RESPONSE OF COOL-SEASON TURFGRASS TO FOLIAR APPLIED AND STABILIZED NITROGEN FERTILIZERS

BY

SHELBY W. HENNING

DISSERTATION

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Doctoral Committee:

Professor Bruce E. Branham, Chair
Professor Donald P. Briskin
Professor Richard L. Mulvaney
Associate Professor Thomas B. Voigt

ABSTRACT

The objective of my work was to determine factors that affect uptake of N by cool-season turfgrasses. Experiments were conducted to determine the quantity of foliar-applied N that is absorbed by turfgrass leaves, ways to optimize the process, and whether other common management practices can affect foliar N uptake under field conditions. Studies were also carried out to determine if foliar-applied N results in greater N use efficiency than traditional soil-applied methods, as well to determine whether foliar-applied ammoniacal N sources lead to enhanced turf performance under energy stress. A further objective was to assess whether stabilized N fertilizers offered a benefit over unamended sources under field conditions. Experiments to address these objectives were carried out at the Landscape Horticulture Research Center in Urbana, IL. The results indicate that approximately 7-34% of foliar-applied N is absorbed by turfgrass within 4-6 h post application, that this uptake is not affected by common management practices, and that the main driver of foliar N uptake is spray volume, with lower spray volumes enhancing foliar uptake. Furthermore, foliar applications proved far superior to traditional soil-based applications of N fertilizer in terms of N use efficiency. No convincing evidence was obtained that foliar applications of ammoniacal N moderate energy stress when turfgrass is cultivated on a highly fertile native soil. Finally, stabilized N fertilizers were found to offer no benefit over unamended N sources to highly maintained turfgrass cultivated under field conditions.

To Jael, Levi, and Isaac, my beautiful children

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CHAPTER I

FACTORS AFFECTING FOLIAR NITROGEN UPTAKE BY CREEPING BENTGRASS

ABSTRACT

Turfgrass managers frequently apply N as a foliar spray when low application rates are desired. This practice is believed to promote N uptake that benefits turf, however, very little information is available concerning the quantity of N absorbed by turfgrass foliage or the effect of various spray parameters on foliar N uptake under field conditions. The study reported herein was conducted to evaluate fertilizer N uptake efficiency of ^{15}N foliarly applied to creeping bentgrass (*Agrostis stolonifera* var. L. *palustris* (Huds.) Farw. ‘Pennlinks’) under field conditions. The effects on the dynamics of foliar N uptake were investigated for spray volume, N-formulation, adjuvant addition, and tank-mixing with commonly applied turf care products. From 7 to 34% of foliar-applied N was taken up, largely within 4-6 h after fertilizer application. Uptake efficiency increased significantly when spray volume was decreased, but was unaffected by N-formulation, adjuvant addition, or tank-mixing.

INTRODUCTION

Foliar N fertilization, particularly with urea, is an increasingly common practice in the turfgrass industry. This trend is due in part to the high water solubility of N fertilizers and their compatibility with other commonly applied turf care products, but the main motivation arises from the capability to uniformly apply low doses of N to high-value areas of turf.

Tracer and non-tracer techniques have been employed to estimate fertilizer N absorption by turfgrass leaves. The tracer approach utilizes the stable isotope, ^{15}N, to directly quantify plant uptake of labeled fertilizer N. The non-tracer, or indirect, alternatives include the difference method and a washing technique. The difference method compares plant N concentration with and without fertilization, and ascribes any increase for the fertilized treatment to fertilizer N uptake. The washing technique quantifies N uptake as the difference between the amount of fertilizer applied and the amount recovered in a foliar rinse.

Indirect methods have been used in several studies to quantify foliar N uptake by turf. The earliest of these was reported by Wesely et al. (1985) for five cool-season turfgrasses maintained in a growth chamber. Their results, utilizing the difference method, showed 31 to 61% uptake in the first 72 h after application, depending on species and cultivar. In a subsequent field study, Wesely et al. (1988) found 49 to 59% uptake by the difference method, following repeated foliar N applications to Kentucky bluegrass (*Poa pratensis* L. cv. ‘Park’). More recently, Gaussoin et al. (2009) used a washing technique to measure uptake efficiencies of 70 to 98% for one warm-season and two cool-season turfgrasses in the first 10 h after foliar N fertilization.

In growth-chamber studies with four cool-season turfgrasses, Bowman and Paul (1989, 1990, 1992) estimated 35 to 55% uptake of foliar-applied ^{15}N over a 48- or 72-h period, and compared these estimates to the corresponding values obtained for fertilizer N uptake efficiency (FNUE) by the washing and difference methods. The washing method was found to significantly overestimate foliar uptake of urea N by Kentucky bluegrass and perennial ryegrass (*Lolium perenne* L.), but not for tall fescue (*Festuca arundinacea* Schreb.) or creeping bentgrass. The authors attributed these disparities to N loss via volatilization due to high urease levels present in turfgrass canopies or microclimate conditions favoring volatile loss caused by differences in canopy architecture. In further studies with the latter species, no differences were detected among the three methods for estimating foliar uptake of N applied as $(NH_4)_2SO_4$ or KNO_3, nor was there a difference in FNUE when perennial ryegrass was treated with foliar formulations involving urea, $(NH_4)_2SO_4$, or KNO_3 (Bowman and Paul, 1992).

More recently, foliar FNUE has been evaluated under field conditions, through time-course studies by Stiegler (2010) and Stiegler et al. (2011) with ^{15}N-fertilized creeping bentgrass (‘Penn A1’) and hybrid bermudagrass *Cynodon dactylon* (L.) Pers x C. *transvaalensis* Burtt Davey ‘Tifeagle’). The results obtained with creeping bentgrass showed a significant effect of N formulation on foliar FNUE, and a higher foliar FNUE 1-h post-treatment of 43% for urea or $(NH_4)_2SO_4$, as compared to 24% for KNO_3 (Stiegler, 2010). At the final 8-h sampling, FNUE was approximately 56% for urea and $(NH_4)_2SO_4$ but only 31% for KNO_3.

In conjunction with the aforementioned field study, Stiegler et al. (2011) examined the effects of N rate, time of sampling after application, and season on FNUE estimated for a foliar treatment of creeping bentgrass or hybrid bermudagrass putting greens with ^{15}N-labeled urea. Increasing the rate of foliar N application from 0.5 to 1.25 g N m^{-2} led to a 6% reduction in FNUE when averaged for both species over the course of the study, which was attributed to the higher N concentration causing more rapid spray droplet drying or slight epidermal cell damage at the cuticle. Foliar N uptake was maximized at approximately 50% FNUE for both species, but this occurred in only 4 h for bermudagrass, while 24 h was required with bentgrass. In a two-yr seasonality study, foliar FNUE was repeatedly estimated by conducting 24-h N uptake studies at approximately 30-d intervals from May to September. No consistent trends were established for relating FNUE to photosynthetically active radiation, leaf wetness, relative humidity, air temperature, or wind speed, presumably reflecting the complex nature of foliar N uptake and/or the limited number of environmental parameters selected for evaluation.

Although the dynamics of foliar N uptake by turfgrass have been investigated previously, very limited information is available on this topic from field studies using ^{15}N-labeled fertilizer, nor has a systematic evaluation been made to determine how FNUE is affected by common application practices such as varying spray volume, adjuvant addition, or tank-mixing. The work reported herein was designed to address these uncertainties in the most conclusive manner possible, by quantifying turfgrass recovery of ^{15}N applied by foliar fertilization under field conditions.

MATERIALS AND METHODS

The study site was located on a Drummer silty clay loam (fine-silty, mixed, superactive, mesic Typic Endoaquolls) under a 10-yr-old stand of creeping bentgrass (cv. ‘Pennlinks’) at the University of Illinois Landscape Horticulture Research Center at Urbana, IL. The turf was maintained at 1.3 cm height of cut and irrigated as needed to prevent moisture stress. Regular pesticide applications were made to control fungal diseases.

Four experiments were conducted altogether, each involving two repetitions using a randomized complete block design with four replications. Plots measuring 0.3 m^2 were treated as precisely as possible by applying N fertilizer treatments through a hole removed from the center of a 1-m^2 plywood sheet placed on the turf area. Unless otherwise specified, fertilizer N was applied in a single pass of the treatment area as urea (0.5 atom % ^{15}N) at a rate of 4.9 kg ha^{-1}, using a CO_2-pressurized backpack sprayer fitted with an even flat fan nozzle (2002EVS; TeeJet Technologies, Wheaton, IL) at 206 kPa and a spray volume of 374 L ha^{-1}.

To evaluate the effects of spray volume on foliar uptake of fertilizer N, two studies were initiated on 15 May 2009 and 19 May 2009. In each experiment, foliar N was applied to plots at 187, 374, 561, 748, or 935 L ha^{-1}. Calibration of spray volume was achieved by changing spray nozzles (187 L ha^{-1}, 2001EVS; 374 L ha^{-1}; 2002EVS; 561 L ha^{-1}, 2003EVS; 748 L ha^{-1}; 2004EVS; 2005EVS, 935 L $ha^{-1;}$ products of TeeJet Technologies, Wheaton, IL) and by walking in time with a digital metronome set to different beats per minute (BPM) (DM70, Seiko Consumer Products, Torrance, CA).

Two studies were conducted to determine the effect of N form on foliar uptake, the first being initiated on 22 May 2008 and the second on 31 May 2009. In each experiment, labeled N was applied as urea (1.2 atom % ^{15}N), $(NH_4)_2SO_4$ (0.9 atom % ^{15}N), or $Ca(NO_3)_2$ (0.9 atom % ^{15}N).

Studies were initiated on 16 July 2008 and 19 August 2008 to ascertain whether tank-mixing affects foliar uptake of urea. In both cases, urea (0.5% ^{15}N enrichment) was applied alone or in combination with the labeled rate of (i) chlorothalonil (Daconil Ultrex, Syngenta Crop Protection, Inc., Wilmington, DE); (ii) trinexapac-ethyl (Primo Maxx, Syngenta Crop Protection, Inc., Wilmington, DE); (iii) a biostimulant (Rennaisance, Floratine Products Group, Collierville, TN); and/or (iv) an indicator dye (Tracker, Lesco, Inc, Troy, MI).

To determine whether adjuvants enhance foliar N uptake, experiments were conducted on 23 June 2008 and 11 July 2008. In these experiments, urea enriched to 0.5 atom % ^{15}N was applied at 4.9 kg ha^{-1} alone or with the labeled rate of (i) a non-ionic surfactant (NIS) (X-77; Loveland Products, Loveland, CO), (ii) an organosilicone (Kinetic), (iii) methylated seed oil (MSO), or (iv) a crop oil concentrate (Agri-Dex) (ii-iv are products of Helena Chemical, Memphis, TN).

In all experiments, plots were sampled 2, 4, 6, and 8 h after ^{15}N application. Samples were obtained by collecting four 3.8-cm dia. cores from each plot with a sampling tool consisting of a 5-cm section of 3.8 cm dia. steel pipe fitted with a handle. So as to remove residual fertilizer not absorbed by the tissue, the foliage was washed by repeatedly submerging the cores in 7 L of water. Following this procedure, vegetative tissue was removed from the cores with scissors, composited to obtain a single clipping sample per plot, and dried for 24 h in a forced-air oven at 50°C. The clippings were then finely powdered (< 250 μm) in a Shatterbox 20 tissue grinder (SPEX SamplePrep, Metuchen, NJ), and total N analyses were performed by semimicro-Kjeldahl digestion following a pretreatment with $KMnO_4$ and reduced Fe for recovery of ($NO_3^- + NO_2^-$)-N (Bremner, 1996). The quantity of N in the digest was determined by acidimetric titration of NH_3 liberated upon diffusion with 10 *M* NaOH (Stevens et al., 2000), prior to processing for N-isotope analysis using an automated mass spectrometer (Mulvaney et al., 1990, 1997; Mulvaney and Liu, 1991).

Quantitative and ^{15}N data were utilized to calculate FNUE as $100R/A$, where R is the amount of labeled fertilizer N recovered and A is the amount applied. Fertilizer N recovery (R) was calculated as $Q_A(S_T/S_A)(M - B)/(F - B)$, where Q_A is the quantity of N measured for the sample under analysis, S_T is the total dry weight of sample collected, S_A is the dry weight of sample under analysis, M is the measured atom % ^{15}N, B is the background atom % ^{15}N determined for unlabeled plant material, and F is the atom % ^{15}N of the labeled fertilizer.

The MIXED procedure of SAS (SAS Institute, 2008) was used to detect treatment differences. The Type 3 test of fixed effects was performed to determine significance at $P < 0.05$, and significant effects were explored using the LSMEANS statement of the MIXED procedure. Separation of means was accomplished by Fisher's protected least significant difference (LSD) with no adjustment, using the PDMIX800 macro (Saxton, 1998) when appropriate.

RESULTS

Foliar uptake of urea N decreased significantly with increase in the volume of fertilizer solution applied (Table 1.1). Uptake ranged from 7.4 to 16.4% with the lowest spray volume, more than doubling what was achieved with the highest spray volume. Uptake was largely, if not entirely, complete within 4 to 6 h after fertilization. To simplify the remaining presentation, all data subsequently reported represent only a 6-h uptake period.

No significant difference in uptake efficiency was observed among the three fertilizer sources (Table 1.2). Cumulative foliar FNUE was 31% for urea, 34% for $(NH_4)_2SO_4$, and 32% for $Ca(NO_3)_2$.

The inclusion of an adjuvant with foliar-applied urea did not promote incorporation of fertilizer N into turfgrass foliage (Table 1.3). At no sampling time was there a significant increase in uptake due to the presence of any of the adjuvant classes included in the study. Foliar FNUE was 31% without adjuvant addition, 31% for NIS, 29% for MSO, and 28% for organosilicone and crop oil concentrate.

Foliar N uptake was unaffected by tank-mixing urea with four commonly applied turf care products (Table 1.4). No significant differences were detected in FNUE, even when all of the products were combined in a single tank mix. With or without the additives, foliar uptake of fertilizer N was on the order of 20%.

