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Nitrogen Use Efficiency of Polymer-Coated Urea

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Nitrogen Use Efficiency of Polymer-Coated Urea

Curtis Joel Ransom

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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ABSTRACT

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Master of Science

Plants require N to complete their life cycle. Without adequate concentration of N, crops will not produce their potential yields. For turfgrass systems, N fertilizer application allows for the maintenance of functional, aesthetic, and recreational properties. However, fertilizer mismanagement is common and leads to N pollution in the environment. Controlled-release and slow-release fertilizers can enhance nitrogen (N)-use efficiency, reduce N pollution, minimize the need for repeated fertilizer applications, and reduce turfgrass shoot growth and associated costs. In order to evaluate the effectiveness of these fertilizers in the Intermountain West, research is needed.

The timing of N release was evaluated for seven urea fertilizers: uncoated, sulfur coated (SCU), polymer-sulfur coated (PSCU), and four polymer-coated (PCU) with release timings of 45, 75, 120, and 180 d estimated release. These products were placed on bare soil, a Kentucky bluegrass (*Poa pratensis* L.) thatch layer, and incorporated into soil. These three placement treatments were replicated to allow for enough samples to be placed in two locations. The first was outside in a field to represent field conditions with diurnal fluctuating temperatures and the second was placed in a storage facility to replicate laboratory conditions with static diurnal temperatures. The PCU prills incorporated into soil under field conditions generally released N over the estimated release period. However, when applied to bare soil or thatch, N from PCU had 80% or greater N release by 35 d after application regardless of expected release time. Fertilizers under laboratory conditions had minimal N release despite having similar average daily temperatures, suggesting that fluctuating temperatures impact N release. The PSCU and SCU treatments were no different from uncoated urea, showing no slow release properties for this particular product.

Spring-applied N fertilizer trials were conducted over two years to determine the optimal N rate for Kentucky bluegrass. Similar PCU120 products were applied at 50, 75, and 100% of the recommended full rate, while also being compared to an unfertilized control and urea applied either all at once or split monthly. Spring-applied PCU showed minimal initial N response while urea applied all at once resulted in an initial spike of N uptake. Once PCU began to release N, there was minimal difference for all rates compared to urea split monthly for biomass growth, verdure, and shoot tissue N. Although at the 50% rate, there were a few sampling dates with slower growth and lower verdure. The decrease in verdure at this low rate was slight, and it is recommended that PCU could be applied effectively at a reduced rate between 50 and 75%. Although for better results, additional quick release N is required to compensate for early season lag in N release.

Keywords: polymer-coated urea (PCU), controlled-release fertilizer (CRF), urea, turfgrass, Kentucky blue grass (KBG), release rate

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Chapter 1

Evaluating the Nitrogen Release of Slow and Controlled-Release Fertilizers in Field and Laboratory Conditions at Different Placements

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ABSTRACT

Plants require N but fertilizer mismanagement can lead to N pollution in the environment. Controlled-release (CRF) and slow-release (SRF) fertilizers are commonly used to supply N to turf while mitigating N loss. To better match release of N from CRF products to turfgrass, an evaluation of how these products release under field and laboratory conditions is necessary. The timing of N release was evaluated for seven urea fertilizers: uncoated, sulfur coated (SCU), polymer-sulfur coated (PSCU), and four polymer-coated (PCU) with release timings of 45, 75, 120, and 180 d estimated release. These products were placed on bare soil, a Kentucky bluegrass (*Poa pratensis* L.) thatch layer, and incorporated into soil. These three placement treatments were replicated to allow for enough samples to be placed in two locations. The first was outside in a field to represent field conditions with diurnal fluctuating temperatures and the second was placed in a storage facility to replicate laboratory conditions with static diurnal temperatures. The PCU prills incorporated into soil under field conditions released N approximately over the expected release period. However, when applied to bare soil or thatch, N from PCU had 80% or greater N release as soon as 35 d after application, regardless of expected release time. Fertilizers under static laboratory conditions released minimal N despite having similar average daily temperatures—suggesting that fluctuating temperatures impact N release. The SCU treatments were no different from uncoated urea, showing no slow release properties for this particular product. While PSCU had slightly better slow release properties compared to SCU, its release did not match the expected timing as efficiently as PCU.

