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Soil surfactants applied with ^{15}N labeled urea increases bermudagrass uptake of nitrogen and reduces nitrogen leaching[#]

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Abstract

Background : Increasing nitrogen (N) plant uptake efficiency may result in better plant quality and growth, less N susceptible to leaching and potential contamination to surrounding environments. Soil surfactants have been documented to increase water infiltration and enhance water uniformity throughout the soil profile. Thus, applying a surfactant may increase N uptake and use efficiency.
Methods : To investigate this theory, four treatments were applied to bermudagrass grown in leaching columns filled with one of three soils (sand, sandy loam, and sandy clay loam): (1) 10% alkoxylated polyols and 7% of glucoethers surfactant with ^{15}N labeled urea, (2) 10% oleic acid esters of block copolymer surfactant with ^{15}N labeled urea, (3) water with ^{15}N labeled urea, and (4) water without ^{15}N labeled urea. Ambient ^{15}N was determined by the no surfactant and no urea treatment. Each treatment combination was replicated five times and the greenhouse experiment was repeated. Bermudagrass quality and density, leachate volume, and volumetric water content were determined over a 28d period following application. Determination of ^{15}N recovery in plant, soil, and leachate occurred at experiment termination.
Results : Applying either surfactant with urea resulted in significantly higher soil volumetric water content (in sandy loam and sandy clay loam soils) and higher bermudagrass clipping yield (in all soils) than urea. Surfactants applied with urea decreased percent ^{15}N recovery in leachate from sand by 37–46%, increased percent ^{15}N recovery in the sandy loam by 37%, and increased percent utilization of ^{15}N by bermudagrass grown in the sandy clay loam by 61–67% compared to urea applied alone.
Conclusion : Applying surfactants with urea can increase bermudagrass N uptake efficiency and reduce potential N leaching.

Key words: ^{15}N isotope labeled nitrogen / soil volumetric water content

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1 Introduction

Nitrogen (N) is required in the largest amount by plants (Mengel et al., 2006) and therefore N fertilizer has been used extensively all over the world (Halitligil et al., 2002). Forty to 60% of applied N is used by a crop (Sebilo et al., 2013), with the balance remaining in the soil profile, lost through volatilization, denitrification, surface runoff, or leached past the root zone to potentially contaminate water resources (Halitligil et al., 2002; Sieling and Kage, 2006). Nitrogen leaching into surface and groundwater is a particularly important issue in turfgrass cultivation, with an estimated 30% of applied N to turfgrass leached annually (Barton and Colmer, 2006). Brown et al. (1982) and Guertal and Howe (2012) reported leachate N concentrations exceeded the maximum contaminant level for drinking water (> 10 mg L^{-1}; USEPA, 2011) under bermudagrass, one of the most common turfgrass species in the southwest and southeast USA (Snyder et al., 1984; Fagerness et al., 2004; Bowman et al., 2006).

Turfgrass management practices that reduce N leaching include applying N at a rate the plant can utilize (Carpenter et al., 1998; Barton and Colmer, 2006), recycling clippings (Harivandi et al., 2001; Qian et al., 2003) and optimizing irrigation rates and frequencies (Barton and Colmer, 2006; Espevig and Aamlid, 2012). In addition, combining N fertilizer with soil surfactants is being proposed as a management technique to increase N use efficiency and reduce N leaching from turfgrass systems.

Soil surfactants, commonly called wetting agents, have been widely used to ameliorate soil–water repellency in sand-

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based turfgrass systems (Cisar et al., 2000; Hallett, 2008). However, minimal research has evaluated how surfactants in conjunction with a N fertilizer can affect soil water holding capacity, turfgrass yield and N leaching in wettable soils (Lehrsch et al., 2011). When combined with irrigation, surfactants have the potential to improve water use efficiency and nutrient uptake (Chaichi et al., 2015), most likely by the surfactant increasing water infiltration and distribution uniformity throughout the soil profile (Mitra et al., 2006), and subsequently water and dissolved nutrients are more available for plant uptake increasing turfgrass quality, and reducing leaching (Aamlid et al., 2009a; Dekker et al., 2019).

While an increase in turf quality may be due to more N uptake (Johnson et al., 1987), and more N has been found in turfgrass grown on surfactant treated soils (Aamlid et al., 2009a), no scientific research has been completed to trace applied N throughout the soil–plant–water nexus when a surfactant is applied. Adding ^{15}N-enriched material is considered the most reliable way to trace where N moves through a system (Peterson and Fry, 1987; Robinson, 2001; Bedard-Haughn et al., 2003). There are a wide range of surfactant chemistries on the market and under development that claim to help soils retain water, and increase N uptake and turfgrass quality (Zontek and Kostka, 2012; Curtis and Thomas, 2016). In this study, two surfactant chemistries (a new chemistry that contains 10% oleic acid esters of block copolymer and a surfactant that has been available that contains 10% alkoxylated polyols and 7% of glucoethers) and investigated for such claims.