DISCUSSION

Under field conditions in the studies presented here, foliar uptake of fertilizer N by creeping bentgrass typically varied from 7 to 30% of the N applied. This range is lower than FNUE values for foliar-fertilized turfgrass previously reported as 31 to 61% by Wesely et al. (1985), 49 to 60% by Wesely et al. (1988), and 35 to 55% by Bowman and Paul (1989, 1990, 1992). The disparity can probably be linked to several factors. The most obvious applies to the studies by Wesely et al. (1985) and Bowman and Paul (1989, 1990, 1992), as growth occurred in a controlled environment rather than under the variable conditions typical of field research. Environmental conditions can greatly affect the uptake of exogenously applied materials into plant leaves and these effects are thought to be more extreme for water- soluble compounds, such as the fertilizers used in the present research (Ramsey et. al, 2005). The main environmental factors that affect foliar uptake are relative humidity and air temperature, with high levels of each generally optimal (Muzik, 1976; Schonherr, 1979; Tukey and Marczynski, 1984; Ramsey et al., 2005; Schonherr, 2005). Presumably, relative humidity would have been higher and temperature more evenly regulated in controlled environments than those experienced under field conditions. Likewise, spray droplet drying time may have been extended for turf grown in a controlled environment, on account of the high relative humidity that ranged from 80 to 95% in the aforementioned studies. Additionally, fertilizer N response would have been enhanced, either because turf was growing in sand culture that minimized root N uptake (Bowman and Paul, 1989, 1990, 1992) or because FNUE was estimated by the difference method (Wesely et al., 1985, 1988), which tends to give higher values than direct measurements using ^{15}N (e.g., Bowman and Paul, 1989, 1992; Torbert et al., 1992; Schindler and Knighton, 1999; Stiegler, 2010; Nannen et al., 2011).

Relative to previous studies, the lower FNUE observed in this project may also be partly explained by the use of a different turfgrass species but more likely, by a cutting height that was much more limited and therefore would have provided less leaf area for foliar uptake. In contrast to our findings, Stiegler et al. (2011) reported foliar FNUE values that averaged 51% for creeping bentgrass maintained at 3.1 mm height of cut when averaged over repeated (80 observations) studies, although some of their individual values were within the range of what was found in the present study.

Among the trials reported herein, uptake efficiencies were lowest in evaluating spray volume, presumably because this evaluation was performed earlier in the season than other experiments, when air (64 vs. 79-85ºC) and soil (64 vs. 78-82ºC at a 5-cm depth) temperatures were lower. Previous research has shown that foliar uptake of nutrients is enhanced by higher temperatures (Tukey and Marczynski, 1984), and also by the higher relative humidity (Tukey and Marczynski, 1984; Schonherr, 2005) that would have existed later in the growing season. Stiegler et al. (2011) reported foliar FNUE for creeping bentgrass to vary substantially with the season of application, but were unable to identify a specific cause for this inconsistency.

Foliar N uptake by creeping bentgrass was unaffected by applying $(NH_4)_2SO_4$ or $Ca(NO_3)_2$ instead of urea. This finding is consistent with the results of a similar comparison reported by Bowman and Paul (1992) for perennial ryegrass, where 30 to 35% FNUE was obtained with urea, $(NH_4)_2SO_4$, or KNO_3. In contrast, Stiegler (2010) found greater foliar uptake with ammoniacal sources of N than with NO_3^-, and attributed the difference to electrostatic interaction with negatively charged ectodesmata pores (Schonherr, 1976; Tyree et al., 1990). This mechanism cannot explain our findings or those of Bowman and Paul (1992).

Adjuvants are well known from numerous investigations to enhance the uptake of foliar-applied pesticides (e.g., Seaman, 1990; Kirkwood, 1993; Wang and Liu, 2007), but the present study provides no evidence of any positive effect when such amendments are applied with urea. A satisfactory explanation may be provided by the finding that foliar uptake of compounds into plant leaf tissue is inversely correlated with molecular weight and size (Bauer and Schonherr, 1992; Schonherr and Schreiber, 2004). These parameters would have been much lower for urea than for an organic pesticide, and lower still if hydrolysis occurred on the leaf surface, allowing N uptake in the form of NH_4^+. Under such conditions, cuticular transport may have been so rapid as to preclude any benefit from the presence of an adjuvant.

The same factors probably explain why foliar FNUE was unaffected by tank-mixing urea with commonly applied turf products. Due to their considerably greater molecular weight and size compared to urea, the turf-care products would have had very little, if any, effect on foliar N uptake through the cuticle.

To summarize, the work reported shows that foliar N uptake by creeping bentgrass is controlled by spray volume but not by fertilizer N formulation, the use of adjuvants, or tank-mixing with commonly applied turf-care chemicals. Lower spray volumes increase FNUE, presumably because leaf tissue is exposed to a higher deposition rate of fertilizer N. To maximize the efficiency of foliar N fertilization, the spray volume should not exceed 400 L ha^{-1}.

TABLES

Table 1.1. Effect of spray volume on fertilizer N uptake efficiency in the first 8 h after application of ^{15}N-labeled urea.

Spray Volume	Time after ^{15}N application† (h) 2	4	6	8
L ha^{-1}	FNUE‡ (%)			
187	13.2 ± 1.8 a	15.7 ± 4.8 a	18.2 ± 5.7 a	16.4 ± 2.7 a
374	12.1 ± 5.1 a	14.0 ± 4.7 ab	15.7 ± 6.4 ab	14.4 ± 5.3 ab
561	11.1 ± 4.4 a	11.5 ± 3.5 b	11.8 ± 5.4 bc	12.3 ± 2.7 ab
748	11.6 ± 2.6 a	11.8 ± 3.6 b	11.7 ± 2.3 bc	14.0 ± 1.9 b
935	6.2 ± 2.1 b	6.0 ± 3.0 c	7.0 ± 2.3 c	7.4 ± 1.6 c
LSD§	3.4	3.6	5.1	3.3

†Data reported as a mean of 2 experiments with four replications each ± one standard deviation. Values within a column followed by the same letter do not differ significantly ($P < 0.05$).

‡FNUE, fertilizer N uptake efficiency.

§LSD, least significant difference ($P < 0.05$).

Table 1.2. Effect of N formulation on fertilizer N uptake efficiency in the first 8 h after application of ^{15}N-labeled urea.

	Time after ^{15}N application† (h)			
N form	2	4	6	8
	FNUE‡ (%)			
$(NH_4)_2SO_4$	24.7 ± 8.0a	31.2 ± 7.7a	33.5 ± 8.3a	27.6 ± 8.5a
$Ca(NO_3)_2$	25.7 ± 5.8a	29.2 ± 7.0a	31.4 ± 8.7a	26.9 ± 7.1a
Urea	23.3 ± 4.9a	26.6 ± 3.4a	30.9 ± 5.0a	26.1 ± 4.6 a
LSD§	NS	NS	NS	NS

†Data reported as a mean of 2 experiments with four replications each ± one standard deviation. Values within a column followed by the same letter do not differ significantly ($P < 0.05$).

‡FNUE, fertilizer N uptake efficiency.

§LSD, least significant difference ($P < 0.05$).

Table 1.3. Effect of adjuvant addition on fertilizer N uptake efficiency in the first 8 h after application of ^{15}N-labeled urea.

	Time after ^{15}N application† (h)			
Adjuvant	2	4	6	8
	FNUE‡ (%)			
Crop-oil Concentrate	22.0 ± 3.8	24.1 ± 4.1	27.5 ± 6.1	25.0 ± 9.2
Organosilicone	15.2 ± 9.2	19.4 ± 5.0	27.9 ± 8.7	27.1 ± 6.8
Non-ionic surfactant	21.6 ± 7.8	21.9 ± 6.2	30.8 ± 11.6	25.6 ± 8.1
Methylated seed oil	18.3 ± 3.4	22.6 ± 5.8	28.5 ± 7.7	24.4 ± 7.8
Urea	23.1 ± 4.8	23.9 ± 5.7	31.4 ± 10.8	26.8 ± 5.7
Crop-oil Concentrate	22.0 ± 3.8	24.1 ± 4.1	27.5 ± 6.1	25.0 ± 9.2
LSD§	NS	NS	NS	NS

†Data reported as a mean of 2 experiments with four replications each ± one standard deviation. Values within a column followed by the same letter do not differ significantly (*P* < 0.05).

‡FNUE, fertilizer N uptake efficiency.

§LSD, least significant difference (*P* < 0.05).

Table 1.4. Effect of tank-mixing on fertilizer N uptake efficiency in the first 8 h after application of ^{15}N-labeled urea.

Chemical	Time after ^{15}N application† (h)			
	2	4	6	8
	FNUE‡ (%)			
Indicator dye	13.6 ± 5.6	19.5 ± 4.2	18.1 ± 4.1	14.3 ± 7.2
Biostimulant	17.0 ± 4.2	23.4 ± 7.1	18.5 ± 4.4	19.8 ± 6.8
Trinexapac-ethyl	14.1 ± 5.0	20.5 ± 5.9	17.8 ± 8.0	16.6 ± 7.2
Chlorothalonil	17.6 ± 2.3	22.3 ± 4.1	22.9 ± 5.4	15.6 ± 6.2
Urea	18.6 ± 4.5	26.2 ± 7.3	19.7 ± 4.2	18.8 ± 5.4
All the above	18.1 ± 4.8	23.3 ± 5.2	20.5 ± 4.2	22.8 ± 4.2
LSD§	NS	NS	NS	NS

†Data reported as a mean of 2 experiments with four replications each ± one standard deviation. Values within a column followed by the same letter do not differ significantly ($P < 0.05$).

‡FNUE, fertilizer N uptake efficiency.

§LSD, least significant difference ($P < 0.05$).

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CHAPTER II: EFFICIENCY OF FOLIAR- VERSUS GROUND-APPLIED ^{15}N-UREA FOR UPTAKE BY CREEPING BENTGRASS

ABSTRACT

Few comparative experiments have been published concerning the utilization of foliar- and soil-applied N by turfgrass. To better understand how the method of fertilizer application affects N uptake dynamics, recovery studies were conducted for creeping bentgrass (*Agrostis stolonifera* Huds.), following foliar or soil fertilization with 0, 4.9, or 9.8 kg N ha^{-1} as ^{15}N-labeled urea. Fertilizer N dose had no consistent effect on clipping production and did not affect total foliar N concentration in a biologically significant manner. Uptake efficiency was 64 to 99% higher for foliar- than for soil-applied N, which was attributed to less extensive microbial competition through immobilization. The implication is that foliar fertilization reduces the N rate needed to achieve the same growth response, relative to a traditional soil-based application.

INTRODUCTION

Fertilizer N inputs are necessary in providing optimal color, quality, and vigor to intensively managed turfgrasses such as golf course fairways, putting greens, and athletic turfs. Traditionally, these inputs are applied infrequently in medium to high N doses as granular fertilizer broadcast over the turf canopy and intended for root uptake. More recently, there has been a growing trend toward foliar N fertilization with fluid formulations, which offers several benefits over the conventional approach. A major advantage is that low N rates can be applied much more uniformly than is possible with granular products, thereby avoiding the undesirable speckling of turf that can appear with uneven spreading (Howieson and Christains, 2001). This capability allows N to be applied more frequently in low doses, which minimizes N losses and can improve turf quality by ameliorating stress from salinity or heat (Fu and Huang, 2003; Tabatabaei and Fakhrzad, 2008; Zhao et al., 2008). If desired, the need for multiple applications over the same area can be reduced by combining foliar fertilizer inputs with other turf care products, although N rates should be lower than with soil applications if significant turf injury is to be avoided (Spangenberg et al., 1986; Carrow et al., 1988; Gooding and Davies, 1992). In contrast, soil-based N applications can incorporate greater rates of N into the turf system than foliar methods, generally without ill effects (Beard, 1973).

In research utilizing ^{15}N for direct measurement of N uptake by turfgrass under controlled conditions, fertilizer N uptake efficiency (FNUE) for foliar applications has ranged from 31 to 61% (Wesely et al., 1985; Bowman and Paul, 1989, 1990, 1992), while the range in FNUE for field studies using ^{15}N has been from 7 to 56% (See Chapter 1, p.8; Joo et al., 1991; Stiegler, 2010; Stiegler et al., 2011). By comparison, ^{15}N uptake efficiencies for soil-based applications have ranged from 14 to 49% for controlled environments (Starret, 1994; Wherley et al., 2009), and from 38 to 78% under field conditions (Starr and DeRoo, 1981; Horgan et al., 1999; Picchionio and Quiroga-Garza, 1999).

While the aforementioned studies provide independent estimates of FNUE for foliar- and soil-based N applications, there has been little comparative research published investigating N uptake efficiency for foliar- versus traditional soil-based N applications over an extended period of turf growth. Only two relevant experiments have been published evaluating foliar versus granular N applications in turfgrass. Steinke and Stier (2003) evaluated the response of creeping bentgrass (*Agrostis stolonifera* L. 'Penncross'), Kentucky bluegrass (*Poa pratensis* L. '25% blend of 'NuGlade', 'Rugby II', 'Kelly' and 'NuBlue'), and supina bluegrass (*Poa supina* Schrad. 'Supranova') to repeated applications of foliar or granular urea (12 kg ha^{-1} applied at 14-d intervals) with or without a gibberellic acid inhibitor (trinexapac ethyl; ([4-(cyclopropyl-alpha-hydroxy-methylene)-3,5-dioxo-cyclohexane-carboxylic acid ethyl ester]; 0.05 kg a.i. ha^{-1} applied at 0-, 28-, and 56-d intervals) under reduced light conditions (80% shade) over 2 yr. In this study, creeping bentgrass responded more favorably to foliar- than to granular-applied urea in terms of visual quality, whereas N fertilization had no effect on turf density, divot recovery, root mass, chlorophyll content, photochemical efficiency, or leaf N content. Totten et al. (2008) directly compared foliar- and soil-based N fertilization in a 2-yr field study with creeping bentgrass that involved biweekly N applications at low dosage rates. Granular fertilization, followed by a combination of both approaches were found to the best option for producing acceptable turf quality, and required at least 190 kg

N ha^{-1} yr^{-1} in the transition zone of the USA. The method of N application significantly affected turf growth and total foliar N, but the effects varied according to N rate, experimental year, and season of turf evaluation.

Since little other turfgrass research exists regarding the merits of foliar- versus traditional soil-based N applications, the goal of this research was to determine whether either approach offers an advantage over the other, based on direct measurement of ^{15}N in field studies using labeled fertilizer. The parameters of interest included dry matter production, total N concentration, plant N derived from fertilizer (NDFF), and fertilizer N uptake efficiency (FNUE).