Keywords: polymer-coated urea (PCU), control release fertilizer (CRF), urea, nitrogen release rate

INTRODUCTOIN

All plants require nitrogen (N) to complete their life cycles. Nitrogen is vital to various biochemical processes, with the formation of chlorophyll molecules being one of the most important (Marshchner, 2012). Nitrogen is often the primary limiting factor for plant growth due to high demand to facilitate essential biochemical processes, and the fact that soluble soil N is easily lost to the surrounding environment due to its mobile nature (Chatterjee, 2012). Without adequate concentrations of N, plants produce less chlorophyll and proteins, which results in decreased growth and increased susceptibility to pests and diseases (Marschner, 2012).

Heavy applications of N-based fertilizer are often applied to ensure high crop yields and to compensate for losses due to N lost from the soil. The process of applying fertilizers is often inefficient, leading towards a waste of natural resources and money and often results in N lost as a pollutant to the environment through ammonia volatilization, nitrate leaching, and by-products of denitrification, such as nitrous oxide. Nitrogen lost in the various mobile forms contributes to issues in the atmosphere and hydrosphere that ultimately affect human and animal health (Olson et al., 2009; Mulvaney et al., 2009). The use of inefficient fertilizer types often results in further N lost to the environment, degrading water and air quality (Cameron et al., 2013; Zhang et al., 2011). The concern is accentuated in turfgrass systems given that these systems occupy 1.9% of surface area of the U.S. and that the majority of these properties are managed by homeowners, who are largely unaware of potential losses resulting from mismanagement of N fertilizers (Milesi et al., 2005). While some homeowners and turf managers may under apply suitable N rates, most operate under the concept of “if a little is good, more must be better”, and this often results in high N loss into the environment.

Consistent application of N to turfgrass is required to maintain a good density, color, and to increase resistance to pests and environmental stresses. Nitrogen constitutes about 3-4 % of the dry biomass of turf (Marshchner, 2012). Nitrogen fertilizer is generally applied in split applications throughout the active growing season to maintain adequate N concentrations at these optimal concentrations. Recommended rates of fertilizer differ by turfgrass species, with warm-season turfgrass often receiving ~50 kg N ha^{-1} for each month of active growth (Christians, 2007). While cool-season turfgrass, receives a total of ~150-250 kg N ha^{-1} yr^{-1} (Christians, 2007). To meet turfgrass N needs throughout the growing season, N application needs to be somewhat consistent, although a relatively greater amount applied during late fall is beneficial to allow extended deposition of photosynthates, which are deposited into roots to facilitate healthy growth at the beginning of the following growing season.

Control release fertilizers (CRF) and/or slow-release fertilizers (SRF) are often used to increase nitrogen-use efficiency (NUE) and to allow for the provision of N over extended periods of time. As compared to "quick release" fertilizers, CRFs and SRFs are designed to release N over an extended period of time, rather than all at once, in an attempt to better match plant N needs throughout the growing season and to reduce time of exposure for N losses to the environment. Control release fertilizers and SFRs primarily differ in their mode of release. Slow-release fertilizers release through a variety of methods including: microbial processes, chemical reactions, or bursting of a coating due to water vapor infiltration resulting in high internal pressures. Once a point of the coating breaks, the urea becomes exposed and left accessible to be hydrolyzed and further converted to other N forms. This process is relatively more unpredictable compared to CRFs, making additional applications necessary during growing seasons and decreasing N use efficiency (Ellison et al., 2013). This group of fertilizers includes denitrification/nitrification inhibitors, long chain molecules requiring microbial decomposition, and granules coated in a substance to restrict water movement through hydrophobic or hydrophilic attractions (Aviv, 2001).

Control release fertilizers have been developed using a coating around individual granules of fertilizer materials, such as urea. The commonly used polymer coating has micropores that allow soil moisture to diffuse through the coating to dissolve the urea. Urea is a larger molecule than water and, as such, does not immediately cross the membrane into the soil. As temperatures increase, it is thought that the coating warms and expands, increasing the size of the micropores and allowing the urea to eventually reach the soil solution through diffusion. The rate of diffusion follows first-order kinetics with an approximate doubling of the diffusion rate for every 10^{o}C increase (Adams et al., 2013; Ellison et al., 2013; Shaviv et al., 2003).