Since surfactants increase the soil's retention of water and applied nutrients, it is suspected an increase in plant N uptake and a decrease in N leaching can be achieved. The objective of this study was to identify if the two surfactants can reduce N leaching from a turfgrass-soil system while maintaining acceptable quality and growth. Here we use ^{15}N labeled urea to determine exactly how the surfactants influence N partitioning in the turfgrass–soil system.

2 Material and methods

2.1 Location and experiment set-up

The experiment was conducted at Clemson University's Greenhouse Complex, Clemson, SC, USA (latitude 34°40¢26.4¢¢N and longitude 82°49¢57.3¢¢W) from 12 August to 13 September 2015 and repeated from 02 February to 16 April 2016. Leaching columns were constructed from polyvinyl chloride (PVC) pipes with a 10 cm dia. and a height of 46 cm. A 20 · 20 cm mesh, 0.013 cm dia. screen (ADFORS Small Insect, Compagnie de Saint-Gobain S.A., La Défense, Courbevoie, France) was laid over the bottom of the PVC lip, followed by a slip cap to retain soil. Each slip cap had a drilled hole to allow leachate to flow out of the column. Each of five shelves held 12 units (representing one replication) vertically.

Columns were packed with one of three wettable soils that were first screened through a 2-mm sieve and then air-dried in the greenhouse by being spread over a tarp to a 5 cm thickness and turned every few days for two weeks. Play sand (S) (Quikrete , Atlanta, GA, USA) was triple washed with distilled water and was selected as an inert control for the following two agriculturally significant soils found in the southeastern USA: a sandy loam (SL) collected from the Ap (10 cm in thickness) of a Toccoa series at Calhoun Field Station, Clemson SC (34°40¢19.2¢¢N, 82°50¢49.8¢¢W) and a sandy clay loam (SCL) soil collected from the Bt horizon (approximately 18 cm in thickness) of a Lynchburg series at Clemson University's Pee Dee Research and Education Center, Florence SC (34°16¢54.3¢¢N, 79°44¢19.3¢¢W). Soil organic matter was 0.0%, 4.1% and 2.2%, and pH was 7.3, 6.8 and 7.0 for the S, SL, and SCL, respectively (analysis completed at the Clemson University Agricultural Services Laboratory, Clemson, SC, USA). For each soil, columns were packed to a height of 43.5 cm by uniformly tapping using a wooden rod (Jalali and Ostovarzadeh, 2009) to achieve uniform packing and bulk density (1.6, 1.4 and 1.5 g cm^{-3} for S, SL, and SCL, respectively).

Tifway 419 bermudagrass sod (*Cynodon dactylon* L. · C. *transvaalensis* Burtt-Davy) (Carolina Fresh Farms and Garden, Anderson, SC, USA) was washed until the root zone was visually free of soil and then cut to the diameter of the columns. Sodded columns were irrigated with deionized water three times a week [1.3 cm (78 mL) per application] until established. The amount of irrigation used in this study was based off of maximum bermudagrass water use (McCarty and Miller, 2002). The greenhouse temperatures ranged from 27–28°C, with a relative humidity range of 50–55%. Supplementary lighting was only used when the light intensity outside the greenhouse was below 300 watts per square meter (W m^{-2}) for a period of 30 min or more between the 0600 and 1700 h.

The experiment began once the bermudagrass was established. Columns were irrigated with the same amount of water three times a week for four weeks (the duration of the experiment). Four treatments: (1) 10% alkoxylated polyols and 7% of glucoethers surfactant (17.90 kg ha^{-1}) with ^{15}N labeled urea (IRG+N), (2) 10% oleic acid esters of block copolymer surfactant (8.9 kg ha^{-1}) with ^{15}N labeled urea (AGS+N), (3) water with ^{15}N labeled urea (WAT+N), and (4) water without ^{15}N labeled urea (WAT-NO-N) were hand applied at experiment initiation with the irrigation water applied on the first scheduled irrigation day. The surfactants do not contain N and are made of carbon atoms bonded together into long chains. Granular urea (16% enriched ^{15}N, Icon Services Inc, Summit, NJ, USA) was dissolved in the irrigation water at a rate of 24 kg N ha^{-1} and then the surfactants were added to the solution. Urea was selected because it is a common N fertilizer used in agriculture due to its high N content and solubility (Soares et al., 2012; Saggar et al., 2013).

2.2 Measurements

2.2.1 Soil volumetric water content and leachate

Soil volumetric water content (VWC) was measured in the upper 5 cm of the soil before each irrigation event using a

Table 1: Treatments including surfactant chemistries, trade names, manufacturers, rate, and Abbreviation used for both experiments to examine nitrogen partitioning in soil, plant and leachate. Experiments were initiated once surfactants and the urea fertilizer (applied at a rate of 24 kg N ha^{-1}) were mixed into the irrigation water for each individual column and applied to the soil just above the bermudagrass leaf blades.