MATERIALS AND METHODS

Two experiments were conducted in 2009 and 2010 at the University of Illinois Landscape Horticulture Research Center in Urbana, IL. In both cases a creeping bentgrass cultivar (‘Backspin’ in 2009 and ‘Dominant’ in 2010) was maintained at a 1.3 cm height of cut on a Drummer silty clay loam soil (fine-silty, mixed, superactive, mesic Typic Endoaquolls). Table 1 characterizes several physicochemical properties of the soil. Analyses were performed (3 replicates) to determine pH (soil to water ratio, 1:1); CEC by the rapid diffusion method of Mulvaney et al. (2004); total N by semimicro-Kjeldahl digestion (Bremner, 1996)-diffusion (^{15}N Analysis Service, 2000) following a permanganate-reduced Fe pretreatment for recovery of $(NO_3^- + NO_2^-)$-N; organic C by the method of Mebius (1960) and potentially mineralizable N (PMN) by the Illinois soil N test (ISNT) originated by Khan et al. (2001), following the protocol specified in a technical note (^{15}N Analysis Service, 2004). The study site received regular irrigation and fungicide (chlorothalonil, 2,4,5,6-tetrachloroisophthalonitrile; propiconazole, 1-[[2-(2,4-dichlorophenyl)-4-propyl-1,3-dioxolan-2-yl]methyl]-1,2,4-triazole) applications to prevent moisture stress and control fungal diseases. No fertilizer application had been made for at least six mo. prior to either study.

The first experiment was initiated on 5 June 2009 utilizing a completely randomized design with five replications and plots measuring 1.2 by 3 m. Fertility treatments supplying 4.9 kg N ha^{-1} as urea enriched to 4.6 atom % ^{15}N were applied to the plots with a CO_2 pressurized (206 kPa) backpack sprayer fitted with flat fan nozzles (Teejet 2002VS; TeeJet Technologies, Wheaton, IL) calibrated to a spray volume of 187 L ha^{-1}. For plots receiving foliar applications, X77 non-ionic surfactant (NIS; Loveland Products, Greely, CO) was added at 2.5 ml L^{-1} to the spray mixture. Soil applications were made in the same manner but with no use of surfactant, and were followed immediately by incorporation through irrigation with a 2.5 cm dia. garden hose fitted with a soaker-nozzle. For comparison purposes, and to establish background ^{15}N concentration for the study site, each replication included a control that received 0 kg N ha^{-1}. Plots were mown daily for 28 d by making one pass through the center of the plot with a 56 cm wide walk-behind reel mower (Model 220A; John Deere, Moline, IL) fitted with a basket to collect clippings. The clippings were transferred to paper bags and then dried in a forced-air oven for 24 h at 50ºC. Prior to analysis, leaf material was finely powdered (< 250 µm) in a Shatterbox 20 tissue grinder (SPEX SamplePrep, Metuchen, NJ).

Experiment two was initiated on 14 September 2010 and followed the protocol adopted in 2009, except that there were six replications, the N dosage rate was 9.8 kg ha^{-1}, the NIS used for the foliar treatment was Activator 90 (Loveland Products, Greely, CO) at 2.5 ml L^{-1}, and mowing was done twice per week rather than daily.

Environmental conditions were monitored for the duration of each study. Data for precipitation, air and soil (10-cm depth) temperature, relative humidity, and solar radiation were obtained from the Illinois State Water Survey, Champaign, IL.

Total N analyses were performed on powdered leaf material as described previously for soil, followed by N-isotope analysis using an automated mass spectrometer that employs the Rittenberg process (Mulvaney et al., 1990, 1997; Mulvaney and Liu, 1991; Mulvaney et al. 1997). Fertilizer N uptake efficiency (FNUE) was calculated as $100R/A$, where R is the amount of labeled fertilizer N recovered in foliage and A is the amount applied. Fertilizer N recovery (R) was calculated as $Q_A(S_T/S_A)(M - B)/(F - B)$, where Q_A is the quantity of N measured for the sample under analysis, S_T is the total dry weight of sample collected, S_A is the dry weight of sample under analysis, M is the measured atom % ^{15}N, B is the background atom % ^{15}N determined for unlabeled plant material, and F is the atom % ^{15}N of the labeled fertilizer. Percentage recovery of labeled N in the soil was calculated in the same manner, using the appropriate sample weights and a background value for atom % ^{15}N (B) determined by total N analysis of unlabeled soil. Plant or soil N derived from fertilizer (NDFF) was calculated as $100R/T$, where R is labeled N recovery in the plant material under analysis and T is the corresponding total N content.

Treatment differences were evaluated by the MIXED procedure of SAS (SAS Institute, 2008) using repeated measures for model development. The Type 3 test of fixed effects was used to determine significance at $P < 0.05$, and polynomial contrast statements for mean separation of significant treatment responses. To allow a uniform presentation with the same sampling strategy in both experiments, statistical analysis was performed after appropriately combining data collected by daily sampling in experiment one.

RESULTS

Environmental conditions differed between experiments one and two (Fig. 2.1). Air and soil temperatures and solar radiation were higher and increased over time for experiment one, whereas a temporal decline occurred in these parameters for experiment two. Precipitation was also greater for the duration of experiment one than for experiment two, while relative humidity was similar for both experiments.

Clipping yields followed a declining trend in both experiments but showed no consistent effect of foliar- or ground-applied N (Fig. 2.2). In experiment one, there was no significant clipping response to N fertilization. Plot-average clipping yield was highest at the beginning of the trial (8.1-9.8 g) and gradually declined to approximately 0.8 g by 28 days after treatment (DAT), totaling 24.2 g for the control plots, 24.8 g with foliar fertilization, and 26.3 g for the ground-applied treatment. Significant differences did occur in clipping yields from experiment two, but they were not consistent and in some cases more clipping material was collected from the control plots than with either fertilized treatment. In this experiment, plot-average clipping yields increased from approximately 13 g for the first mowing to a maximum of 23 g at 7 DAT, and then declined to < 1 g at the conclusion of the study period. Total offtake per plot averaged

64.4 g for the control treatment, 68.9 g with foliar fertilization, and 62.5 g with ground-applied N.

Leaf N concentrations were considerably lower in experiment one than in experiment two and followed different trends (Fig. 2.3). A significant increase due to fertilization was observed for the first three sampling times in experiment one, but this subsequently disappeared and was never observed in experiment two. No advantage was found for foliar fertilization, relative to the ground-applied treatment.

In both experiments, tissue NDFF was significantly higher for foliar- than ground-applied N (Fig. 2.4). For experiment one, this difference first occurred at 3 DAT when foliar fertilization more than doubled the 2% NDFF obtained for the ground-applied treatment. A similar advantage likewise appeared between 14 and 28 DAT, during which there was a decrease from 7 to 3% NDFF for the foliar application. For experiment two, NDFF was always significantly higher with foliar- than ground-applied N. In both cases, uptake of fertilizer N was maximized at 7 DAT, and then gradually declined throughout the remainder of the study period.

Foliar fertilization significantly increased FNUE in both experiments (Fig. 2.5). In experiment one, recovery of foliar-applied N was maximized 3 DAT at approximately 9.5% FNUE, decreased markedly to 1.7% FNUE at 10 DAT, and subsequent increased to 3.4% FNUE at 14 DAT followed by a decline to 2.8% FNUE at 14-21 DAT and then to 0.8% FNUE at 24-28 DAT. In contrast, the highest FNUE for ground-applied N was 4.8% that occurred in 7 DAT, which decreased to between 1.3 and 1.5% in 10-14 DAT, and then more gradually to 0.3% at the conclusion of the study. The cumulative effect of foliar fertilization was to nearly double the uptake of fertilizer N, from 15 to 29% FNUE.

In experiment two, fertilizer N recovery was increased by foliar application from 5 to 9% 7 DAT, and then gradually declined during the remainder of the experiment. When evaluated over the entire study period, FNUE totaled 23% with foliar-applied N, as compared to 14% for the ground-applied treatment.

DISCUSSION

The major finding from this research is that foliar fertilization substantially increased the efficiency of fertilizer N uptake by turfgrass, by 64 to 99% relative to the conventional practice of broadcast placement on the ground. The implication is that fertilizer N rates can be reduced without sacrificing turf growth or quality.

Response of turfgrass to foliar- and ground-applied N in terms of clipping yield was variable, and for most sampling dates neither method of N placement affected clipping yield. The larger clipping yield for experiment two relative to experiment one was likely due to a higher N dosage rate as well as a less frequent mowing schedule. Regardless, the general trend for both experiments was that clipping yield decreased following fertilizer application. For experiment one, this trend reflects the general physiological response of bentgrass in reducing clipping yield during periods of high temperature, as well as the increased stress of daily mowings, which replaced the 3- to 4-d mowing intervals that existed for regular plot maintenance prior to initiation of the trial. The reduction in clipping yield over the course of experiment two was likely due to declining air and soil temperatures during the latter part of the growing season.

A major objective of the work reported was to determine whether foliar N application is more efficient in supplying N to turfgrass, as opposed to ground-applied fertilization. This is exactly what was observed in both experiments, as FNUE was increased by 64 to 99%. These increases can likely be attributed to the effectiveness of foliar placement for circumventing N immobilization in the soil, since soil microbes preferentially assimilate ammoniacal N (e.g., Jansson et al., 1955; Jansson et al., 1958; Azam et al., 1993). In terms of FNUE, the lower N dosage rate of 4.9 kg N ha^{-1} used in experiment two was much more efficient overall than the 9.8 kg ha^{-1} N for foliar N application. As for clipping production, these differences in FNUE may be related to the physiological response of the turf to climactic conditions. For example, experiment one was initiated during the height of summer when temperatures were well above what is considered optimal for creeping bentgrass, while experiment two was initiated in early September when temperatures are declining and bentgrass responds with a reduced growth rate prior to entering quiesence. This explanation is consistent with reports that higher temperatures or humidities enhance foliar uptake for some nutrients (Tukey and Marczynski, 1984; Schonherr, 2005); however, a different interpretation emerges from a recent 2-yr field study by Stiegler et al. (2011), because temporal variations in the uptake of urea ^{15}N were unrelated to the date of application or any of the environmental parameters studied.

The present finding that FNUE was decreased by a higher foliar N rate is fully consistent with the common observation that plant growth is most responsive to the lowest rate of an applied nutrient. In noting this trend for foliar N uptake, Stiegler et al. (2011) cited two factors that could potentially reduce the efficiency of higher N rates: (1) saturation of channels available for N entry into the leaf, and (2) partial blockage of entry channels by foliar salt damage. Interestingly, the FNUE of soil applications was quite similar at 14-15% for both experiments in our work, despite the fact that different plot areas were utilized so as to avoid confounding by a previous ^{15}N application. This similarity was unexpected, since the experiments were not conducted concurrently.

A common practice by turfgrass professionals is to apply low doses of N, such as those used here, at approximately weekly intervals to highly maintained turfgrasses. Regarding FNUE, the present study shows that the primary benefit of foliar N application occurred in the first 3-7 d after application. The implication is that frequent foliar N applications at low doses are optimal for increasing FNUE; however, a subsequent increase in FNUE was noted in experiment one, 14-21 d after fertilization. The latter is presumed to be an anomaly caused by the drift of unlabeled N applied to adjacent plots 8 d after initiation of the labeled study, which could have stimulated mineralization of immobilized ^{15}N.

Although overall FNUE was enhanced by foliar N application, NDFF values did not exceed 10%, demonstrating unequivocally the dominance of mineralization over fertilization in supplying N for plant uptake. This finding was not unexpected, as the turf was growing on a highly fertile Mollisol with ample N-supplying capacity indicative of the estimate of PMN obtained from the ISNT for the study site. The result was extensive dilution of labeled fertilizer N by unlabeled soil N, which would have increased progressively with time as fertilizer N was consumed through clipping removal, immobilization, or loss, in contrast to the ongoing mineralization of soil N.

Considering that the soil at the study site was naturally high in fertility and showed very limited clipping response to N fertilization, there was little reason to expect an appreciable fertilizer effect on total N concentrations in the clipping material. Very little effect was indeed observed, as fertilization increased plant N concentration by 0.5% at most in either experiment. This finding is consistent with previous work by Steinke and Stier (2003), which showed no gain in total N when creeping bentgrass received multiple applications of foliar- or surface-applied urea at 12 kg N ha^{-1} cultivated on a Troxel silt loam (fine-silty, mixed, superactive, mesic, Pachic Argiudolls). Frequent low-dosage foliar N applications should be more effective for managing turfgrass on a coarse-textured soil of low N supplying power, such as a high-sand growing medium typical of many putting greens.

In summary, the work reported demonstrates that foliar application of N is considerably more efficient than a traditional ground-based approach. In order to maximize the benefit of foliar N fertilization, turfgrass managers should keep application rates low (~4.9 kg N ha^{-1}), increase the frequency of N application to every 7-14 d, and delay irrigation for at least 4-6 h after application. Properly implemented, foliar N nutrition reduces the application rate needed to achieve the same results as traditional soil-based fertilization regimes, but as with any fertilizer practice, native soil fertility ultimately determines the need for fertilization and the benefits that can be achieved. Foliar fertilization is likely to be more beneficial when turfgrass is being grown on soils with low N supplying power than under high levels of native fertility; however, such soils may also require a higher N rate by ground applications in order to sustain sufficient growth over an entire growing season.

TABLE

Table 2.1. Selected properties of the surface 30 cm soil at the experimental site.

Property	Value
pH	6.8
CEC† (cmol kg^{-1})	18.8
Total N (g kg^{-1})	1.5
Organic C (g kg^{-1})	22.8
C:N	16:1
PMN (mg kg^{-1})‡	285.4

†CEC, cation-exchange capacity
‡PMN, potentially mineralizable N

FIGURES

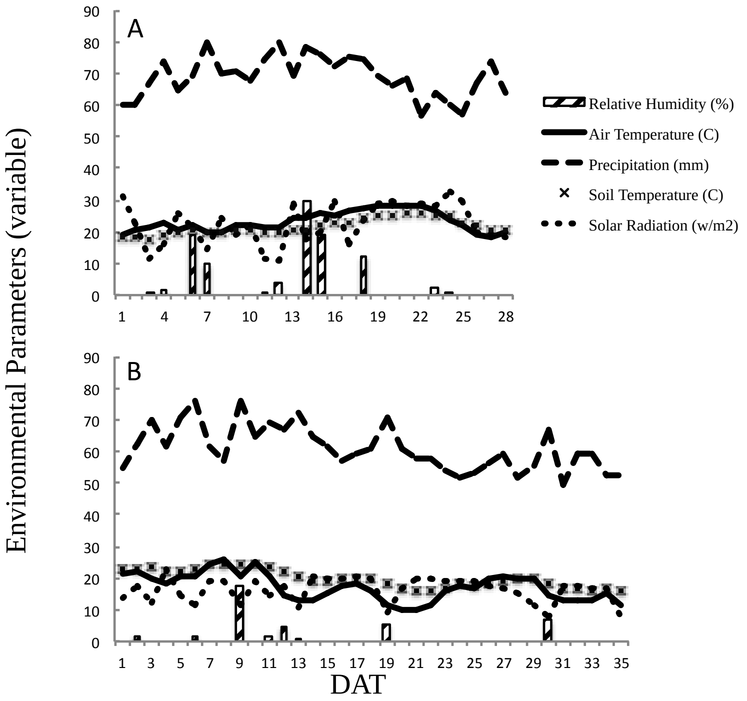

Fig. 2.1. Selected environmental conditions for experiment 1 [A] and experiment 2 [B].