By altering the thickness of the coating, the rate of N diffusion is reduced. Knowing the plant's N needs and the average soil or air temperature, an appropriate combination of coating thicknesses can be used to match plant N needs (Ellison et al., 2013; Fujinuma et al., 2009; Olson-Rutz et al., 2009; Shaviv and Mikkelsen, 1993). The use of CRFs has increased plant yields and quality (Cahill et al., 2010; Knight et al., 2007), while decreasing the amount of N lost as NO_3^- (Pack and Hutchinson, 2003; Wilson et al., 2010), NH_3 (Knight et al, 2007; Rochette et al., 2009), and N_2O (Halvorson et al., 2008; Halvorson et al., 2010; Hyatt et al., 2010; Jassal et al., 2008) in both turfgrass and agricultural systems (Ellison et al, 2013; Grant, 2008; LeMonte et al., 2011; Torello et al., 1983).

To effectively use these specialty fertilizers, more accurate information regarding N release is needed. Determining the release of N is initially performed in a laboratory setting at a constant temperature. While some research has shown laboratory results accurately match field results (Du et al., 2006; Shaviv et al., 2003), other research has indicated that N is released slower in standing water used as the medium for release in the laboratory than in the field (Adams et al., 2013; Trenkel, 1997; Wilsen et al., 2009). Differences in conditions between a prill applied under field conditions as compared to a laboratory study could be important. An N release laboratory evaluation is typically done by adding prills to a flask of water continuously stirred at a constant room temperature (~20–22^{o}C). Discrepancies between lab and field data may be a result of 1) saturated anaerobic compared to unsaturated aerobic field conditions, 2) constant stirring resulting in friction wear on the coating, 3) fixed room temperature in contrast to widely fluctuating diurnal and seasonal shifts in temperature, 4) differences in light intensity and type (full sun vs. partial shade under plant canopy vs. full or partial day exposure to artificial light in a lab), and 5) equilibrium chemistry feedback mechanisms (if the concentration of the urea in solution is too high, it may result in an impact on the diffusion rate). High fluctuations have resulted in increased rates of release during wetting and drying cycles, causing mass flow of water inward and outward across the polymer coating (Adams et al., 2013).

Another approach to determine N release based on field conditions is the buried bag technique. This involves adding prills to a bag and burying it to a desired depth or placing it on the soil surface and measuring N loss via weight loss over time as the N diffuses out of the bag and into the surrounding soil. The accuracy of these methods depends on the material of the bag and the size of holes in the bag (Carson and Ozores-Hampton, 2012; Golden et al., 2013). A bag containing smaller holes will also act as a barrier to moisture, and thus adequately sized holes are required to allow moisture to move through the bag (Golden et al., 2013). This method better simulates actual field conditions than current methods, although possible problems may arise due to ions diffusing into the bag and/or to equilibrium feedback chemistry due to a large number of prills in a concentrated space.

Buried bags are often used and considered an accurate and easy method to characterize N-release dynamics, although it is not a perfect method. Carson and Ozores-Hampton (2012) found discrepancies where prills not placed in a bag resulted in higher initial release of N. Later measurements showed minimal differences between the methods, resulting in the researchers accepting the buried bag method as the more acceptable way of measuring N release. It is hypothesized that the buried bag method may not be as accurate as expected, especially when used with longer release fertilizers, and when prills are positioned on top of the soil or turfgrass surfaces. Prills placed on the surface are subjected to more wetting and drying periods, as well as to higher temperature fluctuations which results in faster release and lower NUE (Fujinuma et al., 2009). To further understand the N release of prills, laboratory and field studies will be conducted to evaluate N release in settings common to turfgrass systems. A understanding of temperature differences is better needed to help predict N release form CRFs and SRFs

MATERIALS AND METHODS

We conducted laboratory and field experiments to measure N release rates from various urea fertilizers, as affected by temperature fluctuations and placement. Placement treatments included: 1) soil incorporation at a depth of 2.5 cm, 2) placement on bare soil surface, and 3) placement on the surface thatch layer (thatch thickness approximately 1.5 cm) of Kentucky bluegrass (KBG; *Poa pratensis* L.). The study was conducted beginning June 26, 2011 and ending December 22, 2011—simulating a common scenario when CRFs are applied early summer and extending to a date when the longest expected release fertilizer product (180 d) should have had complete N release.

Temperature treatments included: 1) fluctuating diurnal temperatures under field conditions and direct sunlight and 2) static diurnal room temperature in a storage facility without insulation or air conditioning/heating. Static diurnal room temperatures fluctuated +/- 1^{o}C around the daily average within a 24 hour period, with measurements taken every 8 hours with a thermometer and AM400 data logger (MK Hansen, Wenatchee, WA, USA). Although daily fluctuations were static, long term measurements differed with beginning average daily temperatures recorded at 23.0^{o}C but dropping towards the end of the trial with a low of 10.6^{o}C (Fig. 1). Ideally, the average daily air temperatures for both treatments would be similar throughout the study, with the difference being the daily highs and lows.

