrient run-off in dense turf due to the reduction in velocity as water travels a more tortuous path through densely populated turf stands, thus resulting in higher infiltration rates (Linde et al., 1995; Gross et al., 1990, 1991; Easton and Petrovic, 2004). However these studies were conducted largely on fine texture soils, with low infiltration rates, which is less of a concern in Florida due to the predominately sandy soil in populated coastal water-sheds. Erickson et al. (2001) showed that minimal inorganic N run-off was possible from a well fertilized, dense St. Augustinegrass turf on a 10% slope due to intense precipitation. Therefore, research focusing specifically on the relationship between St. Augustinegrass density and how this impacts NO_3-N run-off and leaching may be of importance in Florida.

As shown, significant scientific data obtained over many years document that certain CRNS at higher-application rates offer negligible contributions to ground-water degradation. Our findings on a field-based St. Augustinegrass lawn system in Florida are consistent with previous studies and clearly demonstrate that both PCU and BSD can be applied at the N rates employed in this study (i.e. up to 147 kg ha^{-1}) without significant risk from N species pollution of important ecological water resources or drinking water supplies in Florida. Therefore we encourage local and state legislative bodies to consider revising their policies to permit higher-application N rates of BSD and PCU to allow judicious fertilization throughout the restrictive season to curve potentially negative impacts of St. Augustinegrass managed under insufficient PAN. (i.e. reduced turf density and RLD).

Nitrogen Leaching Influenced by N Source

Nitrogen loads were influenced by N sources at each application rate, although N rate brackets (i.e. 49 and 98 kg N ha^{-1}) that utilized quick-release N, initially offered the highest total N loads of this study. During cycle 1, urea at 49 kg N ha^{-1} leached 6.5 % of applied N and UPCU2 at 98 kg N ha^{-1}, 12 % of applied N (Tables 3-4, 3-15). For urea, an additional 7% of applied N was leached in cycle 2 (Table 3-5), but thereafter maximum N losses were 2.3%

(Table 3-9) with the majority of cycle means showing N losses < 1% of applied N (Tables 3-6 - 3-8, 3-11 - 3-13).

Nitrogen leaching from sources applied at N rates of 98 kg ha^{-1} were analogous to that observed under lower N strategies, whereby initial high N loading from UPCU2, were followed by losses ≤ 1.3% of applied N, although during the WS in 2008 losses of 3.6% of applied N were noted (Table 3-17). As mentioned above, N leached from BSD and PCU at the elevated N rate over extended re-application intervals produced the lowest N leaching with average values of 0.9% of applied N leached over the study period. To put this into context, total N losses from BSD and PCU at 147 kg N ha^{-1} were lower than the N inputs from the city irrigation water supply (Tables 3-20 – 3-22). Increased incidences of NO_x-N in CRL leachates that were in excess of MCL standards were reported, which resulted in higher N leaching values as the study progressed. However, steady increases of 3.3, 4.0, and 4.2 kg ha^{-1} of total N leached represented only 2.2, 2.7, and 2.9 % of applied N leached in cycle 1, 3, and 4 respectively.

Relative Recovery of Inorganic Nitrogen in Percolate and Clipping

Evidently, low levels of N leaching resulted from fertilizer N strategies employed in this study. However, equally low levels of relative N recovery were also apparent, particularly during the cooler DS. For example, when averaged across each cycle, maximum relative N recovery from PCU3 and PCU2 were 56.4, and 51.7% of N inputs during the WS of 2008, respectively and only 3.6 and 3.9% of N was recovered during the DS from these sources. This clearly represents a large proportion of N unaccounted for. In his review, Petrovic (1990) reported that five major categories of the N cycle explain the fate of N applied to turfgrass: plant uptake, atmospheric loss, soil storage, leaching, and run-off.

Plant uptake was quantified in the form of N recovered in clippings, however, temperature and season have been shown to influence N recovered in clippings and may explain considerably lower relative N recovery under DS conditions. Many studies indicate that the majority of N applied to turf is recovered in clippings (Hummel and Waddington, 1981; Starr and Deroo, 1981), but most studies were conducted under near optimum conditions for plant growth. South Florida is unique in that respect since growth persists year round for warm-season grass albeit with significant reductions during the DS. Few studies have focused on N recovery from turf under sub-optimal temperatures. Mosdell and Schmidt (1985) examined N recoveries under temperatures deemed below optimum from Kentucky bluegrass under growth chamber conditions. They reported N recovery was 39% lower than comparative recoveries under favorable temperatures for growth. Other studies that have examined N leaching and visually turf responses in temperate climate reported insufficient growth to quantify tissue N concentrations from October to April (Mangiafico and Guillard, 2006; Weyner and Haley, 1993). In addition, since visual symptoms of fertilizer response were observed during these below optimum periods, N uptake may have been allocated to other plant parts (roots, crowns, stems, and stolons). Petrovic (1990) reported that 31 and 20 % of applied N could be apportioned in crowns and roots, respectively. Hummel and Waddington (1984) could only account for 1.5% of applied N in roots of Kentucky bluegrass. While, Varshovi (1995) observed that N recovery in roots and stolons of bermudagrass varied between 5 and 11% of applied N depending on N source.

Potential Nitrogen Losses other than Leaching or Plant Uptake

In this study, the portion of N in unmown parts of the plant may have been small and N run-off may be of little consequence due to the topography and soil texture. Thus atmospheric loss and/or soil storage may have been the major sinks for applied N. Atmospheric loss of applied fertilizer N can occur either through ammonia (NH_3) volatilization or as denitrification (Petrovic, 1990). Ammonia volatilization from surface applied NH_4-based fertilizers is influenced by soil pH, soil moisture, temperature, relative humidity (RH), fertilizer source, cation exchange capacity (CEC), and depth of incorporation (Nelson, 1982). Reports of the magnitude of NH_3 losses from surface applied urea on turf are inconsistent and range from 10% (Torello et al., 1983) to 68% of applied N (Fenn and Kissel, 1974). The majority of fertilizers in this experiment (9 of 12) were urea based, volatile N loss may have been substantial given that environmental factors (i.e. high temperature and RH) were particularly favorable for volatilization during the WS. Irrigation was supplied post-application in efforts to limit NH_3 losses, but the rate (0.6 cm) may have been insufficient. Titko et al. (1987) and Bouwmeester et al. (1985) reported that irrigation rates of 2.5 and 2.4 cm respectively were required to eliminate potential volatile losses from surface applied urea.

Soil conditions were also conducive of volatile N loss (Table 2-1). Torello et al. (1983) reported NH_3 loss under acidic soil conditions (pH 6.4) was negligible. Conversely, under alkaline soils NH_3 losses can be severe. Research shows that appreciable NH_3 is formed at a soil pH > 7.5 (Vlek and Craswell, 1981; Titko et al., 1987). Even with mildly alkaline soil pH (7.1) in this study, palpable NH_3 volatilization may have occurred (Table 2-1), since sharp increases in soil pH due to urea hydrolysis are expected for short intervals following urea application (Kissel et al., 2008).

Guertal et al. (2007) reported that N source influenced NH_3 volatilization on warm-season grass. The extent of gaseous N flux from their treatments were urea > methylene urea > sewage sludge > PCU. These findings may explain our highest N recovery with PCU (98 and 147 kg N ha^{-1}); however, it fails to account for lower N recovery from CRL (12% Urea; 18% methylene urea and triazone) relative to urea at 49 kg ha^{-1}. Clapp and Parham (1991) also found lower NH_3 losses from a methlyene urea and triazone fertilizer compared to urea, although, application method and soil factors may have influenced gaseous losses in our experiment.

Firstly, in the present study CRL was the only source to be applied in liquid form and researchers have shown greater NH_3 losses from dissolved versus granularly applied urea (Torello, 1983; Titko, 1987). Secondly, increased organic matter (OM) reduces NH_3 loss through the contribution of OM to CEC, which influences the retention of NH_4. Soil analysis revealed significantly lower OM and CEC in CRL1 plots compared to urea (Table 2-1). Increased NH_3 volatilization may explain progressively lower N recovery, yield and density from CRL (Tables 2-4, 2-5, 3-1, 3-8, 3-9, 3-12), particularly since slower accumulations of OM were observed in CRL plots compared to urea. NH_3 loss may help to explain low N recovery during the WS, because N losses of 40% are not unusual in tropical climates when conditions are favorable (Francis et al., 2008). However, environmental factors such as high temperature and RH that could enhance the magnitude of NH_3 losses in the WS were considerably lower during the DS (Appendix A), when N recoveries were consistently lowest (Tables 3-7, 3-8, 3-12 - 3-14, 3-16, 3-19, 3-22), therefore, other factors may have contributed.