Data shown are the mean daily value for each parameter.

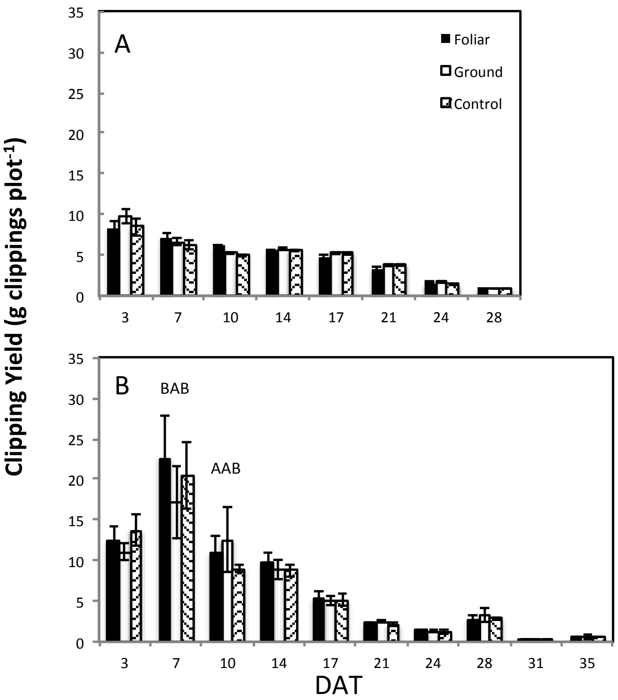

Fig. 2.2. Clipping yield with and without foliar or ground application of fertilizer, as measured on different days after treatment (DAT). Data reported as the mean of five replications in experiment 1 [A] or of six replications in experiment 2 [B]. For sampling dates with letter groupings, treatments sharing the same letter do not differ significantly ($P < 0.05$). Error bars indicate one standard deviation of the mean.

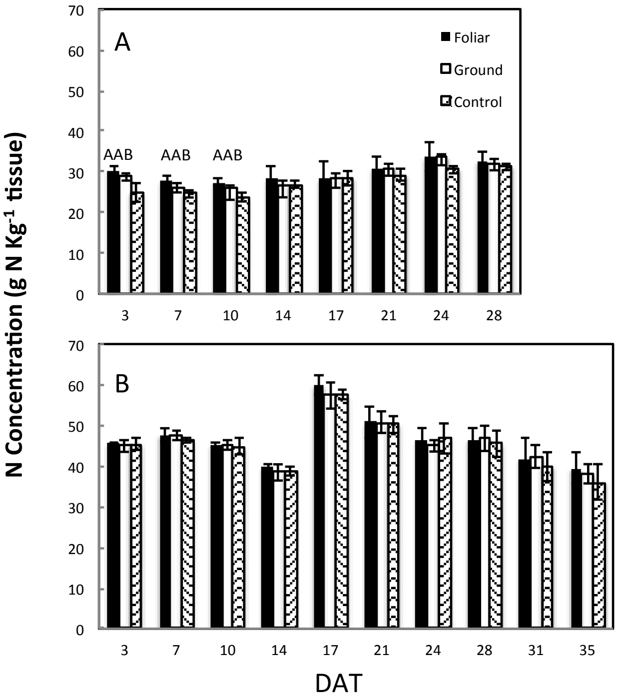

Fig. 2.3. Foliar N concentration with and without foliar or ground application of fertilizer, as measured on different days after treatment (DAT). Data reported as the mean of five replications in experiment 1 [A] or of six replications in experiment 2 [B]. For sampling dates with letter groupings, treatments sharing the same letter do not differ significantly (*P* < 0.05). Error bars indicate one standard deviation of the mean.

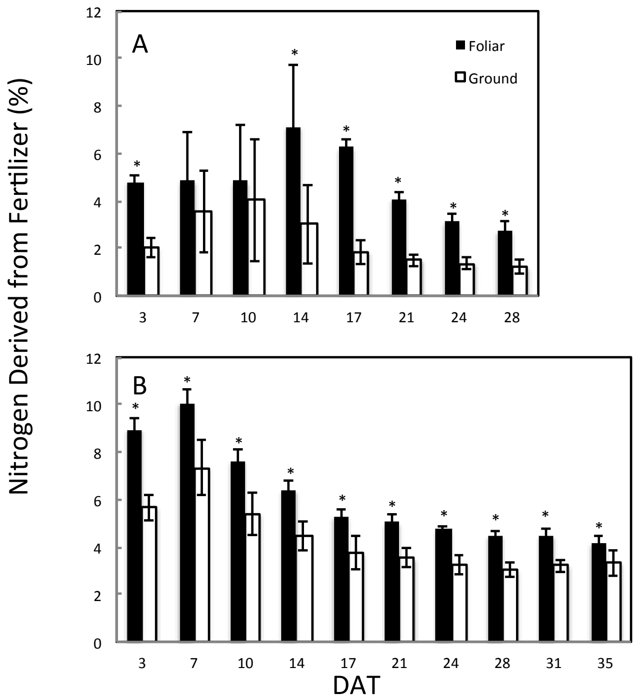

Fig. 2.4. Percent N derived from fertilizer in the vegetative tissue of turfgrass, as measured on different days after treatment (DAT) with foliar- or ground-applied N. Data reported as the mean of five replications in experiment 1 [A] or of six replications in experiment 2 [B]. Treatments indicated with a '*' are significantly different ($P < 0.05$). Error bars indicate one standard deviation of the mean.

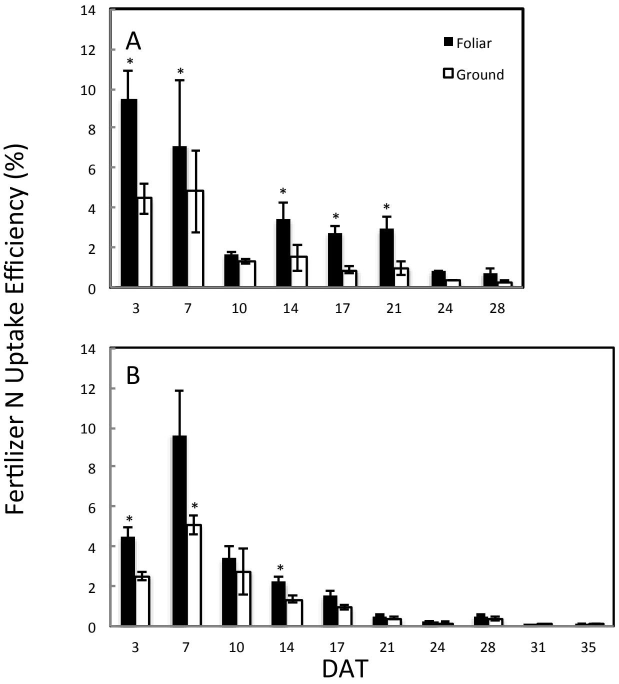

Fig. 2.5. Percentage recovery of fertilizer N in turfgrass leaf material, as measured on different days after treatment (DAT) with foliar- or ground-applied N. Data reported as the mean of five replications in experiment 1 [A] or of six replications in experiment 2 [B]. Treatments indicated with a '*' are significantly different ($P < 0.05$). Error bars indicate one standard deviation of the mean.

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CHAPTER III

OPTIMIZING FOLIAR NITROGEN NUTRITION TO IMPROVE TURF PERFORMANCE UNDER ENERGY STRESS

ABSTRACT

Foliar absorption and incorporation of ammoniacal (NH_4^+) N into turfgrass leaf tissue could provide significant energy savings to turfgrass under shade or mowing stress and potentially improve fertilizer N uptake efficiency (FNUE). A two-yr field study was undertaken to determine the benefit of foliar-applied NH_4^+ over NO_3^- or NH_4^+ fertilizer applied as a foliar spray or to the soil. Stress was imposed to the turf by decreasing cutting height from 3.2 to 2.8 or 2.4 mm. Fertility treatments consisted of repeated doses of 4.9 kg N ha^{-1} at 7-d intervals in the form of urea or $Ca(NO_3)_2$. No consistent benefit was observed for foliar-applied NH_4^+ over ground-applied NO_3^- or NH_4^+ in terms of turfgrass clipping yield, color, or quality. The lack of consistent turf response to foliar NH_4^+-N was attributed to the use of a highly fertile native soil as the study site, which diluted any positive effect that may have been provided by foliar NH_4^+-N nutrition.

INTRODUCTION

Nitrogen is the nutrient most frequently applied and most abundantly used to increase turfgrass growth rate, vigor, and visual color and quality. The many impacts on plant growth and development are well known, but one aspect of N metabolism deserves attention as a possible means to improve turf quality under suboptimal conditions that cause energy stress, such as shade or low cutting heights. Under such conditions, photosynthesis may not generate sufficient energy to achieve optimum growth and physiological functioning. Increasing the plant's energy status, by either enhancing photosynthetic production of reduced C compounds or decreasing the demand for photosynthate, will increase net plant productivity.

Plant roots primarily assimilate N as NO_3^- and then must expend energy in reducing NO_3^- to NH_4^+ for incorporation into amino acids, proteins, nucleic acids, and other N-containing compounds. The reductive process occurs in two steps, consuming eight electrons derived from photosynthetic energy. The first step requires two electrons donated by NAD(P)H and is catalyzed by the enzyme, NO_3^- reductase (Evans and Nason, 1954; Solomonson and Barber, 1990; Campbell, 1999). The second step uses six electrons carried by ferredoxin, which is formed during the light reactions of photosynthesis, to reduce NO_2^- to NH_4^+ via the enzyme NO_2^- reductase (Joy and Hageman, 1966). These reductions are estimated to consume up to 25% of the plant's photosynthetic energy (Solomonson and Barber, 1990), suggesting considerable potential for increased growth if plant N uptake occurs partly in the form of NH_4^+.

Nitrogen acquisition by plants, primarily involving root absorption of NO_3^-, is a complex process that is inherently linked to microbial N transformations in soil, particularly mineralization, immobilization, and nitrification. Mineralization, also known as ammonification, is the microbial conversion of organic N to inorganic (mineral) NH_4^+, mainly involving aerobic heterotrophs that require organic C as a source of energy. Their activities are stimulated by the input of fresh residues, and also benefit from adequate but not excessive soil moisture, warm temperatures (40-60°C is optimal), good aeration, and the absence of soil acidity. This same group of microbes is responsible for immobilization, which has the opposite effect of mineralization as inorganic N is incorporated into microbial biomass. The marked preference for immobilization of NH_4^+ over NO_3^- (e.g., Jansson et al., 1955; Jansson, 1958; Azam et al., 1993) arises from the same difference that motivated the present study, namely, a lower energy requirement for N assimilation. The supply of organic C is critical to both mineralization and immobilization because of their need for a heterotrophic energy source, and indirectly regulates NH_4^+ availability for nitrification, the chemoautotrophic oxidation of NH_4^+ to NO_2^- by *Nitrosomonas* spp. and of NO_2^- to NO_3^- by *Nitrobacter* spp. In tandem, these bacteria have an important ecological effect on plant N availability, which inherently benefits from lower heterotrophic competition for NO_3^- as opposed to NH_4^+.

One approach to minimizing the plant's energy use for NO_3^- reduction is to provide NH_4^+ through the foliage, which would have the important advantage of controlling microbial competition for fertilizer N uptake. This strategy has not been seriously evaluated, but there are indications that it could be successful. For example, a Wisconsin study by Steinke and Stier (2003) demonstrated that foliar applications of urea can improve the performance of creeping bentgrass (*Agrostis stolonifera* L.) under shade. Bowman and Paul (1989, 1990, 1992) examined the foliar uptake of urea, $(NH_4)_2SO_4$, and KNO_3 in several turfgrass species. They found that between 35 and 40% of the N applied was absorbed by grass leaf tissue. This is in line with data from other researchers who found 30-34% uptake of urea N applied to maize (*Zea mays* L.) (Below et al., 1985) and 44-69% uptake by soybean (*Glycine max* L. Merr.) (Vasilas et al., 1980). Wesely et al. (1985) reported 31-61% uptake by eight turfgrass species fertilized with urea.

There is good reason to expect that foliar feeding of ammoniacal N could increase FNUE by turfgrass, because this form of N is readily immobilized in the presence of carbonaceous inputs. A lower N rate would suffice if microbial competition were limited by foliar placement, and would have the further advantage of decreasing the potential for excessive NO_3^- production that promotes N loss through leaching and/or denitrification.

The work reported herein was undertaken to ascertain the benefits, if any, of foliar N fertilization for improving turf performance under energy stress, as well as FNUE. To ensure meaningful findings, replicated N response trials were conducted in the field, and different levels of turf stress were achieved by utilizing mowing height as a treatment variable.

MATERIALS AND METHODS

The study was conducted at the University of Illinois Landscape Horticulture Research Center at Urbana, IL, from 16 August to 23 October 2008, and then again from 19 June to 6 August 2009. In both cases, a randomized complete block design was utilized with four replications and plots measuring 1.2 by 5.5 m, which were maintained under creeping bentgrass (*Agrostis stolonifera* Huds. cv. ‘A-4’) on a Drummer silty clay loam (fine-silty, mixed, superactive, mesic Typic Endoaquolls) with regular irrigation and fungicide applications. Prior to initiating the study, an application of granular urea supplying 49 kg N ha^{-1} was made to the plot area in early May 2008, and the site was topdressed with sand (Waupaca Sand Solutions, Waupaca, WI) twice per week. No further supplemental fertilization or topdressing was employed throughout the course of the study. Stress treatments were applied by maintaining the turf at a 3.2, 2.8, or 2.4 mm height of cut. Fertility treatments involved the application at 7-d intervals of 4.9 kg N ha^{-1} as either urea or $Ca(NO_3)_2$, using a CO_2-pressurized (206 kPa) backpack sprayer fitted with a XR2002 VS nozzle (TeeJet, Technologies, Wheaton, IL) and a spray volume of 375 L ha^{-1}. For foliar applications, X77 non-ionic surfactant (NIS; Loveland Products, Greely, CO) was added to the spray mixture at 0.25% (v/v). The surfactant was omitted from ground-applied treatments, and the application was immediately followed by irrigation using a 2.54 cm diameter garden hose fitted with a soaker-nozzle. For comparison purposes, control plots were included that received no supplemental N over the experimental period.