In contrast, fluctuating diurnal temperatures, measured using a weather station, were more complex than the ideal comparison. Only the first 77 d (June 26-September 11) maintained a similar average daily temperature, within 1^{o}C of each other. After September 11, the difference between the average air temperatures increased, with indoor temperatures continually maintaining a higher average (Fig. 1). Diurnal fluctuating temperatures initially started with an average temperature around 23.5^{o}C and dropped to -3.6^{o}C by the end of the study, with an average standard deviation of 8.9^{o}C each day. Although not directly measured in the plot area on a daily basis, the temperature extremes at the soil surface were roughly double the average temperatures during the summer months of this trial, potentially reaching highs above 50^{o}C. While soil temperature at the depth of incorporated prills was not measured, it was expected to fluctuate to a lesser degree based on principals of damping depth and specific heat capacity of the soil (Campbell and Norman, 1998).

Fertilizers used included: 1) urea (46-0-0), 2) sulfur coated urea (SCU; 39-0-0-19S), 3) polymer-sulfur coated urea (PSCU; 41-0-0-4S), 4) Duration CR© 45 (PCU 45), 5) Duration CR© 75 (PCU 75), 6) Duration CR© 120 (PCU 120), and 7) Duration CR© 180 (PCU 180). The PSCU and PCU products were supplied by Agrium Advanced Technologies (Loveland, CO, USA). The PCU products have estimated release timings as indicated by the number in the name (i.e. PCU 45 has an estimated release timing of 45 d, PCU 75 of 75 d, etc.) and PSCU has an estimated release time of 45 d. The release timings are based on the time required to release 80% or greater of the N in the fertilizer (Agrium, 2004) in tests conducted in laboratory trials at 20°C in water baths, with an estimated doubling of N release rate for every 10°C increase in temperature (Adams et al., 2013).

Fertilizers were applied to the A_p horizon of soil (Timpanogos fine-loam, mixed, mesic Calcic Argixerolls), which was gathered from the Brigham Young University experimental farm (near Spanish Fork, UT, USA; 40°4′1.77″ N Latitude 111°37′44.99″ W Longitude). The soil had a pH of 7.1 and 4% OM. Soil was air dried and sieved through a 2 mm screen. Soil was placed in plastic 6 cm square pots to a depth of 4.5 cm with a landscape fabric liner (Weed-barrier® 1 oz., DeWitt Company, Sikeston, MO, USA) to prevent soil loss. For thatch treatments, 4.5 cm depth of KBG sod, grown on the same soil, was cut to fit the size of each pot. For treatments where fertilizer was incorporated, soil was added to pots to a height of 2 cm, prills were placed on soil, and then covered with 2.5 cm of soil. For all treatments, prills were placed in rows spaced about 0.5 to 1 cm away from the wall of the container and from adjacent prills.

Enough pots were made for each placement treatment and location treatment to be replicated three times for weekly measurements, as well as to provide enough replications to allow for a weekly destructive harvest that would extend the length of anticipated N release, specific to each fertilizer. For example, it is known that urea would have 100% release within the first few hours and so only one week's worth of samples were made, totaling 18 experimental units, three replications for all three positions and duplicated twice for both locations (three replications x three positions x two locations = 18 experimental units). Whereas fertilizer with a release expected to extend longer than a week, more units were required as each unit was destructible harvested. In order to maintain similar replications across time, 18 experimental units were made for each sampling date and for each fertilizer treatment. The amount of units made, depended on the expected release of each fertilizer. For example, PCU 180 was expected to release up to 180 d or about 26 weeks, resulting in a total of 468 experimental units (26 weeks x 18 reps =468 experimental units) This was repeated for each fertilizer with enough experimental units made to allow for 18, 12, 8, 8, and 12 sampling dates for PCU 120, PCU 75, PCU 45, PSCU, and SCU, respectively. A total of 1746 experimental units were made. Pots were completely randomized within the storage facility or field location. Weekly samples were also randomly chosen to account for potential differences in microclimates that may occur from each location. Once samples were shown to release 80% or greater of the original N amount, further analysis of that fertilizer was stopped. Pots were watered to saturation weekly with irrigation water, by misting each pot with a hand sprayer.