Surfactant	Active ingredient	Manufacturer	Rate (kg ha^{-1})	Abbreviation
IrrigAid Gold	10% alkoxylated polyols and 7% of glucoethers	Aquatrols Corporation of America, Paulsboro, NJ	17.90	IRG+N
Agstone^{TM} 15	10% oleic acid esters of block copolymers	Agstone, LLC, Greenville, SC	8.90	AGS+N[a]
	Water + urea	–	–	WTR+N
	Water without urea	–	–	WTR-NO-N[b]

[a] A new surfactant chemistry.
[b] WTR-NO-N was used to account for natural ^{15}N abundance occurring in soil, plant and water.

hand-held time domain reflectometry device (Dynamax, Inc., Houston, TX, USA). Values were averaged for each week. Leachate was collected after each irrigation in cups placed under each column. Leachate volume was measured using a graduated cylinder, collected and placed in 100 mL Nalgene bottles (U.S. Plastic Corporation, Lima, Ohio, USA) and stored in a freezer at –4°C (Dubourg et al., 2015).

2.2.2 Bermudagrass color and growth

Each week, bermudagrass color and density ratings were observed visually. For both parameters, a rating scale of 1 to 9 (9 = dark green turf/dense turf, 1 = dead / brown turf, and 6 = minimally acceptable turf) was used (Aamlid et al., 2009b; Trenholm and Unruh, 2009). The bermudagrass was maintained at a 2.5-cm height weekly and individual column clippings were collected throughout the experiment. Clippings were oven-dried at 60°C and weighed. At the end of the experiment, aboveground biomass was removed and any remaining soil gently washed away. The columns were emptied and roots were carefully removed and washed to remove as much soil as possible. Both aboveground biomass and roots were oven-dried at 60°C for 48 h and weighed (Engelsjord et al., 2004; Erickson et al., 2010), with subsamples ashed in a muffle furnace (Thermo Fisher Scientific Inc., Hudson, NH, USA) and reweighed (Smit et al., 2013; Rowell, 2014).

2.2.3 Preparation and analysis of samples for ^{15}N analysis

At the end of each experiment, soil samples were extracted from each column using a 2.5-cm diameter soil corer for the full column depth. Soil samples were placed in brown bags and air-dried at room temperature. Subsamples (50 g) from each soil were ground to a fine powder using a grinder (Wayfair LLC, Boston, MA, USA), then subsamples were packed into 12.5 · 5 mm tin capsules. To prevent contamination, the grinder and all equipment were completely cleaned between samples using compressed air and a brush. For each column, plant subsamples were ground (clippings, roots, and aboveground biomass in the same proportion as their weights) to a fine powder using the same grinder as the soil samples. Plant subsamples (3–4 mg for bermudagrass grown in all soils) were packed into 12.5 · 5 mm tin capsules.

At experiment termination, the leachate samples that were collected over the study period were thawed at room temperature (24°C) and were filtered using 25 mm quartz filters. After drying at 60°C for 48 h (Dubourg et al., 2015), these quartz filters were folded into 8 · 11 mm tin capsules using two tweezers. The tin capsules containing plants, soils and leachate filters were loaded into 96 well Elisa plates (Thermo Fisher Scientific, Waltham, MA, USA) and sent to the University of Saskatchewan Stable Isotope Facilities, Saskatchewan, Canada, for ^{15}N analysis.

2.2.4 ^{15}N recovery and fluxes

Natural ^{15}N abundance for turfgrass, soil, and leachate were determined from columns receiving the WAT-NO-N treatment (mean of five measurements) (Cannavo et al., 2013). Total ^{15}N recovery (TR) was calculated as the summation of the ^{15}N fluxes using the following equation:

$$\mathrm{TR} = \%\mathrm{UFN} + \%\mathrm{RFN_S} + \%\mathrm{RFN_L}, \tag{1}$$

where %UFN is the percentage use of ^{15}N fertilizer by bermudagrass, $\%\mathrm{RFN_S}$ or $\%\mathrm{RFN_L}$ are the percentage recovery of ^{15}N fertilizer in soil or leachate.

The ^{15}N fluxes were determined using the following equations (Jose et al., 2000; Bedard-Haughn et al., 2003; Allen et al., 2004):

$$\%\mathrm{UFN} = 100 \cdot \frac{\mathrm{S} \cdot (\mathrm{a} - \mathrm{b})}{\mathrm{R}}, \tag{2}$$

where S is the N content in the bermudagrass, R is the ^{15}N applied rate, a is the atom% ^{15}N abundance in fertilized bermudagrass, b is the natural atom% ^{15}N abundance in bermudagrass.

$$\%\mathrm{RFN_S} \text{ or } \%\mathrm{RFN_L} = 100 \cdot \left(\frac{\mathrm{a} - \mathrm{c}}{\mathrm{b} - \mathrm{c}}\right) \cdot \left(\frac{\mathrm{N_b}}{\mathrm{N_f}}\right), \tag{3}$$

where a is the atom% ^{15}N abundance in the fertilized soil material (or leachate), b is the atom% ^{15}N abundance in the labeled fertilizer, c is the atom% ^{15}N abundance in the non-fertilized soil (or leachate), N_p is the total N of soil sample (or leachate), and N_f is the total amount of ^{15}N applied to the soil as labeled fertilizer.