Denitrification is a multi-step respiratory pathway by which facultative anaerobes reduce NO_3^- to molecular N in anaerobic soil with organic or inorganic electron donors and N oxide electron acceptors (Coyne, 2008). Sand soils are generally not associated with substantial N losses through denitrification, however, the soil profile within the lysimeter (i.e. constructed system with distinct textural layers, designed to prevent sand particulate migration and reduce percolate impediment) may have facilitated anaerobic conditions during the DS when percolate flow is notably reduced (Appendix B). For example, Brown and Duble (1975) demonstrated having coarse textured strata within the soil profile created a perched water table and increased the water retention of the entire profile. In essence, a saturated zone would persist between the gravel and the sand in the lysimeter system and during periods of infrequent precipitation the replenishment of oxygenated water may be limited and anaerobic conditions may develop. Since organic electron donors would be available from seasonal regeneration and decomposition of root structures, conditions may be conducive for biological denitrification during the DS. Under soil temperatures consistent with the season (20.9 – 25.5^{o}C), denitrification losses ranging from 0.2 – 0.9 kg N ha^{-1} d^{-1} have been reported (Lensi and Chalamet, 1982; Groffman et al., 1991).

Soil storage (immobilization), essentially the opposite of mineralization, in that immobilization is the conversion of inorganic N (NO_3-N and NH_4-N) to organic forms. On average OM content of the upper 10 cm soil layer increased by ~1.5% over the 24-mo study period. The level in which fertilizer N is incorporated into OM is largely a function of turf stand maturity and during the period of increasing soil OM some of the fertilizer will be immobilized (Petrovic, 1990). Few studies have investigated the amount of fertilizer N that is eventually incorporated into OM under turf conditions and the author could not find published literature documenting this process in warm-season grass turf. Starr and Deroo (1981) evaluated the fate of N on cool-season grasses using labeled ^{15}N and found that 15 – 21% of applied N was stored in the organic content of a sandy loam soil, 4-mo after the last application. Watson (1987) reported similar conclusions ~2-mo after last fertilizer applications to perennial ryegrass grown on a sandy loam soil and noted that 13 – 17% of fertilizer N from urea was stored in the organic soil component.

These findings suggest that soil storage or immobilization of fertilizer N in coastal soils in Florida may be significant, especially in immature residential landscapes which have been shown to accumulate N rapidly in the first 10-yr period. More research is warranted to determine the influence of St. Augustinegrass lawn maturity on the fertilization requirements based on the capacity of a soil to accumulate fertilizer N in the soil organic-N pool. Long-term evaluations may show that reduced inorganic-N inputs are needed as the soil OM content reaches equilibrium and remains relatively constant, thus removing a potential fertilizer N sink.

Conclusion

This experiment has shown that various N strategies can be employed under St. Augustinegrass lawn conditions without serious implications to inorganic-N groundwater degradation. Based on these findings, N leaching from established residential St. Augustinegrass landscapes is expected to provide minor contributions to the pool of non-point source N pollutants in coastal watershed systems. Furthermore, we find little benefit in N rate regulation in addition to that set forth by state legislative bodies. In fact, restrictive fertilization seasons may have a detrimental environmental impact. For example, CRL at 147 kg N ha^{-1} that was allocated an N-release duration (180-d) far in excess of recommended re-application window (60 to 90-d) demonstrated severe symptoms of N deprivation (i.e. reduced turf density and quality). Incidences of NO_x-N leaching in excess of MCL standards were exacerbated progressively as these visual assessments deteriorated. These findings may provide valuable information of the potential ramifications of restrictive season legislation. If counties and municipalities are insistent on such fertilization boundaries, new revisions are required to enable certain CRNS to be applied at higher pre-applications N rates than currently permitted, prior to 120-d restrictive periods in order to sustain St. Augustinegrass density and root growth. For instance, PCU and BSD demonstrated the lowest inorganic-N leaching at N rates of 147 kg ha^{-1}, and were capable of sustaining acceptable St. Augustinegrass visual assessments for 120-d durations.

However, only low levels of applied N could be recovered in St. Augustinegrass clippings and inorganic-N leachates. We proposed three potential factors that may explain unaccounted for the majority of N not accounted for; (i) NH_3 volatilization, (ii) denitrification, and (iii) soil storage. Ammonia volatilization may be more prevalent under WS conditions and may have induced losses of ~40% or more of applied N depending on the N source. Hydrological factors may have been most favorable during the DS due to lysimeter specifications and N losses may have been substantial. Due to turf stand immaturity and low soil OM levels, soil storage or immobilization of applied fertilizer N may have been in the magnitude of ~15%, although this value is based on temperate research conditions. The relatively low levels of N recovered in this study suggest that inorganic-N leaching is not a major N flux in residential landscapes fertilized with these N sources but gaseous N loses may be more prevalent. Much more research is required in Florida to better understand the fate of applied N to a St. Augustinegrass under varying degrees of lawn maturity.

Table 3-1. The influence of N source applied at 49 kg N ha^{-1} on flow-weighted concentration of NO_3-N (mg L^{-1}) averaged over each 60-d cycle across 2007 and 2008.

TREATMENT†	2007					2008					
	--- Wet Season ---			- Dry Season -		--- Wet season ---			--- Dry Season ---		
	C1‡	C2	C3	C5	C6	C7	C8	C9	C10	C11	C12
	mg [NO_x-N] L^{-1}										
BSD1§	0.62	0.44	0.47	0.40	0.39	0.75	0.59	0.46	0.40	0.30	0.33
PCU1	0.64	0.43	0.43	0.41	0.30	0.48	0.59	0.44	0.38	0.29	0.31
CRL1	0.54	0.73	0.43	0.76	0.45	0.47	1.51	0.50	0.42	0.32	0.45
UPCU1	0.62	1.81	0.41	0.40	0.40	0.51	0.62	0.50	0.43	0.32	0.39
UREA1	6.40	3.09	0.38	0.41	0.32	2.32	0.59	0.50	0.34	0.25	0.95
CONTRAST¶											
UREA1 vs. OTHERS	*	***	NS	NS	NS	NS	NS	NS	NS	NS	NS
UREA vs. UPCU1	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
PCU1 vs. BS1	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CRL1 vs. BS1 & PCU1	NS	NS	NS	**	NS	NS	NS	NS	NS	NS	NS

NS, *, **, ***, = $P>0.05$, $P<0.05$, $P<0.01$, $P<0.001$

† Treatment code: CRL = Control release liquid; PCU = Polymer-coated urea; BSD = Activated sewage sludge biosolid; and UPCU = Urea in equal N combination with polymer-coated urea.

‡C = Means of 3 replications, averaged over each 60-d cycle.

§ The numeric demarcation that follows each treatment code indicates N rate and application frequency with 1 representing 49 kg ha^{-1} applied every 60-d.

¶ Single degree contrasts performed at the alpha level 0.05.

Table 3-2. The influence of N source applied at 98 kg N ha^{-1} on flow-weighted concentration of NO_3-N (mg L^{-1}) averaged over each 120-d cycle across 2007 and 2008.

TREATMENT†	------- 2007 -------			------- 2008 -------		
	C1‡	C2¶	C3	C4	C5	C6
	---------------- mg [NO_x-N] L^{-1}----------------					
BSD2	0.55	0.43	0.39	0.50	0.41	0.34
PCU2	0.53	0.55	0.35	0.48	0.43	0.26
CRL2	1.03	0.43	1.29	1.21	0.49	0.47
UPCU2	10.49	0.40	1.75	0.52	0.36	0.36
CONTRAST§						
UPCU2 vs. OTHERS	**	NS	NS	NS	NS	NS
CRL2 vs. BSD2 & PCU2	NS	NS	NS	NS	NS	NS
BSD2 vs. PCU2	NS	NS	NS	NS	NS	NS

NS, *, **, ***, = P>0.05, P<0.05, P<0.01, P<0.001

† Treatment code: CRL = Control release liquid; PCU = Polymer-coated urea; BSD = Activated sewage sludge biosolid; and UPCU = Urea in equal N combination with polymer-coated urea.