At the time of sampling, all applied prills from each pot to be measured were hand removed and rinsed to remove soil particles and placed into a desiccator at 20-22^{o}C for 72 h. Prills were then inserted into a pH 5.6 HCl solution made with double deionized water in a 13 ml plastic vial, filled completely with essentially no atmospheric head space and stored 5 - 10 ^{o}C, for 120 d after completion of the study, to insure complete diffusion of N from the prills and into solution. At the time of analysis, solutions were removed from cold storage, diluted to a volume of 145 ml with a 0.28 N sodium acetate buffer at pH 4.7 to maintain an acidic pH to limit NH_3 volatilization potential. Urease powder was added and solutions were stored for 7 d at 20-22°C to facilitate complete conversion of urea to NH_4^+. Kissel (1998) showed a complete conversion at four d at 27°C, and, therefore, we assumed that an additional three d would result in completion of the reaction at a slightly lower temperature.

Before analysis of the solutions, each vial was shaken by hand for 60 s and left on a flat surface for 60 s to allow any undissolved urease to settle out of solution. One ml was removed from the middle of the vial, and diluted with 49 ml of pH 3.0 HCl solution. Analysis of NH_4^+ and NO_3^- was done colorimetrically with a Flow Injection Analyzer (Lachat Instruments QuickChem 8500 Series 2, Loveland, CO, USA). Process blanks were used to validate minimal N contamination throughout the procedure. As expected, due to conditions not being conducive for nitrification, NO_3^--N was found to be negligible in the solutions and, therefore, only NH_4-N was used to estimate N release rate. The amount of N released from each batch of prills was determined by subtracting the concentration found in solution from the initial amount present.

Before the completion of the study, pH measurements were taken from each sample, to identify the effectiveness of the buffer solution to maintain $pH < 7$. If any sample pH was above 7, it was noted for future analysis. Some fertilizer types, like PCU 180, contained more N in the prills, resulting in a larger pH change with some samples going above 7, while SCU had little to no N remaining, resulting in a minimal change in the pH. To conserve resources during analysis of samples from future sampling dates, any fertilizer type that resulted in a final pH above 7 received a greater concentration of buffer (0.31 N), while those fertilizer types that had a minimal change in pH, received a decrease in buffer concentration (0.14 N). Any fertilizer types that were shown to have a change in pH, but did not pass pH 7, received no change in buffer concentration (0.28 N) for the following sampling date. This was continually monitored and each analysis of prills was adjusted accordingly.

Data was checked for normality and analyzed by analysis of variance (ANOVA) with R (R Project for Statistical Computing, http://www.r-project.org/), with significance indicated at $P \leq 0.05$. Any significant means were separated using a Tukey-Kramer test and at the $P \leq 0.05$ level of significance. The initial ANOVA resulted in highly significant results for nearly every parameter and their interactions. However, minimal difference in N release between prills placed on bare soil and thatch was observed and, in an effort to simplify the results, a step wise deletion using contrast comparisons was done. Non-orthogonal treatment contrasts were used to validate the observed lack of difference between bare soil and thatch. An initial ANOVA model indicated that an estimated mean for thatch and soil surface applications were within two standard deviations of each other. A second ANOVA model was run with both thatch and soil surface applied treatments combined into a single variable. Both models were analyzed by running another ANOVA, with both models not significant from each other ($P = 0.2474$). The lack of significance indicates that there was no observed difference in N release when any of the fertilizers used in this trial were applied to either thatch or to bare soil surface. All statistical analyses were run using this simplified model combining bare soil and thatch placement into a "surface applied" parameter compared to the "incorporated" parameter. The simplified ANOVA resulted in all parameters and possible interactions being significant at P <0.00,1 except the four-way interaction of source*placement*temperature*date ($P = 0.499$).

RESULTS

PCU Incorporated at Fluctuating Temperatures

For PCU prills incorporated into the moist soil and exposed to field conditions with fluctuating diurnal temperatures, the N release rates followed a somewhat expected pattern for PCU 120 (Fig. 2b), PCU 75 (Fig. 3a), and PCU 45 (Fig. 3b) with >80% of applied N released after 98, 84, and 56 d, respectively. These release rates were within 9-22 d of projected timing. Although not as close to the targeted timing, PCU 180 incorporated into the soil also showed an effective controlled release pattern with >80% of N released by 112 d (Fig. 2a). It is not surprising that these release rates were faster than the targeted timing, since the estimate is based on 20^{o}C conditions and the average temperatures during the initial dates of this trial were in excess of this temperature.