Leaf tissue was collected weekly by making one pass down the center of the plot with a walk-behind reel mower (Jacobsen E-Walk 62290, Charlotte, NC). The resulting clippings were transferred to a paper bag and placed in a forced-air oven at 40°C for 24 h prior to weighing. For statistical analysis, clipping values were composited and reported on a monthly basis.

Turfgrass color and quality ratings were recorded every 7 d following treatment application, and were based on a scale of 1-9, with 9 as optimum and 1 as very poor. The minimum acceptable rating for either parameter was 6.0.

Treatment differences were detected by the MIXED procedure of SAS (SAS Institute, 2008), using models developed with repeated measures when appropriate. Significance was determined by the Type 3 test of fixed effects, and significant effects were explored with the LSMEANS statement of the MIXED procedure. Mean separations were carried out at $P < 0.05$ using polynomial contrast statements. Since sampling was done in different months during 2008 and 2009, the two years were analyzed separately for each parameter evaluated.

RESULTS

In 2008, clipping production of creeping bentgrass was affected by mowing height, sampling time, and their interaction (Table 3.1). The significant interaction occurred in September, when clipping production was nearly doubled by increasing the height of cut from 2.8 (49.5 g plot^{-1}) to 3.2 mm (98.5 g plot^{-1}), whereas the yield was intermediate with a 2.4 mm cutting height (71.4 g plot^{-1}). In 2009, the main effects of N form, mowing height, and sampling time on clipping production were all significant (Table 3.1). There was also a significant two-way interaction between N formulation and mowing height that occurred in both the June and July sampling periods. In each of these sampling times, the foliar and granular urea treatments consistently increased clipping production (Table 3.1). With the exception of granular $Ca(NO_3)_2$ in June, clipping yields per plot were lower for all other treatments (Table 3.1). During 2009, when significant differences were detected in N form and in the interaction of placement by time, the foliar $Ca(NO_3)_2$ treatment and the control consistently produced lower clipping yields as compared to the other treatments.

In 2008, turfgrass color was affected by N form and placement as well as time of sampling (Table 3.2). The interaction of N form and placement was significant, as was the interaction of time of sampling with either mowing height or N form and placement (Table 3.2). For the interaction of N form and placement by time, differences were found only in October with all fertility treatments providing a significant color response over the control. The interaction of mowing height and time was significant for the months of September and October. During the September sampling period, turfgrass color was superior with either of the two lower cutting heights (2.4 or 2.8 mm), whereas in October this advantage was apparent only for the lowest cutting height (2.4 mm).

Results in 2009 were similar, except that the main effect of mowing height was also significant. Differences in turfgrass color occurred only in June (Table 3.2), when the interaction of N form and placement with sampling time was significant. Turf color was improved by increasing the height of cut and was better with granular than with foliar urea, while all other fertility treatments showed a further reduction of similar magnitude. For the remainder of the 2009 sampling period, no differences were detected in color response.

Significant treatment effects on turfgrass quality occurred only in 2009 (Table 3.3). Analysis of variance indicated that the main effects of N form and placement, mowing height, and time of sampling were all significant. The only significant interaction was between mowing height and sampling time. This interaction was similar for every sampling period, such that turfgrass quality declined with decreasing height of cut.

DISCUSSION

If foliar NH_4^+ nutrition is effective for increasing the efficiency of plant bioenergetics, then some improvement in dry matter production, color, and quality should have occurred when turf was stressed by lower mowing heights. Clipping yields in 2008 were unaffected by foliar feeding with NH_4^+, while in 2009, there were only two occasions where fertility treatments differed in regard to clipping production, and only one time when ammoniacal N forms provided a benefit over NO_3^--N fertilization. Contrary to our hypothesis, foliar fertilization was of no value for increasing turf growth. In fact, the opposite effect occurred in the two cases noted previously, as clipping yield was greater with ground-applied urea than with the foliar treatment. Daily mowing may have contributed to this difference, if root uptake was more effective for prolonging the presence of fertilizer N in the plant. Growth was slowest with the foliar NO_3^- treatment, perhaps reflecting a lower absorption rate compared to NH_4^+-N (Stiegler et al., 2011), although this view is inconsistent with evidence reported in chapter 1 and by Bowman and Paul (1992).

Mowing height was found to affect clipping yield in both years of the study. In 2008, differences occurred once, as clipping height was nearly doubled by increasing cutting height from 2.8 to 3.2 mm, while the lowest cutting height (2.4 mm) was intermediate in clipping yield. During 2009, the 2.4 and 2.8 mm cutting heights yielded more clippings than did the 3.2 mm height, but the difference was not always significant. The latter finding may reflect a shift in photosynthetic allocation toward increased shoot growth with very low heights of cut. There is, moreover, a likelihood that leaf weight measurements were affected by recurring deposition of earthworm cast material, which along with the previously applied topdressing sand was unavoidably harvested during clipping collection. Considerable care was taken to remove as much of this material as possible during sample weighing, but some contamination was unavoidable, and this would have been most extensive with the 2.4 mm height of cut, introducing a positive bias that may have led to overestimation of clipping production.

Throughout the course of the study, color response followed a similar trend to what was observed for clipping production. During the first year of the experiment, the only significant response to N form and placement appeared in October, when turf color was better for all fertility treatments than for the control plots. A different trend was noted during the first rating month in 2009, in that urea-N produced superior turf color compared to the NO_3^--N treatments or the control, which were equal. The effect of mowing height on color ratings differed between the two years of the study. Whenever differences were detected in 2008, the lowest cutting height produced the highest color rating. In contrast, these two parameters were positively related during the June 2009 sampling period, but this relationship was more apparent than real, reflecting the presence of more leaf material with the 3.2 mm height of cut. The absence of any topdressing may also have contributed to color response in the second year of the trial.

Differences in turf quality were limited to 2009, and were mainly linked to the interaction of mowing height and time: as mowing height decreased, so did quality. This finding parallels what was found for turf color, suggesting a common cause. The most likely factor is the frequent topdressing with sand that preceded initiation of the study, as considerable care was taken to prepare the site for extremely low heights of cut. Unfortunately, topdressing could not be continued throughout the course of the study because some of the sand is invariably removed during mowing, which necessarily dulls mower reels. Sharpening requires a specialized process not available on campus, and so would have interrupted the mowing schedule, vitiating the study. An absence of topdressing no doubt contributed to the decline in turf quality observed with the two lowest cutting heights in the second year of the study.

In general, fertilizer formulation and placement had a limited effect on turf growth, color, or quality. This finding attests to the inherently high N-supplying power of the Mollisol at the study site, which would have minimized any response to the energy stress imposed by low mowing heights. A beneficial turf response to foliar feeding NH_4^+ would be more likely with a less fertile soil. Even so, the benefits of ammoniacal fertilization may be limited if the energy requirement for NO_3^- reduction is less than the expected 25% of photosynthate production. Model-based estimates for perennial ryegrass (*Lolium perenne* L.) indicate that this process accounts at most for 8% of the plant’s photosynthetic energy output (Middleton and Smith, 1979). Creeping bentgrass cultivars have been shown to differ in their efficiencies of NO_3^- uptake and metabolism (Bushoven et al., 2002), a factor that may further affect energy requirements for NO_3^- reduction.

The present study is most directly comparable to a 2-yr field experiment conducted by Totten et al. (2008), which involved biweekly fertilization of creeping bentgrass grown on an artificial medium (sand:peat moss = 85:15) using foliar and/or granular N applications at an annual rate of either 127 or 190 kg ha^{-1}. Significant increases were sometimes observed in turfgrass quality but not in clipping yield. When these occurred at the lower N rate, which is more relevant to our work, higher turf quality was obtained by foliar or foliar plus granular fertilization, as compared to granular fertilization alone. At the higher N rate and for every sampling date, foliar applications were more effective for improving turf quality, than either granular fertilization or the combination approach. Not surprisingly, foliar N concentration followed fertilizer rate when significant differences existed.

Foliar application of NH_4^+ fertilizer has the potential to enhance turf performance by providing an energy saving benefit to turf. In our study, when differences were detected for N form and placement, ammoniacal N generally provided a benefit over NO_3^--N fertilization in terms of clipping production and turf color. However, the lack of a consistent overall response to foliar NH_4^+ fertilizer reported in this research was likely due to the highly fertile native soil at the study site, which diluted any positive effect that may have been provided by foliar NH_4^+-N nutrition. Therefore, to realize any possible benefit of foliar NH_4^+ on turf performance in the present research, an increase would have been necessary in fertilizer N rate or application frequency. Our results suggest that foliar-applied NH_4^+ can offer a benefit to turf managers, but further investigations should be undertaken to determine what factors can make foliar application of ammoniacal N fertilizer a viable method for enhancing turf performance under field conditions.

TABLES

Table 3.1. Analysis of variance testing the main effects and their interactions on clipping yield of creeping bentgrass

		2008			2009	
N form and placement	August	September	October	June	July	August
Calcium nitrate foliar	16.7[†]a[††]	76.5a	26.5a	9.7b	14.4c	5.1
Calcium nitrate granular	16.3a	76.1a	26.4a	16.1a	18.1b	6.5
Urea foliar	16.8a	74.1a	25.2a	13.8a	18.1b	6.1
Urea granular	16.0a	72.9a	25.8a	15.6a	19.3a	6.1
Control	17.9a	66.1a	22.1a	11.0b	14.7c	6.1
P	NS	NS	NS	***	***	NS
Mowing height (mm)						
3.2	19.5a	98.5a	28.9	11.3c	16.3	5.0b
2.8	13.8a	49.5c	20.12	14.9a	17.4	5.4b
2.4	16.9a	71.4b	26.53	13.5b	17.1	7.6a
P	NS	***	NS	*	NS	*

Treatment factor	Year	
	2008	2009
	P > *F*	
N form and placement	NS	***
Mowing height	***	**
N form and placement x mowing height	NS	NS
Time	***	***
N form and placement x time	NS	*
Time x mowing height	***	*
N form and placement x time x mowing height	NS	NS

NS = non-significant

* Significant at the 0.05 *P* level

** Significant at the 0.01 *P* level

*** Significant at the 0.001 *P* level

†Values represent the average clipping yield (g plot^{-1}) per treatment.

‡Values within a column followed by the same letter are not statistically different (LSD, $P \leq 0.05$).

Table 3.2. Analysis of variance testing the main effects and their interactions on turfgrass color of creeping bentgrass

	2008			2009		
N form and placement	August	September	October	June	July	August
Calcium nitrate foliar	5.0†a‡	5.9a	5.9a	5.9c	6.5a	6.0a
Calcium nitrate granular	5.0a	5.9a	6.0a	5.8c	6.5a	6.0a
Urea foliar	5.0a	5.9a	6.0a	6.1b	6.5a	6.0a
Urea granular	5.0a	5.9a	5.9a	6.3a	6.5a	6.0a
Control	5.0a	5.9a	4.9b	5.8c	6.5a	6.0a
P	NS	NS	***	***	NS	NS
Mowing height (mm)						
3.2	5.0a	5.8b	5.8b	6.5a	6.5a	6.0a
2.8	5.0a	5.9a	5.8b	6.1b	6.5a	6.0a
2.4	5.0a	6.0a	6.0a	5.4c	6.5a	6.0a
P	NS	***	***	***	NS	NS

	Year	
Treatment factor	2008	2009
	P > *F*	
N form and placement	***	*
Mowing height	NS	***
N form and placement x mowing height	NS	NS
Time	***	***
N form and placement x time	***	***
Time x mowing height	***	***
N form and placement x time x mowing height	NS	NS

NS = non-significant

* Significant at the 0.05 *P* level

*** Significant at the 0.001 *P* level

†Values represent the average turfgrass color (1-9) per treatment.

‡Values within a column followed by the same letter are not statistically different (LSD, $P \leq 0.05$).

Table 3.3. Analysis of variance testing the main effects and their interactions on turfgrass quality of creeping bentgrass

	2009		
N form and placement	August	September	October
Calcium nitrate foliar	5.3†a‡	5.8a	5.4a
Calcium nitrate granular	5.6a	5.9a	5.5a
Urea foliar	6.0a	6.3a	5.8a
Urea granular	6.0a	6.3a	5.9a
Control	5.2a	5.6a	5.4a
P	NS	NS	NS
Mowing height (mm)			
3.2	6.3a	7.2a	6.7a
2.8	5.8b	5.9b	5.7b
2.4	4.8c	4.9c	4.5c
P	***	***	***

Treatment factor	2009
	—*P* > *F*—
N form and placement	**
Mowing height	***
N form and placement x mowing height	NS
Time	***
N form and placement x time	NS
Time x mowing height	***
N form and placement x time x mowing height	NS

NS = non-significant

** Significant at the 0.01 *P* level

*** Significant at the 0.001 *P* level

†Values represent the average turfgrass quality (1-9) per treatment.

‡Values within a column followed by the same letter are not statistically different (LSD, $P \leq 0.05$).

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CHAPTER IV

RESPONSE OF TURFGRASS TO UREA-BASED FERTILIZERS FORMULATED TO REDUCE AMMONIA VOLATILIZATION AND NITRATE CONVERSION

ABSTRACT

Stabilized urea fertilizers are currently being marketed for use in turfgrass, as a more efficient alternative to standard urea that minimizes adverse impacts on the environment. These fertilizers have been evaluated for reducing N losses and increasing grain yield in crop plants, but their effects in turf are not well characterized. The efficacy of two stabilized urea fertilizers containing urease and nitrification inhibitors, NBPT and DCD or butenedioc-methylenesuccinic acid copolymer, in reducing N losses was studied for a 56-d period in a mixed stand of Kentucky bluegrass (*Poa pratensis* L.) and perennial ryegrass (*Lolium perenne* L.) using ^{15}N-enriched fertilizers. Turf responded to a 49 kg ha^{-1} N input with increased color, quality, and biomass production. No benefit of nitrification and urease inhibitors compared to urea was observed for clipping production, N use efficiency, or turfgrass color and quality. Though the efficacy of urease and nitrification inhibitors has been demonstrated both in the laboratory and for row crops, these compounds appear to be of limited value for enhancing N use efficiency in turf.

INTRODUCTION

Urea is the most common N source for turfgrass fertilization. This popularity reflects the same attributes that have made urea the leading synthetic N fertilizer in world agriculture: low cost, high N content, chemical stability, ease of handling, and water solubility. The main drawbacks arise from the limited period of urea N availability for plant uptake, and from the risk of N loss through NH_3 volatilization, NO_3^- leaching, and denitrification.