‡C = Means of 3 replications, averaged over each 120-d cycle.

§ Single degree contrasts performed at the alpha level 0.05.

¶ Sample period (09/01/07 to 01/03/08) is incomplete, flow-weighted concentrations averaged between 09/01/07 and 11/07/07due to missing data.

Table 3-3. The influence of N source applied at 147 kg ha^{-1} on flow-weighted concentration of NO_3-N (mg L^{-1}) averaged over each 180-d cycle across 2007 and 2008.

TREATMENT†	--- 2007 ---	--------- 2008 ---------	
	Wet Season	Wet Season	Dry Season
	C1‡	C3	C4
	------------ mg [NO_x-N] L^{-1}------------		
BSD3	0.48	0.47	0.52
PCU3	0.50	0.53	0.32
CRL3	1.20	2.85	2.43
CONTRAST§			
CRL3 vs. BSD3 & PCU3	*	NS	**
BSD3 vs. PCU3	NS	NS	NS

NS, *, **, ***, = P>0.05, P<0.05, P<0.01, P<0.001

† Treatment code: CRL = Control release liquid; PCU = Polymer-coated urea; BSD = Activated sewage sludge biosolid; and UPCU = Urea in equal N combination with polymer-coated urea.

‡C = Means of 3 replications, averaged over each 180-d cycle.

§ Single degree contrasts performed at the alpha level 0.05.

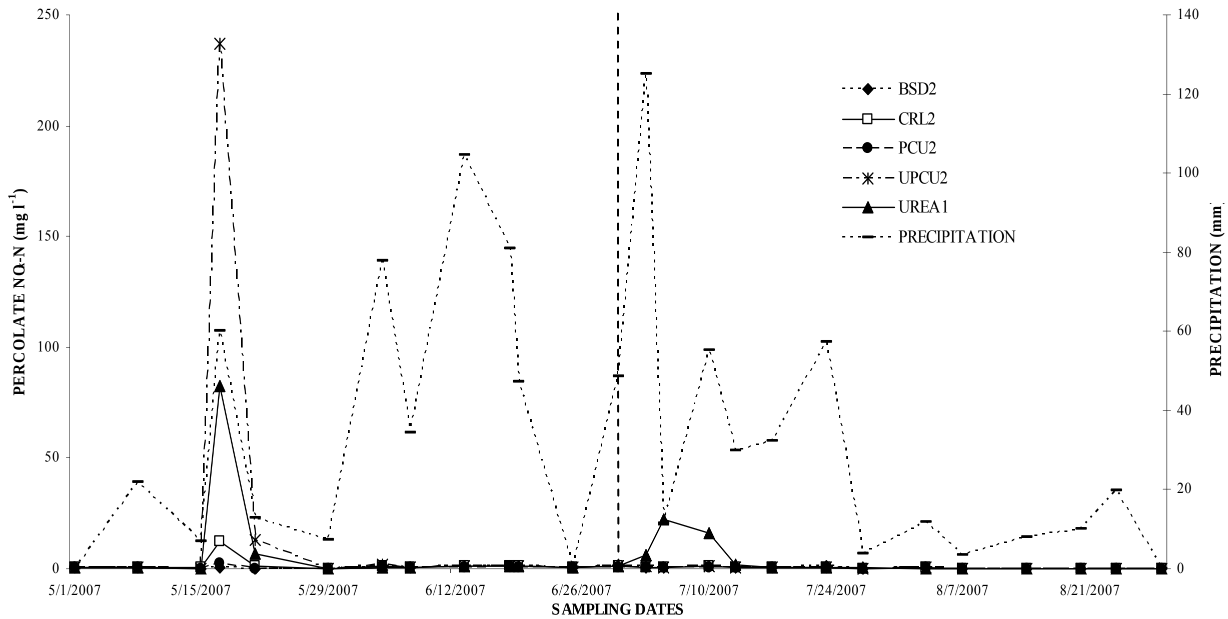

Fig. 3-1. NO_x-N leached in cycle 1 (April 30-August 31, 2007) influenced by N sources applied every 120-d at 98 kg N ha^{-1} and precipitation during the WS. Vertical dashed lines indicate urea fertilization every 60-d at 49 kg N ha^{-1}. Precipitation values summed over each sampling period.

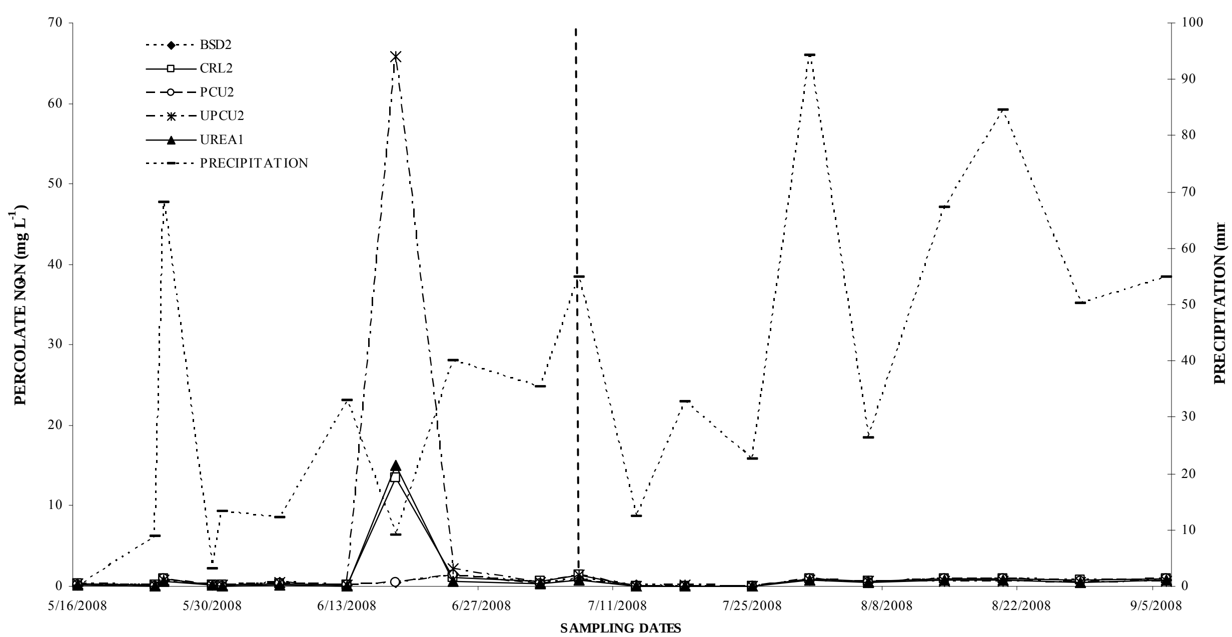

Fig. 3-2. NO_x-N leached in cycle 4 (May 10-Spetmeber 6, 2008), influenced by N sources applied every 120-d at 98 kg N ha^{-1} and precipitation during the WS. Vertical dashed lines indicate urea fertilization every 60-d at 49 kg N ha^{-1}, included for comparative interest. Precipitation values summed over each sampling period.