PCU Surface Applied at Fluctuating Temperatures

However, when the prills were surface applied under field conditions with fluctuating diurnal temperatures to either thatch or bare soil, the N release rates increased dramatically (Figs. 2c, 2d, 3c, and 3d). All PCU fertilizers released > 80 % N within the first 35 d after application regardless of targeted release timing. For PCU 45, the difference was not very great compared to the incorporated treatment (Fig. 3d), but for the others the release rate was significantly less than when the prills were incorporated into the soil (Figs. 2c, 2d, and 3c).

PCU Incorporated at Static Temperatures

The N release from prills stored indoors with static diurnal temperatures, responded variably by fertilizer source and placement method. The prills incorporated into the soil with shorter targeted release rates, had patterns that more closely followed the field conditions with fluctuating diurnal temperatures and only three and two dates where there was a significant difference between temperature treatments (Figs. 3a, 3b; Table 1).

PCU Surface Applied at Static Temperatures

In contrast, there were significant differences at all dates when these fertilizers were surface applied—with very little overall N release (Figs. 3c, 3d; Table 2). The pattern from the two longer targeted N release fertilizer sources also showed very little release over the course of the trial, regardless of placement (Fig. 2). These results are similar to what was observed for the surface applications of the shorter N release products (Figs. 3c and 3d), but in contrast to when they were incorporated (Figs. 3a and 3b).

Urea, SCU, and PSCU

SCU showed no slow release properties regardless of placement and temperature, as it behaved nearly identically to urea—which, as expected, had 100% N release by the first sampling. (Fig. 4). Although PSCU treatments had somewhat better slow/control release properties compared to urea and SCU, it was minimal compared to PCU (Figs. 2-4). Differences between temperature regimes were seen with surface applied PSCU, with all but one sampling date showing field conditions with diurnal fluctuating temperatures significantly higher than prills under static temperatures (Fig. 4).

DISCUSSION

Temperature has the largest effect on N release from PCU fertilizers as diffusion rates are highly dependent on temperature when adequate moisture is available (Golden et al., 2011; Fujinuma et al. 2009; Du et al., 2006). Higher daily peak temperatures at the soil surface caused a high release rate of N for fertilizer applied to a bare soil surface or on a thatch layer. While thatch used in this study was nonliving, an expected greater slow release of N would occur when applied to well-maintained turfgrass, due to the high canopy and resulting cooling effect (Stier et al., 2012).

The effect of temperature is best seen with surface applied PCU products under field conditions with diurnal fluctuating temperatures, where products expected to release at different rates were released at a similar rate. The effectiveness of PCU products to slowly release N for a desired time period depends on the coating thickness, coating type, and manufacturing process (Adams et al., 2013). The high surface temperatures negated the prolonged release expected with thicker coatings, but when incorporated with similar air temperatures under field conditions, PCU products were able to match the expected release time. Previous research has indicated that using the average air temperature in modeling release rates will accurately predict the release of PCU fertilizers (Fujinuma et al., 2009; Shoji et al., 1991; Zvomuya et al., 2003). This statement applies to agronomic situations where fertilizer is incorporated and the soil provides a buffering effect on temperature. As such, broadcasted fertilizer requires additional measurements of parameters such as soil moisture, temperature fluctuations, wind, and relative humidity, to accurately model the release of N (Husby et al., 2003; Fujinuma et al., 2009). One study found that by including soil moisture in models of release, they were able to more accurately estimate release by 10% over temperature alone. These estimates from laboratory testing would often underestimate measurements observed with field conditions (Fujinuma et al., 2009). This indicates that additional measurements may increase the accuracy of estimates for surface applied CRF.

Moisture is essential to the dissolution and outward movement of N from CRF. While research has shown that a level of 50% field capacity or less will negatively affect release of N (Huett, 2000; Lunt and Oertil, 1962; Kochba et al., 1990), others have indicated that a high soil humidity is often enough to insure diffusion, even when soil moisture is below field capacity (Christianson, 1998; Du et al., 2006; Golden et al., 2011). Surface applied fertilizers are often exposed to conditions of soil moisture less than 50% field capacity. Along with minimal soil contact, wind, and high soil temperatures—this may act to quickly remove any available water needed to facilitate diffusion (Fujinuma et al., 2009). Surface applied fertilizer under field conditions did not have the same access to water as those that were incorporated; still there was enough water to facilitate diffusion. The quick change in moisture at the soil surface caused by wetting and drying periods also affects the release rate of N from PCU. With fluctuating temperatures, there is a parallel in fluctuating water potential. This has been shown to increase N release fromm CRF as it promotes a mass flow of N out of the prill and into the soil solution (Adams et al., 2013).