2.3 Experimental design and data analysis

A completely randomized experimental design was used with five replicates per treatment, with soil as the main plot factor, and treatments randomized within soils. Data were found normal (Shapiro–Wilk test) and variance homogeneous (Levene's test). The analysis of variance was used to test the effects of soil and surfactant. Fisher's least significant difference (LSD) test was used for multiple means comparison. All significance tests were performed with a = 0.05 and all calculations were performed using the JMP Pro 12.0.1 software (SAS Institute Inc., Cary, NC).

3 Results

There were no significant interaction effects on any parameters (Tabs. 2 and 3). Soil was a significant factor for all measurements; therefore, results are discussed for each soil separately.

3.1 Soil volumetric water content

Water content in all three soils was maintained mostly between the permanent wilting point (0.01, 0.05, and 0.06 $m^3\ m^{-3}$ for S, SL, SCL respectively) and field capacity (0.07, 0.18, and 0.22 $m^3\ m^{-3}$ for S, SL, and SCL, respectively) (Brady and Weil, 2008; Soil Survey Staff, Natural Resources Conservation Service, 2008) (Fig. 1). Significant differences were observed in VWC each week for each soil and treatment (Tab. 2, Fig. 1). The VWC in S was less than half of VWC measured in the SL and SCL (Fig. 1). In week 1, IRG+N and AGS+N increased the VWC in S compared to WTR+N and WAT-NO-N (Fig. 1A). For the remaining three weeks, VWC in

Table 2: Table of significance from the ANOVA testing the effects of trial, soil, treatments and their interactions on soil volumetric water content, color and density of bermudagrass. Interactions were not significant for all parameters. Significant values ($p < 0.05$) are in bold.

	Week 1	Week 2	Week 3	Week 4
	Soil Volumetric Water Content			
Soil	0.0021	0.0123	< 0.0001	< 0.0001
Treatment	0.0011	< 0.0001	0.0278	0.0190
Trial	0.5621	0.3123	0.3412	0.7743
Soil · Treatment	0.3910	0.2212	0.9321	0.6821
Soil · Trial	0.6321	0.2123	0.0912	0.2890
Treatment · Trial	0.3321	0.3123	0.9012	0.1143
Soil · Treatment · Trial	0.7306	0.3212	0.6998	0.0761
	Bermudagrass Color			
Soil	0.0002	0.0412	0.0077	< 0.0001
Treatment	0.3321	0.0032	< 0.0001	< 0.0001
Trial	0.4284	0.5131	0.8434	0.1265
Soil · Treatment	0.3411	0.9506	0.1228	0.1732
Soil · Trial	0.0879	0.9047	0.6211	0.0821
Treatment · Trial	0.4221	0.4431	0.5609	0.5461
Soil · Treatment · Trial	0.4284	0.2231	0.8434	0.1265
	Bermudagrass Density			
Soil	< 0.0001	0.0311	< 0.0001	< 0.0001
Treatment	0.3423	0.0309	0.0005	< 0.0001
Trial	0.4652	0.1009	0.3321	0.3122
Soil · Treatment	0.6744	0.4533	0.6621	0.4456
Soil · Trial	0.8997	0.5681	0.5546	0.5999
Treatment · Trial	0.9561	0.6743	0.5498	0.9511
Soil · Treatment · Trial	0.6652	0.6675	0.9898	0.0985

Table 3: Table of significance from the ANOVA testing the effects of trial, soil, treatments and their interactions on clipping, leachate volume, ^{15}N leached, ^{15}N total recovery (TR), percent utilization of ^{15}N fertilizer by bermudagrass (UFN), percent recovery of ^{15}N fertilizer in soil (RFN_S), percent recovery of ^{15}N fertilizer in leachate (RFN_L). Interactions were not significant for all parameters. Significant values ($p < 0.05$) are in bold.

	Clipping	Leachate Volume	^{15}N leached	TR	UFN	RFN_S	RFN_L
Soil	0.0041	0.0001	0.0212	< 0.0001	0.0078	0.0001	0.0412
Treatment	0.0044	0.0012	0.0632	< 0.0001	0.0338	0.0311	< 0.0001
Trial	0.3210	0.2311	0.9812	0.5433	0.8783	0.8723	0.7832
Soil · Treatment	0.7213	0.1182	0.4429	0.4532	0.4432	0.3421	0.1765
Soil · Trial	0.4284	0.5531	0.4334	0.1265	0.9211	0.6131	0.7611
Treatment · Trial	0.3476	0.4206	0.3728	0.1982	0.3332	0.1654	0.2144
Soil · Treatment · Trial	0.6321	0.6547	0.1413	0.4218	0.1998	0.7721	0.4413

S was statistically similar regardless of being treated with IRG+N, AGS+N, or WTR+N (Fig. 1A). Significantly higher soil VWC was consistently observed in SL and SCL treated with surfactant-N treatments (IRG+N and AGS+N) (Fig. 1B, C). IRG+N and AGS+N significantly increased soil VWC over WTR+N in 3 of 4 weeks in SL and in all weeks in SCL.