Volatilization losses can occur when urea is hydrolyzed to NH_3 and CO_2 by the ubiquitous enzyme urease, which has numerous plant and microbial sources. Under turfgrass culture, these losses have been attributed to elevated levels of urease activity, reported by Torello and Wehner (1983) to be 18 to 25 times higher for Kentucky bluegrass clippings and thatch than for the underlying soil. In turf, urea N losses via volatilization have been reported to be as high as 55 to 65% (Volk, 1959; Titko et al., 1987). Losses will be much lower if urea is incorporated into the soil profile by rainfall or irrigation (Bowman et al., 1987; Titko et al., 1987; Sharf and Alley, 1988; Knight et al., 2007).

Loss of urea N can also occur by leaching or denitrification, particularly since autotrophic NH_4^+ oxidation is favored by the alkalinity and CO_2 liberated by urea hydrolysis (Marsh et al., 2005). In turf, leaching losses have been reported to be as high as 53% depending on N rate, age of the turfgrass stand, and the intensity of leaching (Petrovic, 1990; Miltner et al., 1996; Frank et al, 2006). Denitrification losses of urea-N are promoted not only by rapid nitrification, but also because hydrolysis creates conditions that favor the accumulation of NO_2^-, which is utilized in preference to NO_3^- (Mulvaney et al., 1997a). Few studies have concentrated on denitrification losses of N from urea applied to turfgrass. Adams et al. (2004) quantified denitrification loss of N from urea applied to turfgrass, but unfortunately their measurements were vitiated by the use of C_2H_2, which would have inhibited nitrification of urea N as well as N_2O reduction to N_2. In a field study by Horgan et al. (2002) involving direct measurement of denitrification using ^{15}N, no gaseous losses were detected from Kentucky bluegrass fertilized with urea. Similar results were reported by Maggiotto et al. (2000) as denitrification losses ranged from 0.05 to 0.33% of urea N applied to turf. Losses with KNO_3, have been much larger, ranging up to 11% in vivo (Horgan et al., 2002) and up to 78% in vitro (Mancino et al., 1988) for Kentucky bluegrass.

One way to reduce the loss of N from urea is by inhibiting the N transformations that lead to these losses. The usual approach is to control the activity of urease with inhibitory compounds that delay urea hydrolysis, so as to limit the accumulation of NH_4^+ and the rise in pH that allow gaseous loss via NH_3 volatilization. To date, hundreds of such compounds have been identified, but very few have proved viable for agricultural use under field conditions (Kiss and Simihaian, 2002). Alternatively, nitrification inhibitors can be employed to retard autotrophic oxidation of NH_4^+-N to NO_3^--N, as a means of controlling N loss by leaching or denitrification. Of more than 60 synthetic compounds thus far identified as nitrification inhibitors, no more than 10% have proven to be of any practical value in the field (Subbarao et al., 2006).

Stabilized-urea fertilizers are commercial formulations that include an inhibitor. One such product, Uflexx**®** (Agrotain International, St. Louis, MO), is marketed specifically for turfgrass N fertilization and contains urea mixed with N-(n-butyl) thiophosporic triamide (NBPT, $C_4H_{14}N_3PS$) for urease inhibition and dicyandiamide (DCD, $C_2H_4N_4$) as a nitrification inhibitor. The former constituent is a water-soluble compound that rapidly decomposes in soil to N-(n-butyl) phosphoric triamide (McCarty et al., 1989), which inhibits hydrolysis by inactivating the urease active site (Manunza et al., 1999). Dicyandiamide is also water soluble, and specifically affects *Nitrosomonas europea* to inhibit the first step of nitrification (Amberger, 1989). The decomposition products include guanylurea, guanidine, and urea, none of which is inhibitory to the nitrification process (Bronson et al., 1989a).

Another inhibitor, Nutrisphere**®** (Specialty Fertilizer Products, Leawood, KS), is a copolymer of maleic (syn. butenedioc) and itaconic (syn. methylenesuccinic) acids occurring as a partial Ca^{2+} salt for use as a coating to ammoniacal N fertilizers to inhibit urease, nitrification, and denitrification (Sanders et al., 2004, 2008; Sanders, 2007). This material is a stable, water soluble, slowly biodegradable, branched polymer that occurs in 30-40 unit lengths. The inhibitory properties of the material reportedly arise from its high negative charge density (1800 meq/100 g). For urease inhibition, this extreme anionic charge density is purported to sequester the Ni necessary for the urease enzyme to function (Sanders, 2007). Nitrification and denitrification are presumably reduced due to ionic binding of any NH_4^+ that may be generated.

Considering the popularity of urea for turf N fertility and the elevated urease levels found in turfgrass leaves and thatch, there is obvious potential for urease inhibition to enhance N use efficiency, particularly when urea cannot be incorporated by irrigation or rainfall. Further potential exists in utilizing nitrification inhibitors to control NO_3^- losses from intensively managed turfgrass under frequent irrigation. These benefits are consistent with yield responses observed in several inhibitor studies with row crops (Schlegel et al., 1986; Gordon, et al., 1987; Webb et al., 1991; Hendrickson, 1992; Zhang et al., 2010); however, experimental evidence is lacking that stabilized fertilizers can provide an effective means of improving turfgrass N management. The work reported herein was undertaken to evaluate this possibility for Uflexx® and Nutrisphere®, with particular emphasis on fertilizer N uptake efficiency (FNUE).

MATERIALS AND METHODS

The research was conducted at the University of Illinois Landscape Horticulture Research Center at Urbana, IL, on a 4 year-old mixed stand of Kentucky bluegrass and perennial ryegrass maintained at 7 cm height of cut. A low-fertility study site was selected, where a 30 cm deep layer of subsoil from a nearby construction site had been established in 1992 as a cap over the existing topsoil. In the analyses reported in Table 1 for the surface 15 cm, pH was determined with a glass electrode (soil to water ratio, 1:1); organic C by the method of Mebius (1960); total N by a $KMnO_4$-Fe modification of a semimicro-Kjeldahl digestion technique (Bremner, 1996), followed by diffusion with NaOH (^{15}N Analysis Service, 2011a); and cation-exchange capacity (CEC) by the rapid diffusion method of Mulvaney et al. (2004). In soil tests performed by Agricultural Soil Management, Champaign, IL, available P was determined using the Bray-1 procedure (Bray and Kurtz, 1945), and available K by flame emission spectroscopy following extraction with 1 *M* $NH_4C_2H_3O_2$ (Warncke and Brown, 1998).

The experiment was initiated on 22 May 2010. During treatment application, the air temperature was 31°C, relative humidity was 50%, and the soil temperature was 26°C at 2.5 cm depth. Air temperature and precipitation data for the study period were obtained from the Illinois State Water Survey, Champaign, IL.

A randomized complete block design was utilized with six replications. Treatments consisted of granular Nutrisphere®, Uflexx®, and urea formulated to commercial specifications and enriched with ^{15}N-labeled urea to 5.5 atom percent ^{15}N by Applied Chemical Technologies, Birmingham, AL. To maximize application uniformity, a 1.8 x 1.2 x 0.8-m (L x W x H) plywood enclosure lined with five evenly spaced horizontal layers of 0.6 mm hardware cloth was set over the plot, and treatments were hand-applied into the enclosure at a rate of 49 kg N ha^{-1}.

To create conditions conducive to N losses by volatilization, irrigation was delayed for 24 h following application. During this period NH_3 volatilization was estimated in duplicate for each plot using 473-mL (1-pint) wide-mouth mason jars that had been modified by removing the bottom with a glass saw. The modified jars were manually forced into the soil to a depth of 2.5 cm, and then sealed by attaching a lid of the same design described by Stevens et al. (2000), but having a petri dish containing 5 M H_2SO_4 instead of H_3BO_3-indicator solution for absorption of gaseous NH_3. After 24 h, the jar was opened and the petri dish removed from the jar lid, the H_2SO_4 solution was decanted into a 25-mL screw top polyethylene bottle, and the transfer was completed by rinsing twice with 5 mL of deionized water. The plots were then irrigated (~0.6 cm) to incorporate the fertilizer into the soil. The NH_3-N collected was liberated by diffusion with 10 M NaOH in a 473-mL mason jar (^{15}N Analysis Service, 2011a), and subsequently quantified by titration with 0.01 M H_2SO_4.

Leaf tissue was collected weekly, with an additional sampling 3 days after treatment (DAT), by making one pass down the center of the plot with a walk-behind reel mower (McLane Manufacturing, Paramount, CA). The clippings were dried in a forced-air oven at 40°C and finely ground (< 250 μm) using a Shatterbox 20 (SPEX SamplePrep, Metuchen, NJ) prior to N analysis. At the conclusion of the study, duplicate 10.8 cm diameter cores were taken from each plot, and all leaf tissue was removed from the plug using scissors and prepared for total N analysis by Kjeldahl digestion-diffusion as previously described.

To quantify fertilizer N in roots and soil, twenty 2.54 cm diameter cores were collected from the surface 15 cm of each plot using a KHS soil probe (M & M Supply Co., Mitchellville, IA). After removal of aboveground plant material, ten cores were freed of soil by gently washing with deionized water and the resulting root mass was prepared for analysis as previously described for vegetative material. The remaining ten cores were each sectioned into two 7.5-cm segments, which were composited by depth and immediately transferred to a forced-air oven at 40°C for drying prior to analysis for total, potentially mineralizable, and inorganic N.

Total N analyses were performed by digesting foliage, roots, or soil as previously described for the capping material. The quantity of N in the digest was determined by acidimetric titration of NH_3 liberated upon diffusion with 10 *M* NaOH, followed by N-isotope analysis using an automated mass spectrometer (Mulvaney et al., 1990, 1997; Mulvaney and Liu, 1991). Fertilizer N uptake efficiency (FNUE) in foliage and roots was calculated as $100R/A$, where R is the amount of labeled fertilizer N recovered and A is the amount applied. Fertilizer N recovery (R) was calculated as $Q_A(S_T/S_A)(M - B)/(F - B)$, where Q_A is the quantity of N measured for the sample under analysis, S_T is the total dry weight of sample collected, S_A is the dry weight of sample under analysis, M is the measured atom % ^{15}N, B is the background atom % ^{15}N determined for unlabeled plant material, and F is the atom % ^{15}N of the labeled fertilizer. Percentage recovery of labeled N in the soil was calculated in the same manner, using the appropriate sample weights and a background value for atom % ^{15}N (B) determined by total N analysis of unlabeled soil. Plant or soil N derived from fertilizer (NDFF) was calculated as $100R/T$, where R is labeled N recovery in the plant material or soil under analysis and T is the corresponding total N content.

Potentially mineralizable N (PMN) was quantified for soil samples by base hydrolysis, using the Illinois soil N test (ISNT) originated by Khan et al. (2001) and described in more detail by a technical note (^{15}N Analysis Service, 2011b). Mineral N [NH_4^+-N and ($NO_3^- + NO_2^-$)-N] was quantified by accelerated diffusion of 2 *M* KCl extracts (Khan et al., 1997).

Turfgrass color and quality ratings were recorded every 7 DAT, based on a scale of 1 to 9, with 9 as optimum and 1 as very poor. The minimum acceptable rating for either parameter was 6.0.

Statistical Analyses were conducted using the MIXED procedure of SAS (SAS Institute, 2008) to detect treatment differences. Models were developed using repeated measures when appropriate. The Type 3 test of fixed effects was used to determine significance at $P < 0.05$.

RESULTS

Physical and Chemical Properties of the Growing Medium

The study site selected was inherently low in fertility because of the presence of an overlying subsoil cap that had been in place since 1990. As documented by Table 4.1, the capping material was a slightly alkaline loam, exhibiting moderate CEC and total N, low available P, and a high level of exchangeable K.

Environmental Conditions During the Study Period

Air temperature and precipitation over the course of the study are reported in Fig. 4.1. During the study, monthly mean air temperatures were above average by 0.7°C in May, 1.6°C in June, and 1.0°C in July. Overall precipitation amounts were slightly lower than average for the months of May and July, but were 185% above average for the month of June. The first precipitation event occurred 3 DAT, and amounted to 8 mm.

Ammonia volatilization

Losses of applied N by NH_3 volatilization were detected for all treatments but were very limited, ranging from 0.01 to 1% and averaging 0.04%. Losses of this magnitude were deemed biologically insignificant, and the data were not subjected to statistical analysis.

Clipping yield

No significant differences in clipping yield were detected among fertilizer treatments throughout the course of the study (Fig. 4.2, $P = 0.58$). Growth response to applied fertilizers reached a maximum at the 21 DAT sampling time and then declined to pre-treatment levels as of 35 DAT. No yield differences were observed from leaf tissue collected from cores taken at the final sampling (56 DAT).

Turf Color and Quality

All treatments exhibited a rapid increase in turf color and quality following N fertilization, although no differences in either color ($P = 0.10$) or quality ($P = 0.07$) were observed throughout the trial (Table 4.2). The increase in color and quality occurred until 21 DAT, after which both parameters remained relatively stable for the remainder of the study.

Nitrogen Recovery

No treatment differences were detected for total N in shoots (Fig. 4.3; $P = 0.53$) throughout the course of the study. Regardless of treatment, N concentration in the foliage was relatively stable for 28 DAT and then gradually declined during the remainder of the experiment (Fig. 4.3). Isotopic analysis of total N digests for ^{15}N showed no significant differences for NDFF in shoots

(*P* = 0.73). Shoot NDFF ranged from 30 to 35% of the N applied at the first sampling, increased at 14 DAT to between 40 and 42%, and then declined to 12 to 15% at the conclusion of the experiment (Fig. 4.4). Similarly, no treatment differences were observed over the study period in FNUE by shoots (Fig. 4.5; *P* = 0.97). At the conclusion of the study, about 20% of the ^{15}N applied had been recovered in the shoots.

For roots likewise, no significant treatment differences were observed at 56 DAT in total N (*P* = 0.57), NDFF (*P* = 0.21), or FNUE (*P* = 0.20). Total N for all treatments averaged 11 g N kg^{-1} root mass. Additionally, from 4 to 5% of fertilizer ^{15}N was recovered in the roots, accounting for approximately 10% of total N in root biomass regardless of treatment.

A parallel evaluation for soil plus roots (Table 4.3) revealed no treatment differences in total N for the surface 7.5 cm (*P* = 0.57) or subsurface (7.5-15 cm) layer (*P* = 0.17), or in NDFF that was around 1% for the surface layer (*P* = 0.89) and tended to be somewhat lower for the subsurface (*P* = 0.51). Recoveries of applied ^{15}N ranged from 16 to 18% for the surface layer (*P* = 0.36), and from 3 to 4% for the subsurface layer (*P* = 0.23).