Surprisingly, when fertilizer was not placed in field conditions but had relatively similar average air temperature, there was a decrease in the overall amount of N released. The static temperature is a close replication of laboratory settings that are traditionally used to determine release of N. Under these conditions, prills are monitored at a constant temperature. These methods do not translate to field conditions under which release rates are often faster rate (Adams et al., 2013; Du et al., 2006). Results from this study in a soil solution also show a lack of similarity to field conditions. Generally, an opposite effect was seen with a decrease in the rate of release under static temperatures.

Our results suggest that care needs to be taken to closely mimic field conditions to more accurately estimate N release. In a laboratory experiment with CRF placed in incubators that replicated diurnal fluctuating temperatures, the rates of nutrient release would mimic the fluctuating temperatures (Husby et al., 2003). The increase in fluctuating temperatures resulted in a higher percent of N released and that corresponds with reported data taken under field conditions with diurnal fluctuating temperatures.

Like CRF which depends on temperatures and diffusion of water for release, SRF like SCU, further depends on microbial activity to breakdown wax coatings (Ellison et al., 2013). While a slow release was expected from SCU, this study showed no slow release properties, regardless of placement method or temperature fluctuation with all treatment releasing 80% or more N by week 1. All SCU prills were observed to be physically cracked even after 7 d from date of application. Not all SCU's would be expected to behave similarly, but in this study it did not perform differently than uncoated urea.

The combination of both SCU and PCU coatings in a PSCU fertilizer did not have as long of an extended release as was expected, although there appeared to be some control/slow release properties, especially when surface applied. Further work is needed to evaluate if this situation is an anomaly, or if this is a consistent problem with this material.

Methodology for Measuring N Release

While bags have been shown to be cost effective and a better method than laboratory incubations in determining in-field release of N (Carson and Ozores-Hampton, 2012), a method is still needed to estimate release rates of PCU broadcasted for turfgrass and horticultural needs. While we tried to develop an accurate method by applying prills to a thatch layer as well as on top of soil surface, it was time consuming and costly. Golden et al. (2013) demonstrated that prills outside of a buried bag showed greater initial N release compared to those placed in a bag although long-term results did not differ. An indication in difference in methods will further be amplified with the use of PCU products of longer duration. This research shows that shorter d release PCU, like that used in the study by Golden et al. (2013) will release more N than that of long term PCU products. While the current method needs adjustment, further research is needed to find a cost effective method to measure release rates of fertilizer that is broadcasted.

CONCLUSION

To optimize CRF characteristics of PCU, the fertilizer would need to be incorporated into the soil. Doing so provided release rates that were extended over a longer period of time compared to surface applied fertilizers due to the temperature buffering when prills are inside the soil compared to the wide fluctuations and high temperatures at the soil surface. Fertilizer applied to bare soil surfaces and thatch layers was more exposed to high surface temperatures, which diminished the longevity of the products. This is of great importance, as all PCU fertilizer applied to the surface, regardless of expected release longevity, 45 to 180 d, released 80% N or greater by 35 d. This should be taken into consideration when applied on turfgrass. Similar considerations with SCU and PSCU should be taken, as minimal slow release properties were shown.

When comparing laboratory and field conditions, fertilizers under laboratory conditions did not perform as expected. Results showed that laboratory conditions slowed the release of N.

If these parameters are used to estimate release under field conditions, release would be overestimated. To better match release with field conditions, release rates should be monitored using all possible field conditions.

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TABLES

TABLE 1: P-values from ANOVA test indicating a significant difference for incorporated treatments between static and diurnal fluctuating temperatures for each sampling date. Samples after 112 d were not included in analysis due to treatments exposed to diurnal fluctuating temperatures releasing ≥ 80% N.

	Source					
Days After Application	PCU 180	PCU 120	PCU 75	PCU 45	SCU	PSCU
7	0.456	0.355	0.800	0.728	0.256	<0.001
14	0.167	0.817	0.548	0.599	0.461	0.212
21	0.341	0.017	0.682	0.970	0.760	0.476
28	0.554	0.759	0.001	0.003	0.912	0.853
35	0.133	0.082	0.005	0.111	0.547	0.872
42	0.017	0.440	0.161	0.101	0.837	0.232
49	0.047	0.194	0.207	0.626	0.879	1.000
56	0.006	0.386	0.572	0.022	0.879	0.219
63	0.027	0.706	0.002		0.586	
70	0.018	0.518	0.835		0.295	
77	0.056	0.054	0.199			
84	0.001	0.018	0.023			
91	0.031	<0.001				
98	0.002	0.002				
105	0.027	0.151				
112	<0.001	0.011				

TABLE 2: P-values from ANOVA test indicating a significant difference for surface applied treatments between static and diurnal fluctuating temperatures for each sampling date. Samples after 35 d were not included in analysis due to treatments exposed to diurnal fluctuating temperatures releasing ≥ 80% N.