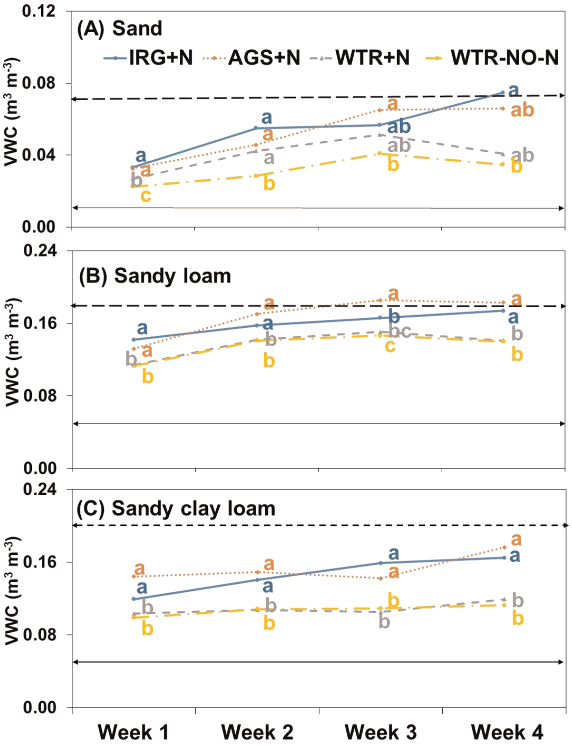

Figure 1: Comparison of the mean soil volumetric water content (VWC) for (A) sand, (B) sandy loam, and (C) sandy clay loam over the four-week experimental period. Treatments are IrrigAid Gold surfactant with N fertilizer (IRG+N), AgStone surfactant with N fertilizer (AGS+N), water with N fertilizer (WTR+N), and water without N fertilizer (WTR-NO-N). Treatment means with the same letters within soil and week are statistically similar using Fisher's least significant difference test with a = 0.05. The black bold arrows indicate permanent wilting point and the black dotted arrows indicate field capacity. Note difference in y axis scales.

3.2 Bermudagrass growth

Within each soil type, there were similar bermudagrass color and density ratings (Fig. 2). Although not significant, it should be noted that both ratings were initially lower in the S than the SL and SCL (Fig. 2). In S, application of AGS+N resulted in significantly better bermudagrass color in 3 of 4 weeks (Fig. 2A). While the AGS-N treatment had the highest density ratings, it was statistically similar to IRG-N and WTR+N in all weeks except week 3 (Fig. 2B). All surfactant treatments resulted in acceptable bermudagrass color and density (rating > 6) when grown on the SL and SCL (Fig. 2 C–F). In SL, turf color and density for AGS+N were better than WAT+N in week three, respectively (Fig. 2C, D). With the exception of density in weeks two and four, where IRG+N was better than WAT+N, bermudagrass grown in SL treated with IRG+N and WAT+N recorded similar color and density (Fig. 2C, D). With the exception of color in week 2 where AGS+N was better than WAT+N, bermudagrass grown in SCL treated with urea performed similarly for color and density (Fig. 2E, F).

In all soils, surfactants influenced total clipping weights (Tab. 3, Fig. 3). For bermudagrass grown in S, total clipping weights from IRG+N was higher than AGS+U and WTR+U (which were similar). Total clipping weights from plants grown in SL and SCL and treated with AGS+N or IRG+N were significantly higher than WTR+N and WTR-NO-N (which were statically similar) (Tab. 3, Fig. 3). Ashed root and aboveground weights were not affected by surfactants (p values , 0.050, data not shown).

3.3 Leachate volume and ^{15}N leached

Total leachate volume from S was higher than SL and SCL (Tabs. 3 and 4). In S, IRG+N and AGS+N recorded similar total volume leached. The IRG+N decreased total volume leached compared to the WTR+N (20%) and WAT-NO-N (22%), and AGS+N also decreased total volume leached compared to the WTR+N (22%) and WAT-NO-N (24%) (Tab. 4). No statistically significant treatment effects on leachate volume were observed in SL and SCL (Tab. 4).