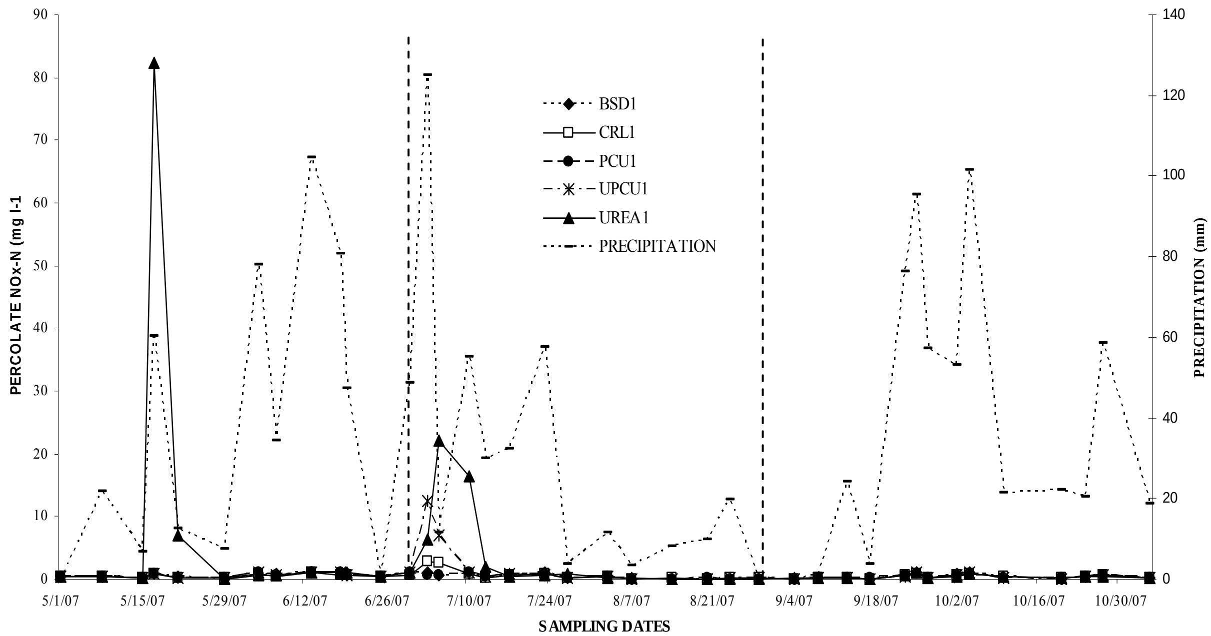

Fig. 3-3. NO_x-N leached during cycles 1-3 (May 10-Spetmeber 6), influenced by N sources applied every 60-d at 49 kg N ha^{-1} and precipitation during the WS. Vertical dashed lines indicate fertilization dates. Precipitation values summed over each sampling period.

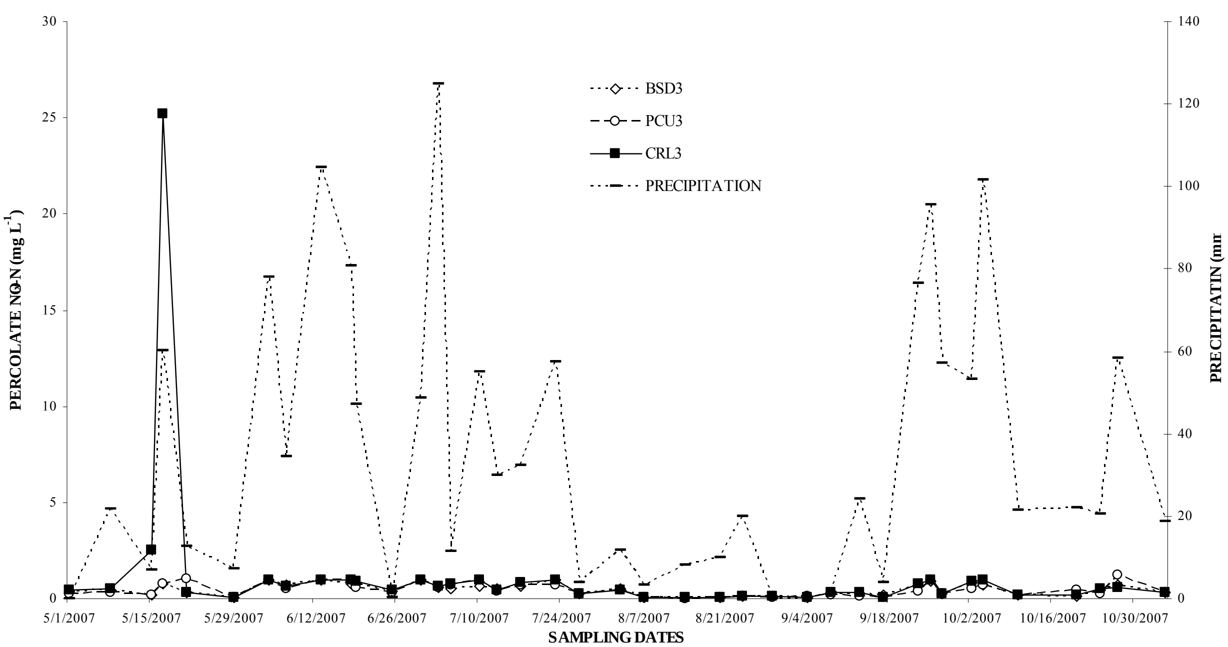

Fig. 3-4. NO_x-N leached in cycle 1 (April 30 – November 7), influenced by N sources applied at 147 kg N ha^{-1} every 180-d and precipitation during the WS. Precipitation values summed over each sampling period.

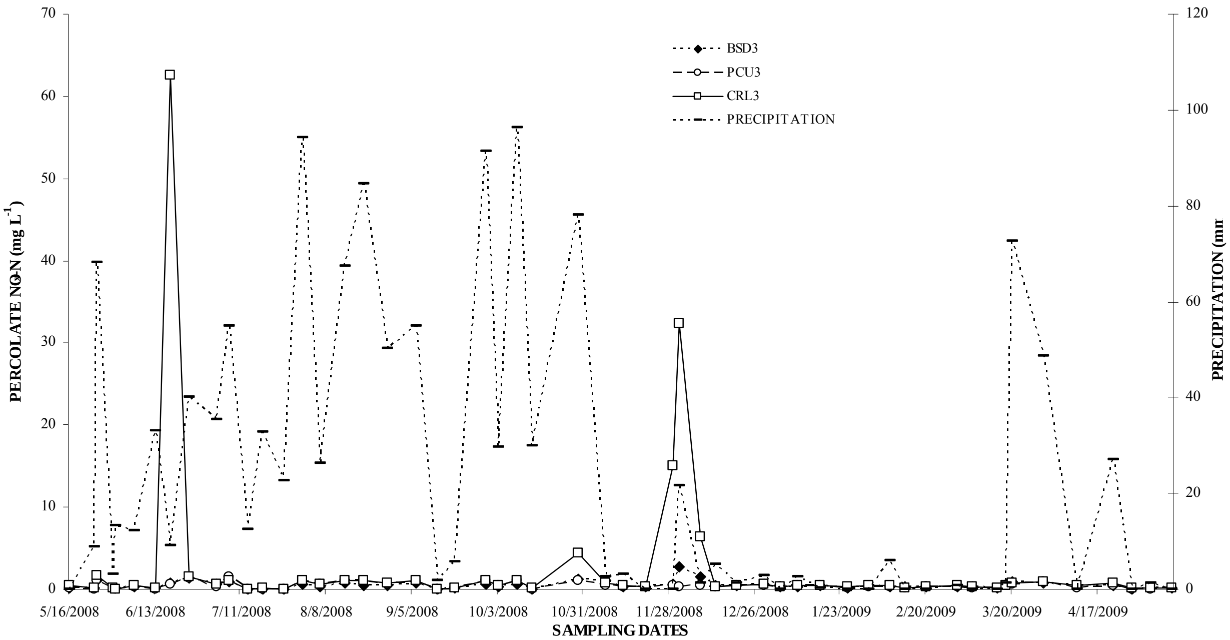

Fig. 3-5. NO_x-N leached during cycles 3 and 4 (May 10, 2008 – May 15, 2009), influenced by N sources applied at 147 kg N ha^{-1} every 180-d and precipitation. Vertical dashed line indicates fertilization date. Precipitation values summed over each sampling period.

Table 3-4. Nitrogen budget of inputs vs. N accounted for by N leaching and St. Augustinegrass N uptake for cycle 1 (April 30 – June 30, 2007).

SOURCE†	NITROGEN BUDGET							
	N INPUTS		INORGANIC-N RECOVERED					
	FERT‡	IRRIG§	NO_x-N	NH_4-N	TN¶	NUP††	NL‡‡	REC§§
	------------------------- kg ha^{-1} -------------------------						----- % -----	
BSD1	49	0.93	0.34	0.55	0.89	2.93	1.8	7.6
PCU1	49	0.93	0.35	0.57	0.93	1.16	1.9	4.2
CRL1	49	0.93	0.29	0.49	0.78	1.56	1.6	4.7
UPCU1	49	0.93	0.34	0.54	0.88	1.98	1.8	5.7
UREA1	49	0.93	2.75	0.49	3.25	3.41	6.5	13.3
CV (%)			23.4	17.1	21.7	40.4		26.2
CONTRAST								
UREA VS. OTHERS			**	NS	**	NS		**
UREA VS. UPCU1			*	NS	*	NS		*
CRL1 VS. BSD1, PCU1			NS	NS	NS	NS		NS
BSD1 VS. PCU1			NS	NS	NS	NS		NS

NS, *, **, ***, = P>0.05, P<0.05, P<0.01, P<0.001

† Source code: CRL1 = Control release liquid; PCU1 = Polymer-coated urea; BSD1 = Activated sewage sludge bio-solid; UPCU1 = Urea in equal N combination with polymer-coated urea; Urea1 = Urea. All sources applied at 49 kg N ha^{-1}every 60-d. ‡ FERT: Fertilizer N applied per application cycle.