Overall, recovery of fertilizer N in all fractions analyzed was 44.0, 43.5, and 47.4% of fertilizer applied for Nutrisphere, Uflexx, and urea, respectively.

Potentially Mineralizable and Inorganic Soil Nitrogen

No treatment differences were detected in estimating PMN (Table 4.3.) by the ISNT for surface (*P* = 0.92) or subsurface soil samples (*P* = 0.75) at 56 DAT, nor was there a significant treatment effect on mineral N recovered from these depths as exchangeable NH_4^+ or as NO_3^- + NO_2^- since no more than trace amounts of label were recovered in these N pools. Somewhat greater recovery of fertilizer ^{15}N occurred in PMN than in mineral N, averaging 0.004% for the surface soil and 0.0005% for the subsurface layer. As with mineral N, these recoveries were deemed biologically insignificant.

DISCUSSION

While there is ample evidence that urease and nitrification inhibitors can retard the conversion of urea to N forms subject to loss, the data presented here suggest that inhibitors do not significantly reduce fertilizer N losses in turf. For the multiple parameters evaluated in our work, neither Uflexx® nor Nutrisphere® provided any benefit beyond standard urea. This finding is at odds with previous evaluations involving agricultural row crops, and probably reflects soil and growing conditions that make turfgrass a very different cropping system. For example, plant populations are far greater with turfgrass than with row crops; rooting depth is much more limited; a highly carbonaceous thatch layer is often present; pesticides and other plant care chemicals are applied to organic matter in the form of leaves and thatch rather than to soil; microbial population and activity is much higher than underlying soil, and pesticide degradation typically occurs more rapidly than for row crops (Branham, 1994; Gardner, et al. 2000, Gardner and Branham, 2001a, b; Magri and Haith, 2009).

Numerous compounds, including those in Uflexx® and Nutripshere® have been shown to retard urea hydrolysis or nitrification in laboratory incubation experiments (e.g., Bremner and Chai, 1986; Bronson et al., 1989b; McCarty et al., 1989; McCarty and Bremner, 1989; Sanders et al, 2008); however, their use under field conditions does not necessarily enhance crop production. When efficacy has been lacking, the usual interpretation has been that the crop was nonresponsive to applied N, N losses were insignificant even in the absence of an inhibitor, and/or a type II error occurred (Scharf and Alley, 1988). In the present study, there were no differences in any measured parameter between unamended or stabilized urea fertilizers. Since the experiment did not include an unfertilized control, no definitive assessment can be made as to fertilizer N response. Still, turfgrass FNUE did not differ among Uflexx® (24%), Nutrisphere® (24%), and unamended urea (26%), demonstrating comparable N loss for each treatment, and also comparable uptake of unlabeled soil N. This finding cannot be attributed to excessive data variability or inadequate replication that would have limited sensitivity in detecting significant treatment differences, and is unlikely to reflect a type II error. Overall, approximately 60% of the applied N could not be accounted for regardless of treatment, and begs the question as to why the stabilized products did not have their intended effect of boosting N efficiency over that of unamended urea. Research has demonstrated that the efficacy of inhibitors is highly dependent on soil properties and environmental conditions (Bremner and Chai, 1986; McCarty and Bremner, 1989; Clay et al., 1990; Joo et al., 1991b), and these factors probably contributed to the lack of inhibitor response observed in our work. The low fertility capping material should have increased fertilizer N response, and the excessive rainfall in June was conducive to N loss, yet the two stabilized fertilizers performed no better than unamended urea.

A beneficial effect of Uflexx® and Nutrisphere® in reducing volatilization of urea N was expected, based on previous field studies demonstrating the efficacy of NBPT and the Nutrisphere® copolymer for this purpose (e.g., Rodgers et al., 1987; Clay et al., 1990; Sanders et al., 2004). To increase the potential for liberation of NH_3, urea hydrolysis was allowed to occur on the soil surface by delaying irrigation for 24 h after fertilizer application, yet surprisingly, NH_3 volatilization during this period was negligible even with unamended urea. This finding is inconsistent with previous reports of substantial NH_3 loss from fertilized turf (Volk, 1959; Titko et al., 1987), but soil differences probably account for the disparity. In particular, CEC would have been greater for the subsoil capping material in the present study than for the sandy soils studied by Volk (1959), Bronson et al. (1989b), and Clay et al. (1990), the effect being to moderate the pH rise upon urea hydrolysis as well as enhance adsorption of the NH_4^+ thereby generated.

The overall quantity of precipitation experienced at the site during the majority of the study was slightly lower and air temperature was slightly higher than normal. As a result, the turf was irrigated regularly to prevent moisture stress, which may have reduced inhibitor effectiveness. For example, NBPT is much less water-soluble than urea (4.3 versus 1210 g L^{-1} at 25°C), so differential transport within the soil profile could have occurred as water moved through the plant-soil interface, causing a physical separation that would reduce inhibitor efficacy for retarding urea hydrolysis. Nutrisphere® is also water-soluble and as such, may be subject to movement itself. The mobility of urea in wet soils has been documented (Chin and Kroontje, 1962) and can be enhanced considerably by macropore flow (Priebe and Blackmer, 1989), a likely occurrence in our study due to the presence of earthworm burrows under turf. Differential mobility can also be a problem with nitrification inhibitors that are highly water soluble, since the substrate is a cation that undergoes soil adsorption. This concern was noted by McCarty and Bremner (1989), and accounts for their finding that the inhibitory effect of DCD on nitrification was readily eliminated by leaching.

Soil temperature also affects the persistence of inhibitors, as is well documented for DCD. Bronson et al. (1989a), for example, reported that an increase in incubation temperature from 8 to 22°C shortened the half-life for nitrification inhibition from 25.8 to 7.4 d, which led them to conclude that DCD may not be suitable as a nitrification inhibitor during periods of warm weather. McCarty and Bremner (1989) reached a similar conclusion from laboratory incubations comparing inhibition at soil temperatures of 20 and 30°C. Throughout the course of the present trial, soil temperatures averaged approximately 21°C at the 10-cm depth, and were likely higher at the soil surface where the treatments were applied. Since appreciable ^{15}N recovery was observed for the surface (0-7.5 cm) soil, enhanced thermal degradation of DCD in this layer may help explain why Uflexx® was of no benefit, relative to unamended urea.

The ineffectiveness of Uflexx® as reported herein is in contrast to the findings of Joo et al. (1987) in a study that involved spraying Kentucky bluegrass with unlabeled urea and differing enrichments of NBPT. Their results showed an increase in clipping yield with the inhibitor that ranged from 20 to 27% and was greatest during the summer, when hot weather would have promoted NH_3 volatilization. In a study of perennial ryegrass by Watson et al. (1990), use of NBPT led to a 20% increase in N recovery estimated by the difference method, and 8.8% higher dry matter yield, 7 wk after a single application of urea that supplied 100 kg N ha^{-1}. Mosdell et al. (1989) evaluated the effectiveness of DCD in reducing urea N conversion to NO_3^- in a field study with Kentucky bluegrass and concluded that DCD was effective for such a short period that its use would seldom be justified for turfgrass. Waddington et al. (1989) came to a similar conclusion that DCD is of no value for increasing FNUE in turf, unless applied at an unrealistically excessive rate.

A positive color response of turfgrass to stabilized fertilizer was reported by Waddington et al. (1989) for turf treated with excessive rates of DCD supplying 80 to 100% of the fertilizer N applied. This response was disregarded as economically unrealistic and was attributed to the fertilizer value of DCD, which functions as a slow-release fertilizer as well as a nitrification inhibitor. No color or quality response was observed in our work with Uflexx® and Nutrisphere®, relative to the use of unamended urea. This finding is consistent with previous research by

Mosdell et al. (1986) documenting no positive effect of DCD on turfgrass color or quality. The study site for their research was on a Hagerstown silt loam (fine, mixed, semiactive, mesic Typic Hapludalfs) that was rather low in CEC, indicating low soil organic C and N-supplying power, a site where turf should have benefited from the use of a nitrification inhibitor. Similarly, the lack of a turf response to Nutrisphere® in the present study leads to the same conclusion reached by Mosdell et al. (1986) in regard to DCD.

The overall recovery of fertilizer N in the foliage, determined by ^{15}N analysis and expressed as FNUE, is comparable to recovery data reported in other ^{15}N research evaluating urease or nitrification inhibitors with turf (Joo et al. 1991a; Lianti et al., 1993; Starrett et al., 1995). The total recovery of applied N in the present study was approximately 25% in the plant and 16% in the roots and soil, totaling approximately 41% regardless of treatment. Joo et al. (1991a) reported recoveries of 29 to 45% of the total applied to Kentucky bluegrass in a field study with ^{15}N-labeled urea alone or stabilized with NBPT. Several fertility studies conducted with unamended fertilizer using ^{15}N technique demonstrate similar recoveries of soil-applied fertilizer in turfgrass (Starr and DeRoo, 1981; Miltner et al., 1996; Frank et al., 2006).

With or without inhibition, there was very little fertilizer N recovery in the soil N pools studied. For total soil N, recovery of ^{15}N was greater in the surface than in the subsurface layer. This is consistent with results obtained in other turfgrass research showing that soil ^{15}N recovery is confined largely to the surface soil layer (Joo et al., 1991a; Horgan et al., 2002; Frank et al., 2006). There was no effect of inhibition on PMN estimated by the ISNT and only trace ^{15}N recovery in this fraction, regardless of whether urea, Uflexx®, or Nutrisphere® had been applied.

At the conclusion of the 8-wk study period, the inhibitors proved to be of no value for decreasing NO_3^- concentrations, relative to unamended urea. Similar findings have been reported from previous studies with Kentucky bluegrass by Mosdell et al. (1986) and Waddington et al. (1989). Waddington et al. (1989) repeatedly applied DCD during a 3-yr study that involved periodic sampling of soil inorganic N, but of 56 evaluations there were only five that showed elevated NH_4^+ levels and three reduced in NO_3^-. Regardless of fertilizer treatment, inorganic soil N accounted for only trace recoveries of ^{15}N in the present study.

The total lack of significant treatment differences for every parameter studied leads us to conclude that the urease and nitrification inhibitors used were of no value for reducing losses of urea-N applied to turfgrass and did not offer any advantages over unamended urea. In one respect, however, this conclusion must be qualified, since the study site was managed under irrigation, and thus volatilization losses may have been reduced. Under irrigated turf conditions, little if any advantage can be expected from the use of a urease inhibitor.

TABLES

Table 4.1. Selected properties of the surface 15 cm soil at the experimental site.

Property	Value
pH	7.2
Organic C (g kg^{-1})	22
Total N (g kg^{-1})	2.2
C:N	10:1
CEC (cmol kg^{-1})†	14
Available P (kg ha^{-1})	21.7
Available K (kg ha^{-1})	369.5
Sand (g kg^{-1})	300
Silt (g kg^{-1})	430
Clay (g kg^{-1})	270

† CEC, cation-exchange capacity.

Table 4.2. Turfgrass color and quality in response to three N fertilizers.

	Color (0-9)†								Quality (0-9)†							
	Days After Treatment															
Treatment	7	14	21	28	35	42	49	56	7	14	21	28	35	42	49	56
Nutrisphere	5.0a	6.8a	7.8a	7.0a	7.8a	7.8a	8.0a	7.8a	5.0a	6.3a	7.0a	7.0a	7.0a	8.0a	7.8a	8.0a
Uflexx	5.0a	7.0a	7.8a	7.0a	7.7a	7.3a	7.8a	7.8a	5.0a	6.5a	7.2a	7.0a	7.0a	7.8a	7.8a	7.0a
Urea	5.0a	7.0a	8.0a	7.0a	7.8a	7.8a	8.0a	7.8a	5.0a	6.5a	6.8a	7.0a	7.0a	8.0a	8.0a	7.0a
LSD	NS§	NS	NS	NS	NS	NS§	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

†Values represent the average of turf color and quality for each treatment.

‡Values within a column followed by the same letter are not statistically different (LSD, $P \leq 0.05$).

§NS, Not significant.

Table 4.3. Nitrogen pools and recovery of ^{15}N in roots and soil 8 weeks after fertilizer application.†

	Nutrisphere		Uflexx		Urea		*P*-Value¶	
Parameter‡	0-7.5 cm	7.5-15 cm	0-7.5 cm	7.5-15 cm	0-7.5 cm	7.5-15 cm	0-7.5 cm	7.5-15 cm
TKN (gkg^{-1})	1.5 ± 0.3§	0.4 ± 0.2	1.4 ± 0.3	0.6 ± 0.1	1.5 ± 0.3	0.4 ± 0.2	0.57	0.17
NDFF (%)	1.1 ± 0.2	0.7 ± 0.5	1.2 ± 0.3	0.4± 0.2	1.2 ± 0.1	1.0 ± 0.7	0.89	0.19
^{15}N Recovery (%)	16.0 ± 2.7	3.8 ± 4.9	16.7 ± 5.5	3.3 ± 2.0	17.9 ± 3.0	4.0 ± 2.9	0.36	0.23
PMN (mgkg^{-1})	209.1 ± 51.1	70.1 ± 15.8	198.2 ± 35	79.1 ± 15.8	202.8 ± 54.8	69.3 ± 8.2	0.92	0.75
^{15}N Recovery (%)	Trace	Trace	Trace	Trace	Trace	Trace	NA	
NO_3^- (mg Nkg^{-1})	7.9 ± 0.9	3.6 ± 0.5	7.4 ± 1.3	4.2 ± 1.1	8.6 ± 1.8	4.3 ± 1.1	0.34	0.29
^{15}N Recovery (%)	Trace	Trace	Trace	Trace	Trace	Trace	NA	
NH_4^+ (mg Nkg^{-1})	7.2 ± 1.4	3.6± 2.0	6.3 ± 0.6	4.9 ± 1.0	7.6 ± 3.7	4.3 ± 1.7	0.62	0.75
^{15}N Recovery (%)	Trace	Trace	Trace	Trace	Trace	Trace	NA	

†Analyses performed with six replications.

‡TKN, total Kjeldahl nitrogen; NDFF, nitrogen derived from fertilizer; PMN, potentially mineralizable nitrogen.

§Mean data reported ± one standard deviation.