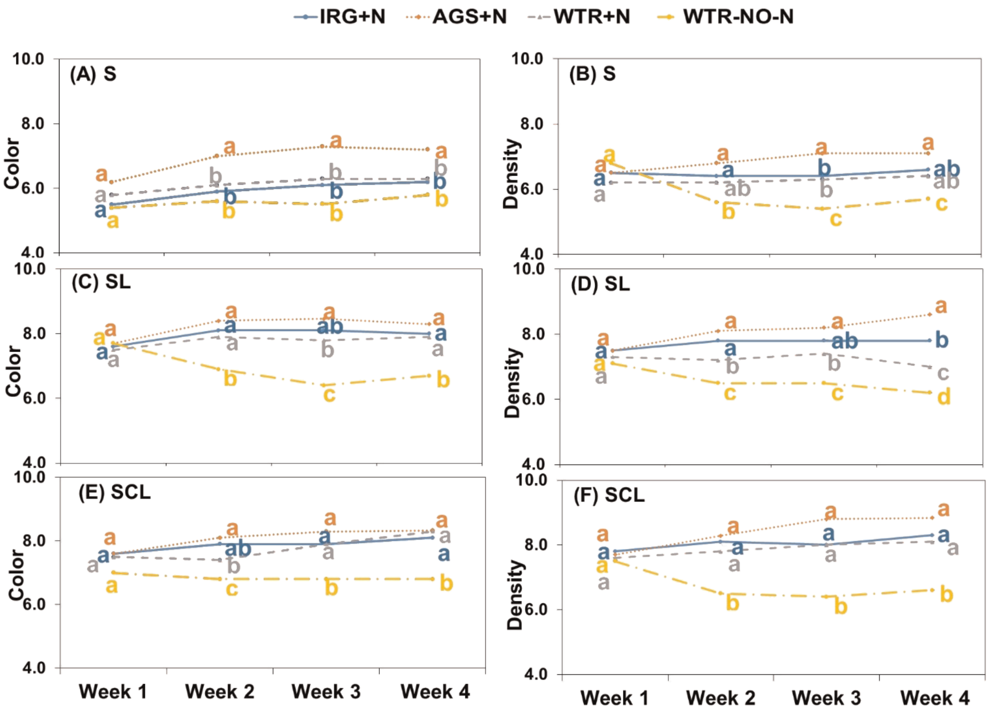

Figure 2: Visual color (A, C, and E) and density (B, D, and F) ratings (1–9 scale: 1 = worst, 6 = acceptable, 9 = best) for bermudagrass grown on sand (S), sandy loam (SL), and sandy clay loam (SCL) over the four-week experimental period. Same letters within week are statistically similar using Fisher's least significant difference test with a = 0.05. Treatments are IrrigAid Gold surfactant with N fertilizer (IRG+N), AgStone surfactant with N fertilizer (AGS+N), water with N fertilizer (WTR+N), and water without N fertilizer (WTR-NO-N).

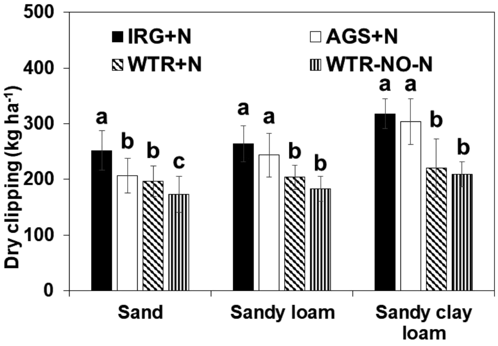

Figure 3: Dry clipping (kg ha^{-1}) over the experimental period from sand (S), sandy loam (SL), and sandy clay loam (SCL). Bars with same letters are statistically similar using Fisher's least significant difference test with a = 0.05. Vertical bars indicate standard errors of the means (n = 5). Treatments are IrrigAid Gold surfactant with N fertilizer (IRG+N), AgStone surfactant with N fertilizer (AGS+N), water with N fertilizer (WTR+N), and water without N fertilizer (WTR-NO-N).

Although not significant, bermudagrass grown in all soils leached less ^{15}N from IRG+N and AGS+N compared to WTR+N (Tab. 4).

3.4 ^{15}N total recovery and fluxes

The WAT-NO-N treatment was used to integrate natural ^{15}N abundance into fluxes and the TR, and thus is not discussed as a treatment. Soil texture had an influence on the results of TR, UFN, RFN_S, and RFN_L (Tab. 3, Fig. 4). The highest TR was from S (84%), with the largest contributing flux being RFN_L (Fig. 4). In comparison, RFN_S was the greatest flux in the SL, and UFN for the SCL (Fig. 4).

No significant differences were observed among treatments in UNF in S and SL. In SCL, IRG+N and AGS+N increased UFN by 61% and 67%, respectively, compared to WAT+N (Fig. 4). In S, both IRG+N and AGS+N had 65% and 100% more RFN_S than WTR+N, respectively. In SL, AGS+N recorded 37% higher RFN_S than WTR+N. All treatments had similar RFN_S in SCL. Using a surfactant reduced RFN_L by 37% (IRG+N) and 46% (AGS+N) compared to WAT-N (Fig. 4) in S. As soil texture became finer (SL and SCL), AGS+N and IRG+N became ineffective in reducing RFN_L compared to WTR+N (Fig. 4).

4 Discussion

4.1 Soil volumetric water content

The VWCs increased with the presence of finer mineral fractions. Differences in VWC among soils may be attributed to the differences in their ability to hold water, with soil having higher clay content retaining more water in the soil (Osman, 2012). Surfactants have been widely proposed as a strategy for improving water use efficiency and increasing soil water

Table 4: Total volume leached (mL) and ^{15}N in leachate (%) from bermudagrass grown on sand, sandy loam and sandy clay loam as affected by IrrigAid Gold surfactant with N fertilizer (IRG+N), AgStone surfactant with N fertilizer (AGS+N), water with N fertilizer (WTR+N), and water without N fertilizer (WTR-NO-N). Means in a column followed by same letter are not significantly different based on Fisher LSD Test (p , 0.05).