§ IRRIG: N supplied via irrigation, concentrations determined weekly and multiplied by volume applied.

¶ TN: Total N summed from NO_x-N and NH_4-N leachates. †† NUP: N-uptake as a product of dry weight yield and tissue N content. ‡‡ NL: N leached, percent of applied. §§ REC: Relative N recovery, the percent of inorganic-N recovered compared to N inputs.

Table 3-5. Nitrogen budget of inputs vs. N accounted for by N leaching and St. Augustinegrass N uptake for cycle 2 (July 1– August 31, 2007).

SOURCE†	NITROGEN BUDGET							
	N INPUTS		INORGANIC-N RECOVERED					
	FERT‡	IRRIG§	NOx-N	NH4-N	TN¶	NUP††	NL‡‡	REC§§
	------------------------- kg ha^{-1} -------------------------						----- % -----	
BSD1	49	0.62	0.23	0.31	0.54	12.6	1.1	26.5
PCU1	49	0.62	0.23	0.34	0.57	5.26	1.2	12.2
CRL1	49	0.62	0.40	0.39	0.79	4.25	1.6	9.7
UPCU1	49	0.62	0.99	0.31	1.30	10.96	2.6	24.7
UREA1	49	0.62	2.31	0.60	2.91	15.43	5.9	36.9
CV (%)			16.8	22.7	13.2	12.0		13.8
CONTRAST								
UREA VS. OTHERS			**	**	**	*		NS
UREA VS. UPCU1			NS	**	NS	NS		NS
CRL1 VS. BSD1, PCU1			NS	NS	NS	NS		NS
BSD1 VS. PCU1			NS	NS	NS	NS		NS

NS, *, **, ***, = P>0.05, P<0.05, P<0.01, P<0.001

Table 3-6. Nitrogen budget of inputs vs. N accounted for by N leaching and St. Augustinegrass N uptake for cycle 3 (September 1 – November 7, 2007).

SOURCE†	NITROGEN BUDGET							
	N INPUTS		INORGANIC-N RECOVERED					
	FERT‡	IRRIG§	NO_x-N	NH_4-N	TN¶	NUP††	NL‡‡	REC§§
	------------------------- kg ha^{-1} -------------------------						----- % -----	
BSD1	49	0.43	0.25	0.24	0.49	5.50	1.0	12.1
PCU1	49	0.43	0.23	0.25	0.49	5.81	1.0	12.7
CRL1	49	0.43	0.24	0.22	0.46	1.15	0.9	3.3
UPCU1	49	0.43	0.22	0.22	0.44	7.93	0.9	16.9
UREA1	49	0.43	0.21	0.21	0.42	8.19	0.8	17.4
CV (%)			8.5	8.1	8.2	35.2		32.1
CONTRAST								
UREA VS. OTHERS			NS	NS	NS	NS		NS
UREA VS. UPCU1			NS	NS	NS	NS		NS
CRL1 VS. BSD1, PCU1			NS	NS	NS	NS		NS
BSD1 VS. PCU1			NS	NS	NS	NS		NS

NS, *, **, ***, = P>0.05, P<0.05, P<0.01, P<0.001

Table 3-7. Nitrogen budget of inputs vs. N accounted for by N leaching and St. Augustinegrass N uptake for cycle 5 (January 6 – March 7, 2008).

SOURCE†	NITROGEN BUDGET							
	N INPUTS		INORGANIC-N RECOVERED					
	FERT‡	IRRIG§	NO_x-N	NH_4-N	TN¶	NUP††	NL‡‡	REC§§
	------------------------- kg ha^{-1} -------------------------						----- % -----	
BSD1	49	0.70	0.16	0.07	0.24	0.53	0.5	1.54
PCU1	49	0.70	0.17	0.08	0.24	1.04	0.5	2.57
CRL1	49	0.70	0.73	0.13	0.86	0.45	1.7	2.64
UPCU1	49	0.70	0.16	0.07	0.23	1.05	0.5	2.57
UREA1	49	0.70	0.17	0.07	0.24	1.21	0.5	2.91
CV (%)			41.0	21.1	31.4	18.1		25.5
CONTRAST								
UREA VS. OTHERS			NS	NS	NS	*		NS
UREA VS. UPCU1			NS	NS	NS	NS		NS
CRL1 VS. BSD1, PCU1			NS	*	NS	NS		*
BSD1 VS. PCU1			NS	NS	NS	*		NS

NS, *, **, ***, = P>0.05, P<0.05, P<0.01, P<0.001

Table 3-8. Nitrogen budget of inputs vs. N accounted for by N leaching and St. Augustinegrass N uptake for cycle 6 (March 8 – May 9, 2008).

SOURCE†	NITROGEN BUDGET							
	N INPUTS		INORGANIC-N RECOVERED					
	FERT‡	IRRIG§	NO_x-N	NH_4-N	TN¶	NUP††	NL‡‡	REC§§
	------------------------- kg ha^{-1} -------------------------						----- % -----	
BSD1	49	0.22	0.017	0.016	0.033	1.29	0.1	2.70
PCU1	49	0.22	0.013	0.013	0.026	2.04	0.1	4.20
CRL1	49	0.22	0.019	0.022	0.041	0.25	0.1	0.60
UPCU1	49	0.22	0.017	0.015	0.031	2.52	0.1	5.18
UREA1	49	0.22	0.014	0.013	0.026	2.71	0.1	5.56
CV (%)			19.6	18.9	18.8	22.3		20.7
CONTRAST								
UREA VS. OTHERS			NS	NS	NS	NS		NS
UREA VS. UPCU1			NS	NS	NS	NS		NS
CRL1 VS. BSD1, PCU1			NS	**	NS	NS		NS
BSD1 VS. PCU1			NS	NS	NS	NS		NS

NS, *, **, ***, = P>0.05, P<0.05, P<0.01, P<0.001

Table 3-9. Nitrogen budget of inputs vs. N accounted for by N leaching and St. Augustinegrass N uptake for cycle 7 (May 9 – July 7, 2008).

SOURCE†	NITROGEN BUDGET							
	N INPUTS		INORGANIC-N RECOVERED					
	FERT‡	IRRIG§	NO_x-N	NH_4-N	TN¶	NUP††	NL‡‡	REC§§
	------------------------- kg ha^{-1}						----- % -----	
BSD1	49	0.47	0.35	0.14	0.49	9.95	1.0	21.1
PCU1	49	0.47	0.22	0.09	0.32	15.39	0.7	31.76
CRL1	49	0.47	0.22	0.10	0.31	1.03	0.6	2.71
UPCU1	49	0.47	0.23	0.99	0.33	14.14	0.7	29.25
UREA1	49	0.47	1.07	0.77	1.15	12.52	2.3	27.63
CV (%)			46.2	13.0	37.5	32.5		28.6
CONTRAST								
UREA VS. OTHERS			NS	NS	NS	NS		NS
UREA VS. UPCU1			NS	NS	NS	NS		NS
CRL1 VS. BSD1, PCU1			NS	NS	NS	**		**
BSD1 VS. PCU1			NS	NS	NS	NS		NS

NS, *, **, ***, = P>0.05, P<0.05, P<0.01, P<0.001

Table 3-10. Nitrogen budget of inputs vs. N accounted for by N leaching and St. Augustinegrass N uptake for cycle 8 (July 8 – September 6, 2008).