¶NA, not applicable

FIGURES

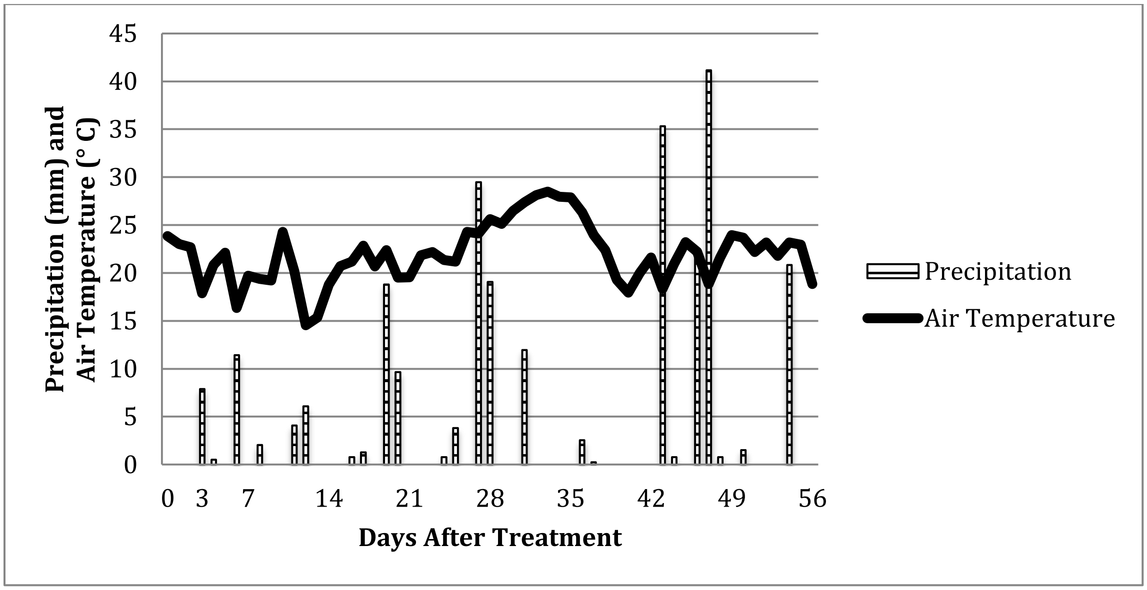

Fig. 4.1. Selected environmental parameters at the study site for the duration of the experiment (56 d).

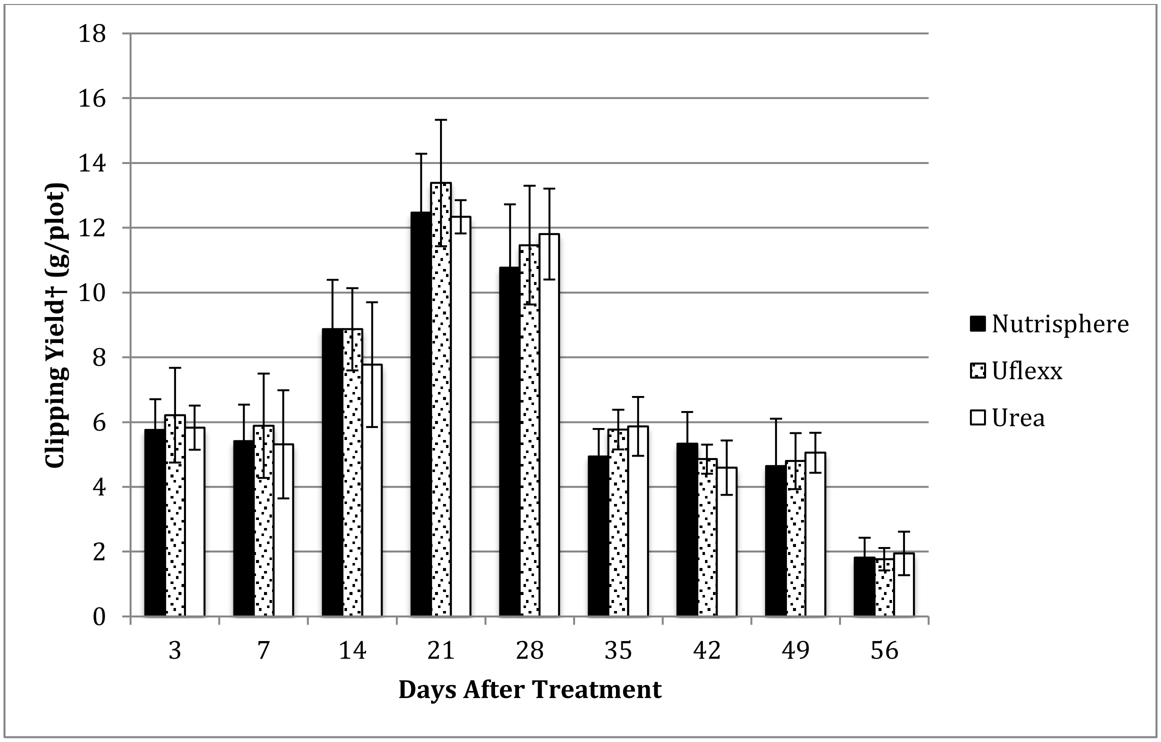

Fig. 4.2. Clipping yield of treated plots. Error bars indicate one standard deviation.

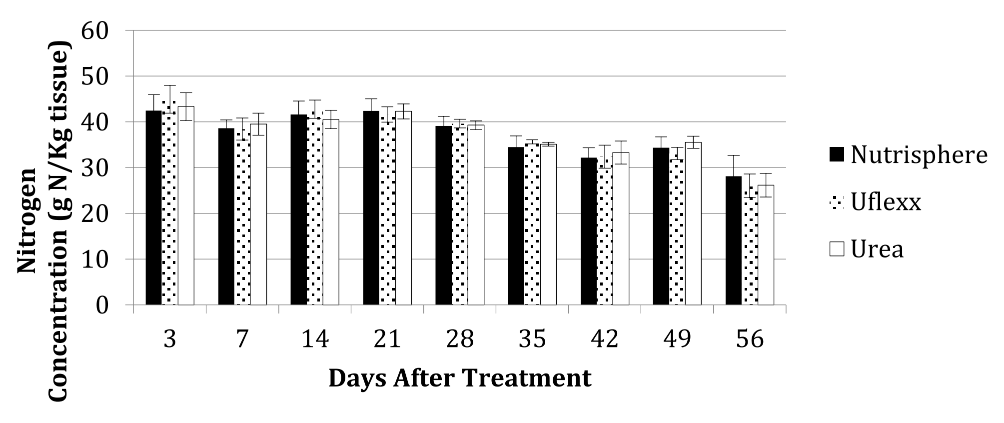

Fig. 4.3. Leaf tissue N concentration (g N /kg^{-1} tissue, dry weight) over the course of the experimental period (56 d). Error bars indicate one standard deviation.

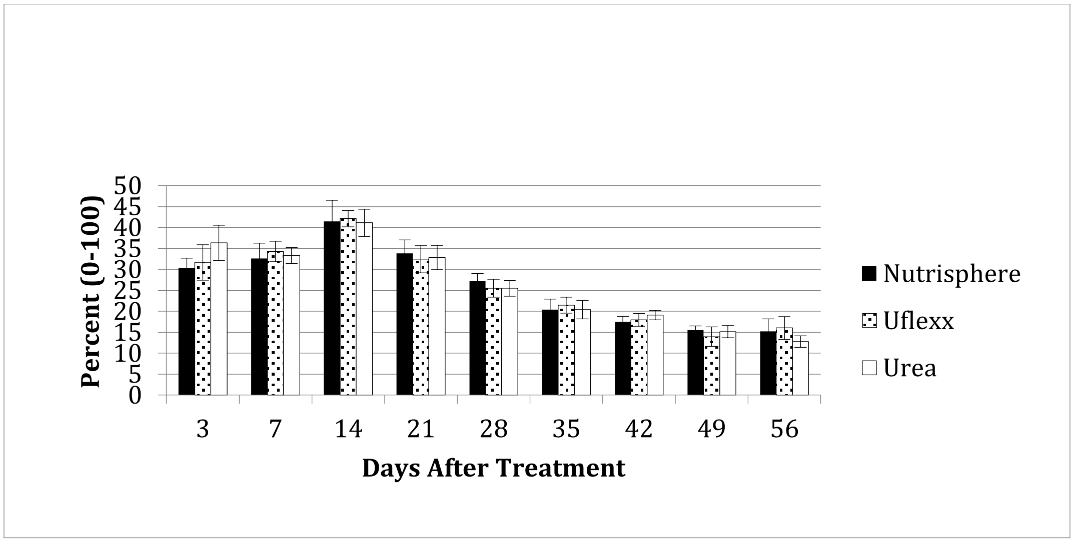

Fig. 4.4. Percent N derived from fertilizer (NDFF) in leaf tissue over the course of the experimental period (56 d). Error bars indicate one standard deviation.

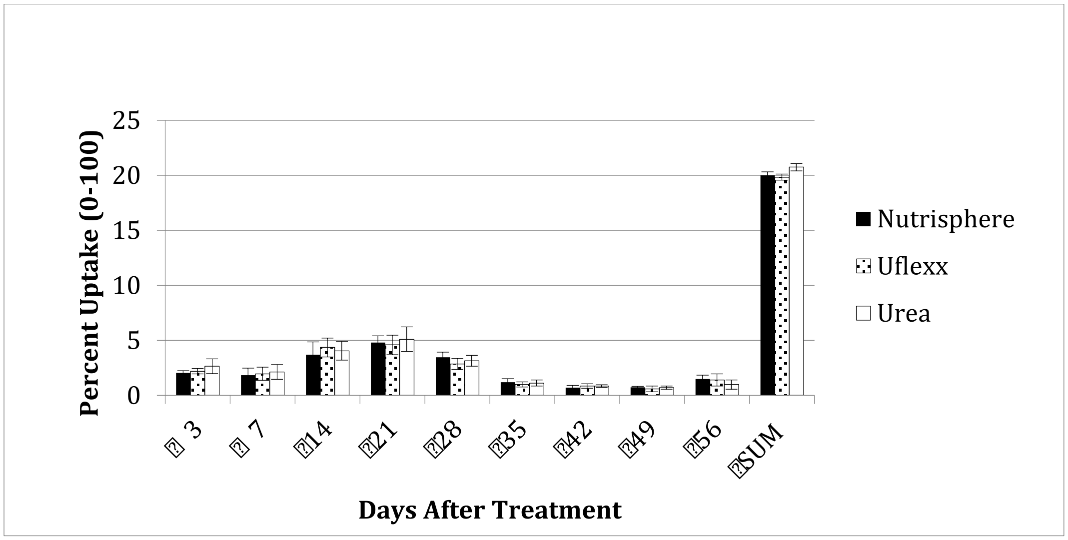

Fig. 4.5. Fertilizer N uptake efficiency (FNUE) of leaf tissue over the course of the experimental period and as a total (56 d). Error bars indicate one standard deviation.

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CHAPTER V

RESEARCH SUMMARY

Turfgrass managers frequently apply N as a foliar spray when a low application rate is desired. This practice is believed to promote N uptake that benefits turf, however, very little information is available concerning the quantity of N absorbed by turfgrass foliage or the effect of various spray parameters on foliar N uptake under field conditions. The study reported herein was conducted to evaluate fertilizer N uptake efficiency of foliarly applied ^{15}N-labeled fertilizers by creeping bentgrass (*Agrostis stolonifera* var. L. *palustris* (Huds.) Farw. 'Pennlinks') under field conditions. The effects of spray volume, N-formulation, adjuvant addition, or tank-mixing of commonly applied turf care products on the dynamics of foliar N uptake were investigated. Foliar-applied N was rapidly absorbed by turf with maximum uptake generally occurring within 4-6 h of fertilizer application and was on the order of 7 to 36% of the amount applied. Foliar N uptake was not affected by N-formulation, adjuvant addition, or tank-mixing. Overall, spray volume was found to be the significant driver of foliar N uptake efficiency, with lower spray volumes yielding greater foliar uptake of applied N than larger spray volumes.

Further research was performed in order to better understand the uptake dynamics of foliar as compared to soil applied N. Nitrogen was applied as a foliar spray or soil applied at 0, 4.9, and 9.8 kg ha-1 as ^{15}N labeled urea. Turf was evaluated for clipping production, total N, plant N derived from fertilizer, and fertilizer N uptake efficiency. The results indicated that N dose had variable effects on clipping production, and did not affect total foliar N concentration in a biologically significant manner. Plant nitrogen derived from fertilizer was a maximum of 10% for foliar applied and 4-6% for soil applied N. Foliar applied N was found to be 99-64 percent more effective than ground applied urea in terms of nitrogen uptake efficiency. The results of these experiments demonstrate that foliar applied urea results in greater uptake efficiency than soil based applications of urea-N, and that fertilizer inputs may be reduced by foliar application to achieve the same N use efficiency as a traditional soil based application.

Foliar absorption and incorporation of ammoniacal nitrogen (NH_4^+) into turfgrass leaf tissue has potential to result in significant savings of photosynthetic energy and potentially improve fertilizer nitrogen uptake efficiency (FNUE). Plants use up to 25% of photosynthetically produced energy to reduce NO_3^- to NH_4^+. Foliar application and absorption of N in its reduced form (NH_4^+) could provide significant energy savings to turfgrasses under shade or mowing stress; however, plant N uptake could be adversely affected by enhanced heterotrophic competition for NH_4^+. A two-year field study was undertaken to determine the benefit, if any, of foliar-applied NH_4^+ over NO_3^- or NH_4^+ fertilizer applied as a foliar spray or to the soil. Stress was imposed to the turf by decreasing cutting height from 3.2 to 2.8 or 2.4 mm. No consistent benefit was observed for foliar applied NH_4^+ over foliar- or ground-applied NO_3^- or NH_4^+ in terms of turfgrass clipping yield, color, or quality. The lack of consistent turf response to foliar NH_4^+-N was attributed to the use of a highly fertile native soil as the study site, which diluted any positive effect foliar NH_4^+-N nutrition may have provided.

Research was conducted regarding stabilized urea fertilizers marketed for use in turfgrass as a more efficient alternative to standard urea minimizing adverse impacts on the environment. These fertilizers have been evaluated for reducing N losses and increasing grain yield in crop plants, but their effects in turf are not well characterized. The efficacy of two stabilized urea fertilizers containing urease and nitrification inhibitors, NBPT and DCD or butenedioc-methylenesuccinic acid copolymer, in reducing N losses was studied for a 56-d period in a mixed stand of Kentucky bluegrass (*Poa pratensis* L.) and perennial ryegrass (*Lolium perenne* L.) using ^{15}N-enriched fertilizers. Turf responded to a 49 kg ha^{-1} N input with increased color, quality, and biomass production. No benefit of nitrification and urease inhibitors compared to urea was observed for clipping production, N use efficiency, or turfgrass color and quality. Though the efficacy of urease and nitrification inhibitors has been demonstrated both in the laboratory and for row crops, inhibitors appear to be of limited value for enhancing N use efficiency in turf.