Treatment	Sand	Sandy Loam	Sandy Clay Loam
	Total leachate (mL)		
IRG+N	214 b	134 a	112 a
AGS+N	209 b	151 a	102 a
WTR+N	268 a	168 a	140 a
WTR-NO-N	276 a	167 a	115 a
	^{15}N in leachate (%)		
IRG+N	0.041 a	0.023 a	0.011 a
AGS+N	0.044 a	0.028 a	0.014 a
WTR+N	0.045 a	0.032 a	0.015 a

capacity for water-repellent soils, which is likely due to their ability to reduce water surface tension, allowing water to infiltrate into the soil pore space and distribute uniformly (Dekker et al., 2005; Madsen et al., 2012). Few studies have examined the impact of surfactants on VWC in non-repellent soils (Chaichi et al., 2015). In this study, the effect of surfactants in increasing VWC for wettable soils was more evident in SL and SCL. Both surfactants increased the VWC similarly. Chang et al. (2020) reported slightly higher soil VWC from surfactants applied to a wettable fine sandy loam soil when irrigation and N fertilizer were applied.

Soil VWC increased by surfactant treatments only in one week in S, perhaps because the surfactant application rates were not high enough to cause significant changes in the VWC in all weeks in this soil. Further research is necessary to evaluate the effectiveness of surfactants on sandy soils at different surfactant application rates and frequencies.

4.2 Bermudagrass growth

There was a clear effect from AGS+N on color and density for bermudagrass grown in S that diminished with increasingly finer-textured soils (SL and SCL). With the exception of density for bermudagrass grown on SL, as long as urea was applied, there was no statistical benefit to adding a surfactant for most color and density observations in the SL and SCL. It should be noted that although a 0.5 increase in color and density may not be statistically different in the present data, some practitioners may consider it to be enough of a difference to adopt a maintenance strategy. Both surfactants resulted in greater clipping yields than WTR+U in the two finer-textured soils. Where AGS+N increased density and color of bermudagrass grown on S, IRG+N increased clipping yield, suggesting that the IRG+N resulted in more blade elongation rather than more blades. Increasing clipping yield in surfactant treated soil may be explained by higher water retention of soils treated with IRG+N and AGS+N compared to soil treated with WTR+N.

The positive effect of surfactants on turfgrass quality and growth has been previously documented (Karnok and Tucker, 2001; Kostka et al., 2008; Oostindie et al., 2008, Dekker et al., 2019). Furthermore, the variability in turfgrass response from different surfactant chemistries is well documented (Cisar et al., 2000; Leinauer et al., 2007; Barton and Colmer, 2006).

4.3 Leachate volume and ^{15}N leached

The greatest leachate volume came from S and decreased with increasing finer mineral fraction in the soils (SL and SCL). This is in agreement with the lower VWC from S compared to SL and SCL. Applying surfactants with urea (AGS+N or IRG+N) reduced the amount of leachate compared to WTR+N in sandy soils. As discussed earlier, surfactants can allow water to infiltrate into soil pore spaces, increasing distribution uniformity, and thus resulting in lower leachate volume (Leinauer, 2002). This finding indicated that incorporating surfactants with irrigation applications in sandy soils provides a more optimal root zone environment for plant growth, reduces the potential of water loss to the surrounding environment, and improves irrigation efficiency. This finding has application where turfgrasses are grown in sandy soils with shallow water tables, for example, on golf

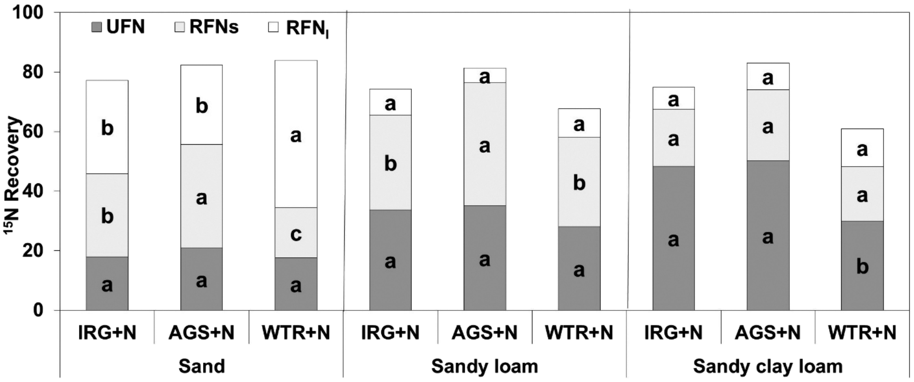

Figure 4: Surfactant impact on percent utilization of ^{15}N fertilizer by bermudagrass (UFN), percent recovery of ^{15}N fertilizer in soil (RFN$_S$), and percent recovery of ^{15}N fertilizer in leachate (RFN$_L$) from bermudagrass grown on sand, sandy loam, and sandy clay loam at the end of the experiment. Bars with the same letter within each soil are statistically similar using Fisher's least significant difference test with a = 0.05. Treatments are IrrigAid Gold surfactant with N fertilizer (IRG+N), AgStone surfactant with N fertilizer (AGS+N), and water with N fertilizer (WTR+N). Total ^{15}N recovery (TR) was calculated as the summation of the UFN, RFN$_S$, and RFN$_L$ for each bar.

courses, sports fields, right-of-ways, and lawns on sand-based Entisols found along the coast in the southeastern USA.