SOURCE†	NITROGEN BUDGET							
	N INPUTS		INORGANIC-N RECOVERED					
	FERT‡	IRRIG§	NO_x-N	NH_4-N	TN¶	NUP††	NL‡‡	REC§§
	------------------------- kg ha^{-1}						----- % -----	
BSD1	49	1.24	0.22	0.37	0.58	16.7	1.2	34.3
PCU1	49	1.24	0.22	0.35	0.58	20.1	1.2	41.2
CRL1	49	1.24	0.57	0.38	0.95	4.1	2.0	10.1
UPCU1	49	1.24	0.23	0.43	0.66	18.1	1.3	37.4
UREA1	49	1.24	0.22	0.38	0.60	15.8	1.2	32.7
CV (%)			22.4	12.1	26.2	21.1		34.0
CONTRAST								
UREA VS. OTHERS			NS	NS	NS	NS		NS
UREA VS. UPCU1			NS	NS	NS	NS		NS
CRL1 VS. BSD1, PCU1			NS	NS	*	**		*
BSD1 VS. PCU1			NS	NS	NS	NS		NS

NS, *, **, ***, = P>0.05, P<0.05, P<0.01, P<0.001

Table 3-11. Nitrogen budget of inputs vs. N accounted for by N leaching and St. Augustinegrass N uptake for cycle 9 (September 6 – November 13, 2008).

SOURCE†	NITROGEN BUDGET							
	N INPUTS		INORGANIC-N RECOVERED					
	FERT‡	IRRIG§	NO_x-N	NH_4-N	TN¶	NUP††	NL‡‡	REC§§
	------------------------- kg ha^{-1} -------------------------						----- % -----	
BSD1	49	0.52	0.020	0.024	0.044	10.1	0.1	20.5
PCU1	49	0.52	0.019	0.027	0.046	10.9	0.1	22.1
CRL1	49	0.52	0.022	0.025	0.047	3.2	0.1	6.6
UPCU1	49	0.52	0.023	0.024	0.047	12.0	0.1	24.3
UREA1	49	0.52	0.022	0.025	0.047	12.1	0.1	24.5
CV (%)			10.9	20.5	21.7	23.2		23.2
CONTRAST								
UREA VS. OTHERS			NS	NS	NS	*		*
UREA VS. UPCU1			NS	NS	NS	NS		NS
CRL1 VS. BSD1, PCU1			NS	NS	NS	**		**
BSD1 VS. PCU1			NS	NS	NS	NS		NS

NS, *, **, ***, = P>0.05, P<0.05, P<0.01, P<0.001

Table 3-12. Nitrogen budget of inputs vs. N accounted for by N leaching and St. Augustinegrass N uptake for cycle 10 (November 14 – January 13, 2008).

SOURCE†	NITROGEN BUDGET							
	N INPUTS		INORGANIC-N RECOVERED					
	FERT‡	IRRIG§	NO_x-N	NH_4-N	TN¶	NUP††	NL‡‡	REC§§
	------------------------- kg ha^{-1} -------------------------						----- % -----	
BSD1	49	0.83	0.167	0.205	0.371	0.69	0.7	2.13
PCU1	49	0.83	0.152	0.200	0.352	0.77	0.7	2.51
CRL1	49	0.83	0.172	0.311	0.483	0.38	1.0	1.48
UPCU1	49	0.83	0.172	0.254	0.426	0.92	0.9	2.70
UREA1	49	0.83	0.134	0.260	0.395	1.20	0.8	3.21
CV (%)			15.5	26.9	20.4	13.3		21.3
CONTRAST								
UREA VS. OTHERS			NS	NS	NS	**		*
UREA VS. UPCU1			NS	NS	NS	NS		NS
CRL1 VS. BSD1, PCU1			NS	NS	NS	*		*
BSD1 VS. PCU1			NS	NS	NS	NS		NS

NS, *, **, ***, = P>0.05, P<0.05, P<0.01, P<0.001

Table 3-13. Nitrogen budget of inputs vs. N accounted for by N leaching and St. Augustinegrass N uptake for cycle 11 (January 14 – March 12, 2008).

SOURCE†	NITROGEN BUDGET							
	N INPUTS		INORGANIC-N RECOVERED					
	FERT‡	IRRIG§	NO_x-N	NH_4-N	TN¶	NUP††	NL‡‡	REC§§
	kg ha^{-1}						%	
BSD1	49	0.13	0.106	0.497	0.603	0.290	1.2	1.82
PCU1	49	0.13	0.098	0.267	0.364	0.319	0.7	1.39
CRL1	49	0.13	0.107	0.529	0.637	0.192	1.3	1.68
UPCU1	49	0.13	0.113	0.451	0.564	0.355	1.1	1.87
UREA1	49	0.13	0.081	0.301	0.382	0.367	0.8	1.53
CV (%)			22.9	20.6	17.8	11.7		12.2
CONTRAST								
UREA VS. OTHERS			NS	NS	NS	NS		NS
UREA VS. UPCU1			NS	NS	NS	NS		NS
CRL1 VS. BSD1, PCU1			NS	NS	NS	*		NS
BSD1 VS. PCU1			NS	NS	NS	NS		NS

NS, *, **, ***, = P>0.05, P<0.05, P<0.01, P<0.001

Table 3-14. Nitrogen budget of inputs vs. N accounted for by N leaching and St. Augustinegrass N uptake for cycle 12 (March 13 – May 15, 2008).

SOURCE†	NITROGEN BUDGET							
	N INPUTS		INORGANIC-N RECOVERED					
	FERT‡	IRRIG§	NO_x-N	NH_4-N	TN¶	NUP††	NL‡‡	REC§§
	kg ha^{-1}						%	
BSD1	49	0.21	0.111	0.137	0.249	2.60	0.5	5.8
PCU1	49	0.21	0.109	0.124	0.231	3.16	0.5	6.9
CRL1	49	0.21	0.167	0.365	0.532	0.65	1.1	2.4
UPCU1	49	0.21	0.135	0.141	0.277	2.98	0.6	6.6
UREA1	49	0.21	0.671	0.126	0.797	2.97	1.6	7.7
CV (%)			37.8	9.3	23.6	16.8		15.2
CONTRAST								
UREA VS. OTHERS			**	*	*	NS		NS
UREA VS. UPCU1			*	NS	*	NS		NS
CRL1 VS. BSD1, PCU1			NS	***	*	***		**
BSD1 VS. PCU1			NS	NS	NS	NS		NS

NS, *, **, ***, = P>0.05, P<0.05, P<0.01, P<0.001

Table 3-15. Nitrogen budget of inputs vs. N accounted for by N leaching and St. Augustinegrass N uptake for cycle 1 (April 30 – August 31, 2007).

SOURCE†	NITROGEN BUDGET							
	N INPUTS		INORGANIC-N RECOVERED					
	FERT‡	IRRIG§	NO_x-N	NH_4-N	TN¶	NUP††	NL‡‡	REC§§
	------------------------ kg ha^{-1} ------------------------						----- % -----	
BSD2	98	1.55	0.60	0.94	1.54	10.0	1.5	11.6
PCU2	98	1.55	0.56	1.02	1.59	17.9	1.6	19.5
CRL2	98	1.55	1.11	0.95	2.05	7.5	2.1	9.6
UPCU2	98	1.55	11.10	0.87	11.97	16.1	12.0	28.2
UREA1	98	1.55	12.76	1.09	13.84	18.9	13.9	32.8
CV (%)			20.9	21.5	16.1	16.2		9.1
CONTRAST								
UREA VS. OTHERS			**	NS	**	NS		***
UREA VS. UPCU2			**	NS	**	NS		***
CRL2 VS. BSD2, PCU2			NS	NS	NS	*		*
BSD2 VS. PCU2			NS	NS	NS	NS		*

NS, *, **, ***, = P>0.05, P<0.05, P<0.01, P<0.001

† Source code: CRL2 = Control release liquid; PCU2 = Polymer-coated urea; BSD2 = Activated sewage sludge bio-solid; UPCU2 = Urea in equal N combination with polymer-coated urea; Urea1 = Urea. All sources applied at 98 kg N ha^{-1}every 120-d, expect Urea1 applied at 49 kg N ha^{-1}every 60-d

‡ FERT: Fertilizer N applied per application cycle. § IRRIG: N supplied via irrigation, concentrations determined weekly and multiplied by volume applied. ¶ TN: Total N summed from NO_x-N and NH_4-N leachates. †† NUP: N-uptake as a product of dry weight yield and tissue N content. ‡‡ NL: N leached, percent of applied. §§ REC: Relative N recovery, the percent of inorganic-N recovered compared to N inputs.

Table 3-16. Nitrogen budget of inputs vs. N accounted for by N leaching and St. Augustinegrass N uptake for cycle 3 (January 6 – March 7, 2008).

SOURCE†	NITROGEN BUDGET							
	N INPUTS		INORGANIC-N RECOVERED					
	FERT‡	IRRIG§	NO_x-N	NH_4-N	TN¶	NUP††	NL‡‡	REC§§
	------------------------ kg ha^{-1} ------------------------						----- % -----	
BSD2	98	0.92	0.175	0.085	0.260	1.350	0.3	1.63
PCU2	98	0.92	0.176	0.086	0.449	2.983	0.5	4.19
CRL2	98	0.92	0.890	0.273	0.976	0.573	1.0	0.84
UPCU2	98	0.92	1.238	0.087	1.325	3.540	1.3	4.92
UREA1	98	0.92	0.183	0.088	0.271	3.910	0.3	4.22
CV (%)			19.2	19.9		28.5		24.2
CONTRAST								
UREA VS. OTHERS			NS	NS	NS	NS		NS
UREA VS. UPCU2			*	NS	NS	*		*
CRL2 VS. BSD2, PCU2			*	**	NS	*		*
BSD2 VS. PCU2			NS	NS	NS	NS		NS

NS, *, **, ***, = P>0.05, P<0.05, P<0.01, P<0.001

Table 3-17. Nitrogen budget of inputs vs. N accounted for by N leaching and St. Augustinegrass N uptake for cycle 4 (May 16 – September 6, 2008).

SOURCE†	NITROGEN BUDGET							
	N INPUTS		INORGANIC-N RECOVERED					
	FERT‡	IRRIG§	NO_x-N	NH_4-N	TN¶	NUP††	NL‡‡	REC§§
	------------------------ kg ha^{-1} ------------------------						----- % -----	
BSD2	98	1.7	0.424	0.413	0.837	19.1	0.8	20.0
PCU2	98	1.7	0.402	0.446	0.848	50.7	0.9	51.7
CRL2	98	1.7	1.018	0.642	1.661	3.5	1.7	5.2
UPCU2	98	1.7	3.185	0.370	3.555	27.5	3.6	31.2
UREA1	98	1.7	1.298	0.457	1.756	28.4	1.8	30.2
CV (%)			31.4	9.9	22.8	16.4		11.7
CONTRAST								
UREA VS. OTHERS			NS	NS	NS	NS		NS
UREA VS. UPCU2			NS	NS	NS	NS		*
CRL2 VS. BSD2, PCU2			NS	*	NS	***		***
BSD2 VS. PCU2			NS	NS	NS	**		**

NS, *, **, ***, = P>0.05, P<0.05, P<0.01, P<0.001

Table 3-18. Nitrogen budget of inputs vs. N accounted for by N leaching and St. Augustinegrass N uptake for cycle 5 (September 7 – January 13, 2008).

SOURCE†	NITROGEN BUDGET							
	N INPUTS		INORGANIC-N RECOVERED					
	FERT‡	IRRIG§	NO_x-N	NH_4-N	TN¶	NUP††	NL‡‡	REC§§
	------------------------ kg ha^{-1} ------------------------						----- % -----	
BSD2	98	1.35	0.164	0.206	0.370	11.30	0.4	11.67
PCU2	98	1.35	0.151	0.201	0.349	10.64	0.4	10.96
CRL2	98	1.35	0.197	0.254	0.450	3.48	0.5	3.92
UPCU2	98	1.35	0.134	0.174	0.309	12.75	0.3	13.06
UREA1	98	1.35	0.157	0.286	0.442	13.30	0.4	13.74
CV (%)			21.1	24.9	22.8	14.9		14.1
CONTRAST								
UREA VS. OTHERS			NS	NS	NS	**		**
UREA VS. UPCU2			NS	NS	NS	**		**
CRL2 VS. BSD2, PCU2			NS	NS	NS	***		***
BSD2 VS. PCU2			NS	NS	NS	NS		NS

NS, *, **, ***, = P>0.05, P<0.05, P<0.01, P<0.001

Table 3-19. Nitrogen budget of inputs vs. N accounted for by N leaching and St. Augustinegrass N uptake for cycle 6 (January 14 – May 15, 2008).

SOURCE†	NITROGEN BUDGET							
	N INPUTS		INORGANIC-N RECOVERED					
	FERT‡	IRRIG§	NOx-N	NH4-N	TN¶	NUP††	NL‡‡	REC§§
	------------------------ kg ha^{-1} ------------------------						----- % -----	
BSD2	98	0.33	0.243	0.689	0.936	1.45	1.0	2.42
PCU2	98	0.33	0.191	0.873	0.587	3.26	0.6	3.91
CRL2	98	0.33	0.338	0.391	1.210	0.54	1.2	1.77
UPCU2	98	0.33	0.260	0.718	0.987	1.45	1.0	2.48
UREA1	98	0.33	0.753	0.426	1.174	3.35	1.2	4.59
CV (%)			29.9	15.2	19.0	21.8		20.6
CONTRAST								
UREA VS. OTHERS			NS	NS	NS	**		***
UREA VS. UPCU2			NS	NS	NS	NS		NS
CRL2 VS. BSD2, PCU2			NS	*	NS	**		*
BSD2 VS. PCU2			NS	NS	NS	**		*

NS, *, **, ***, = P>0.05, P<0.05, P<0.01, P<0.001

Table 3-20. Nitrogen budget of inputs vs. N accounted for by N leaching and St. Augustinegrass N uptake for cycle 1 (April 30 – November 7, 2008).

SOURCE†	NITROGEN BUDGET							
	N INPUTS		INORGANIC-N RECOVERED					
	FERT‡	IRRIG§	NO_x-N	NH_4-N	TN¶	NUP††	NL‡‡	REC§§
	------------------------- kg ha^{-1} -------------------------						----- % -----	
BSD3	147	1.98	0.79	1.10	1.89	20.87	1.3	15.27
PCU3	147	1.98	0.78	1.33	2.11	42.49	1.4	29.94
CRL3	147	1.98	1.98	1.32	3.30	11.63	2.2	10.02
UREA1	147	1.98	12.97	1.30	14.27	27.10	9.6	27.73
CV (%)			23.7	10.3	18.1	13.1		6.4
CONTRAST								
UREA VS. OTHERS			**	NS	*	NS		**
CRL3 VS. BSD3, PCU3			NS	NS	NS	**		***
BSD3 VS. PCU3			NS	NS	NS	**		***

NS, *, **, ***, = P>0.05, P<0.05, P<0.01, P<0.001

† Source code: CRL3 = Control release liquid; PCU3 = Polymer-coated urea; BSD3 = Activated sewage sludge bio-solid; Urea1 = Urea. All sources applied at 147 kg N ha^{-1}every 180-d, expect Urea1 applied at 49 kg N ha^{-1}every 60-d

‡ FERT: Fertilizer N applied per application cycle.

§ IRRIG: N supplied via irrigation, concentrations determined weekly and multiplied by volume applied.

¶ TN: Total N summed from NO_x-N and NH_4-N leachates.

†† NUP: N-uptake as a product of dry weight yield and tissue N content.

‡‡ NL: N leached.

§§ REC: Relative N recovery, the percent of inorganic-N recovered compared to N inputs.

Table 3-21. Nitrogen budget of inputs vs. N accounted for by N leaching and St. Augustinegrass N uptake for cycle 3 (May 10 – November 13, 2008).

SOURCE†	NITROGEN BUDGET							
	N INPUTS		INORGANIC-N RECOVERED					
	FERT‡	IRRIG§	NO_x-N	NH_4-N	TN¶	NUP††	NL‡‡	REC§§
	------------------------ kg ha^{-1} ------------------------						----- % -----	
BSD3	147	2.23	0.403	0.363	0.765	45.62	0.5	31.09
PCU3	147	2.23	0.471	0.499	0.969	83.22	0.6	56.42
CRL3	147	2.23	3.173	0.834	4.006	4.92	2.7	5.98
UREA1	147	2.23	1.32	0.482	1.802	40.47	1.2	28.33
CV (%)			31.9	8.53	21.5	12.7		11.8
CONTRAST								
UREA VS. OTHERS			NS	NS	NS	NS		NS
CRL3 VS. BSD3, PCU3			NS	***	NS	***		***
BSD3 VS. PCU3			NS	NS	NS	**		**

NS, *, **, ***, = P>0.05, P<0.05, P<0.01, P<0.001

Table 3-22. Nitrogen budget of inputs vs. N accounted for by N leaching and St. Augustinegrass N uptake for cycle 4 (November 13 – May 15, 2008).