Further, the trend that surfactant treatments (AGS+N or IRG+N) numerically reduced ^{15}N leached from bermudagrass grown on all soils suggested that incorporating a surfactant may have potential benefits to surrounding nitrogen sensitive environments. Long-term monitoring may be needed to quantify the positive effects of N-surfactant treatments on ^{15}N leaching. Shaddox et al. (2016) reported reduced NO_3-N and NH_4-N leaching from sand-based root zones that incorporated surfactant modified soil amendments.

4.4 ^{15}N fluxes and recovery

The ^{15}N fluxes and total recovery were in agreement with results from VWC, bermudagrass color and density, and leachate volumes from the three soils and surfactant treatments. The total ^{15}N recovery for the three soils were not equal to inputs, a finding that can be attributed to N loss through denitrification and volatilization (Engelsjord et al., 2004). The amount of N loss due to denitrification would be expected to be low under the well-drained conditions that persisted in the present experiment (Naeth et al., 1990; D'haene et al., 2003; Hergoualc'h et al., 2009). However, it is suspected that ammonia volatilization from urea would be a primary N loss because urea hydrolyzes quickly in the soil under warm, humid conditions (Soares et al., 2012). Warm temperatures and high humidity directly after irrigation in the greenhouse may have influenced volatilization (McGarry et al., 1987). Ammonia volatilization from urea has been documented to range from 20.1% to 39% from different turfgrasses grown on varying soils (Nelson et al., 1980; Bowman et al., 1987; Stiegler et al., 2011; Knight Huckaby et al., 2012).

The ^{15}N recovery from plant, soil, and leachate in our experiment were higher than Wherley et al. (2011), lower than Fagerness et al. (2004), and similar to Miltner et al. (1996). The reason that S had the greatest total recovery in this study is because of the low water holding capacity of S, resulting in an increase in water and N leaching through the profile, which is in agreement with S having the greatest RFN_L.

The addition of surfactants with ^{15}N urea applied with irrigation had the greatest impact on different fluxes based on soil texture (more specifically the type of porosity associated with each soil texture). In particular, as there was an increase in fines (and assumed more micropores), there was a shift in VWC, and the availability of the ^{15}N to be transformed and utilized by the bermudagrass: increased UFN from SCL where the two surfactant treatments (AGS+N or IRG+N) were applied was most likely a result of the increased soil VWC (documented throughout this study), a condition that most likely resulted in water present in an adequate amount for enough time for the hydrolysis of urea and microbial activity for urea transformation to plant-available nitrogen forms (Carrow et al., 2001; Dekker et al., 2019). In the case of the SL, the greatest recovery was from the soil in which there are fewer micropores and more macropores than the SCL (as suggested by the lower VWC than the SCL). Providing less optimal conditions (amount of water and time) for microbial activity, perhaps there was less urea transformation to plant-available forms in the SL. In the SL, AGS+N resulted in more RFN_s than the IRG+N and WTR+N. The soil that would be dominated with macropores (the S) had the greatest RFN_L. It is notable that only in S was the ^{15}N recovery from two fluxes (RFN_L and RFN_S) was positively influenced by the addition of the surfactants (reduced RFN_L, and increased RFN_S).

Our results suggest that as irrigation water use efficiency increases (as evident of increased VWC in this study, due to presence of surfactant), so does nutrient uptake (as evident of bermudagrass growth in this study) and parallel Chaichi et al. (2015), who reported that surfactants increased irrigation water use efficiency and corn grain yield, and Chang et al. (2020), who reported surfactants increased VWC and better turf quality when applied to fine sandy loam soil. In this study, surfactants incorporated into the irrigation water with ^{15}N urea resulted in soils retaining more water, which contains dissolved nutrients within it, in the soil profile, thus decreasing N leaching and increasing available N for plant uptake.

5 Conclusions

This study investigated if bermudagrass quality and N leaching grown on three soils were affected by the application of surfactants with fertilizer. Surfactants increased soil water retention compared to water alone. Subsequently, dissolved N within the water was available for bermudagrass roots to take up, leading to an increase in fertilizer efficiency and reduced N loss through leaching. Perhaps more differences would have been statistically identified for ^{15}N fluxes and total recovery if the experiment was conducted over a longer period of time to include multiple surfactant applications and different surfactant application amounts. The results from this study provide the first evidence that application of surfactants in conjunction with a nitrogenous fertilizer can be a management strategy to increase bermudagrass uptake of N and reduce N leaching from turfgrass systems, especially from sand-based soils such as those found along the southeastern USA coast. These soils tend to have seasonally shallow high-water tables that are hydrologically connected to surface water bodies and thus are susceptible to contamination. Reducing N leaching to these natural resources can be accomplished by adding a surfactant with the fertilizer and irrigation water.

Due to the macroporosity and subsequent rapid drainage and drought-like conditions, sand soils have been the primary focus for investigating surfactant use. This study is one of the few works documenting the influence of surfactants on turfgrasses grown on finer-textured soils. The increase in VWC and N uptake from bermudagrass (as determined by UFN) grown on SCL soil treated with surfactant documented in this research suggests that surfactants may be a useful tool for increasing nutrient use efficiency in turfgrasses grown on finer textured soils.

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Data Availability Statement

Research data are not shared.

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