SOURCE†	NITROGEN BUDGET							
	N INPUTS		INORGANIC-N RECOVERED					
	FERT‡	IRRIG§	NO_x-N	NH_4-N	TN¶	NUP††	NL‡‡	REC§§
	------------------------ kg ha^{-1} ------------------------						----- % -----	
BSD3	147	1.17	0.584	0.943	1.532	3.093	1.0	3.12
PCU3	147	1.17	0.363	0.655	1.016	4.353	0.7	3.62
CRL3	147	1.17	2.677	1.549	4.227	1.127	2.9	3.61
UREA1	147	1.17	0.888	0.687	1.569	4.543	1.1	4.13
CV (%)			14.5	11.9	7.7	10.3		8.5
CONTRAST								
UREA VS. OTHERS			NS	NS	NS	**		NS
CRL3 VS. BSD3, PCU3			**	**	***	***		NS
BSD3 VS. PCU3			NS	NS	NS	NS		NS

NS, *, **, ***, = P>0.05, P<0.05, P<0.01, P<0.001

APPENDIX A
CLIMATOLOGY DATA

Table A-1. Climatology data (May-April, 2007 and 2008) for Ft. Lauderdale (FLREC), FL, with long term norms.

MONTH	AIR TEMPERATURE 2007 MAX.	AIR TEMPERATURE 2007 MIN.	AIR TEMPERATURE 2007 AVG.	AIR TEMPERATURE 2008 MAX.	AIR TEMPERATURE 2008 MIN.	AIR TEMPERATURE 2008 AVG.	NORM.†	TOTAL RAINFALL 2007	TOTAL RAINFALL 2008	SOIL TEMPERATURE (10 cm) 2007	SOIL TEMPERATURE (10 cm) 2008	RELATIVE HUMIDITY 2007	RELATIVE HUMIDITY 2008	TOTAL SOLAR RADIATION 2007	TOTAL SOLAR RADIATION 2008
	^{O}C							mm		^{O}C		%		W m^{-2}	
MAY	33.5	15.0	25.0	35.1	16.5	26.6	25.8	109.2	100.6	26.0	27.7	70	71	242.7	276.8
JUNE	34.5	19.8	26.3	33.1	21.4	27.5	27.3	479.3	60.2	27.3	28.4	77	80	233.0	227.4
JULY	34.1	15.3	26.7	33.6	21.6	27.3	28.1	264.4	262.6	28.3	28.0	79	82	222.0	215.2
AUGUST	35.0	22.7	28.7	34.7	22.8	28.1	27.9	43.4	239.3	29.2	28.3	76	83	238.2	201.6
SEPTEMBER	34.9	22.1	27.6	32.4	21.9	27.8	27.2	287.0	160.3	28.3	28.0	80	82	193.0	188.9
OCTOBER	32.7	22.6	27.1	31.7	11.5	25.1	25.5	265.4	204.5	26.5	25.5	82	78	150.1	166.4
NOVEMBER	29.3	12.8	22.8	31.5	9.2	20.8	22.8	59.7	27.2	23.4	22.6	75	76	158.7	165.1
DECEMBER	29.5	10.3	22.8	28.6	9.7	20.8	20.1	17.3	10.7	23.0	21.2	81	80	145.6	129.5
JANUARY	29.2	3.3	20.2	29.3	4.6	18.6	19.6	41.7	2.8	21.1	20.7	77	76	141.4	153.7
FEBRUARY	31.9	8.7	22.3	30.3	2.2	19.1	19.2	126.5	6.9	22.4	21.2	77	70	169.4	187.4
MARCH	32.3	10.4	22.6	30.2	6.4	21.3	22.1	140.2	122.7	22.7	23.0	74	68	193.2	207.4
APRIL	32.2	12.7	23.6	32.0	10.6	23.9	23.6	84.8	28.4	25.1	26.0	71	66	259.5	252.3
MEAN	32.4	14.6	24.6	31.9	13.2	23.9	24.1	159.9	102.2	25.3	25.1	77	76	195.6	197.6

NORM † = Average from 2003 to 2007.

APPENDIX B
PERCOLATE VOLUMES

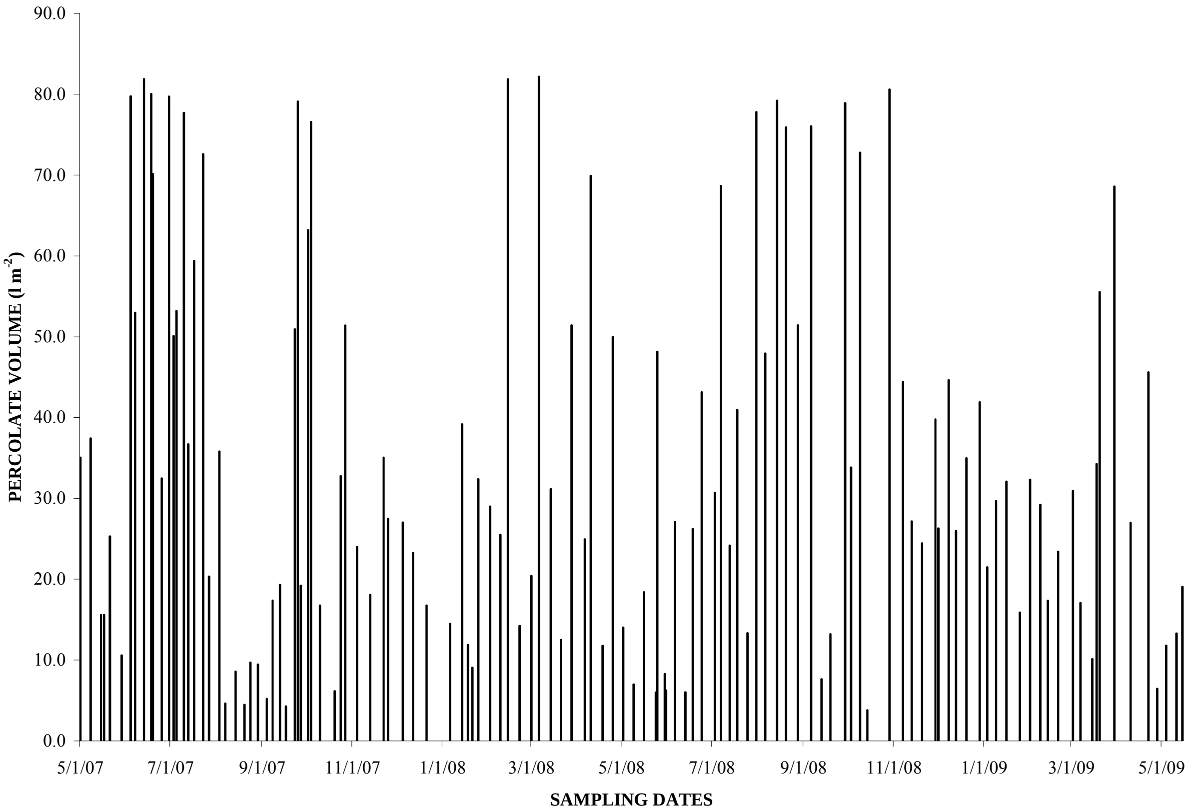

Fig. B-1. Percolate volumes averaged across each treatment collected over the 24-mo study period, indicating generally lower percolate during the DS (November 1 – May 1), although sporadic significant precipitation induced percolation was evident.

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BIOGRAPHICAL SKETCH

Neil G. M. Young is the son of Dr. Graham and Anne Young and was born and raised in Aberdeen, Scotland. Neil spent much of his youth on the golf links with his father, where he became interested in turfgrass and the environment. Neil worked on golf courses during school holidays from the age of 13 and pursued a career in turfgrass management the traditional way in Scotland, by conducting an apprenticeship in greenskeeping. Later, Neil received a Bachelor of Science degree in turfgrass science from the University of Central Lancashire, England in May 2005. He chose to travel and work internationally in the turfgrass industry for several years before deciding to attend graduate school. Neil joined the Soil and Water Department at the University of Florida and began his graduate studies investigating the environmental implications of turfgrass fertilization under the supervision of Dr. George H. Snyder in May 2007. He received his Master of Science degree from the University of Florida in the Fall of 2009.