	Source					
Days After Application	PCU 180	PCU 120	PCU 75	PCU 45	SCU	PSCU
7	0.073	0.004	0.077	<0.001	0.106	0.016
14	0.013	0.306	0.445	0.959	0.733	0.337
21	0.003	0.015	<0.001	<0.001	0.065	<0.001
28	<0.001	<0.001	<0.001	<0.001	0.006	<0.001
35	0.003	<0.001	<0.001	<0.001	0.012	0.025

FIGURES

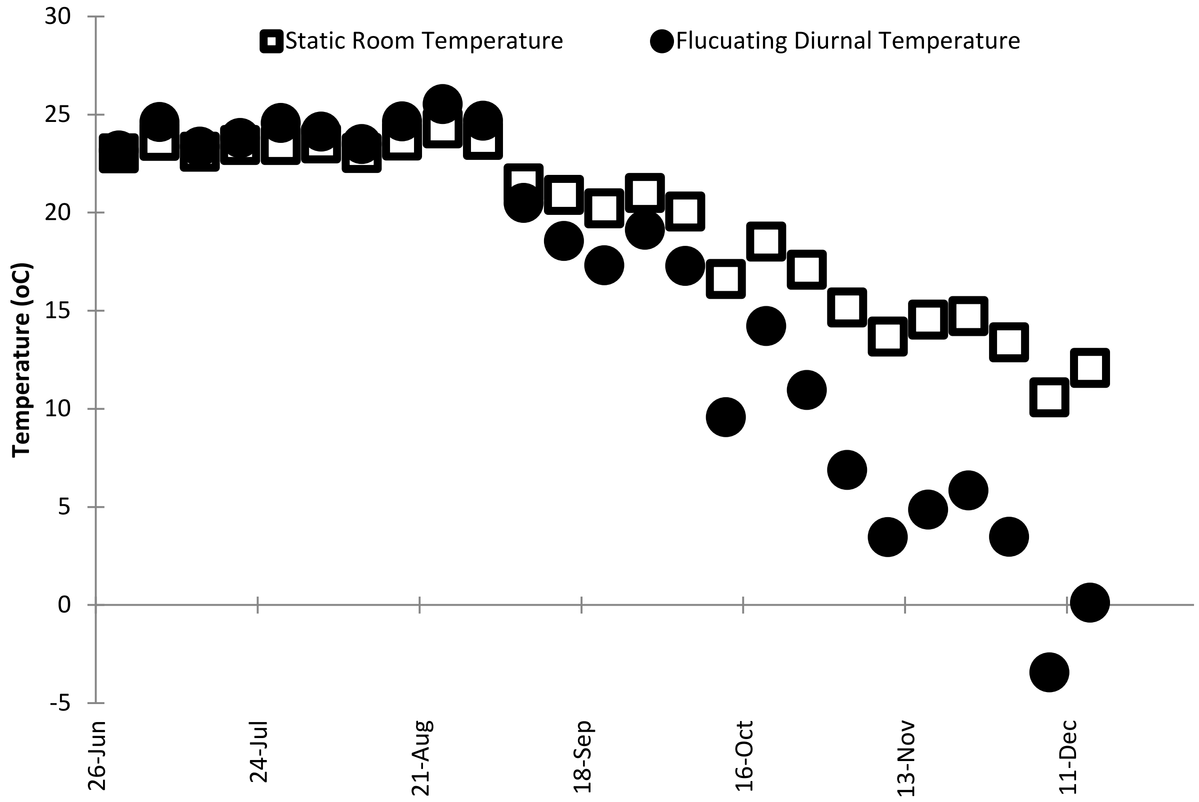

Figure 1: Weekly average air temperatures taken at respective locations. Diurnal temperature readings were taken from a weather station in close proximity to samples. Static temperatures were measured using thermometers and data logger and missing data was interpolated using data from BYU weather station. Temperature measurements were taken about 2 meters off the ground.

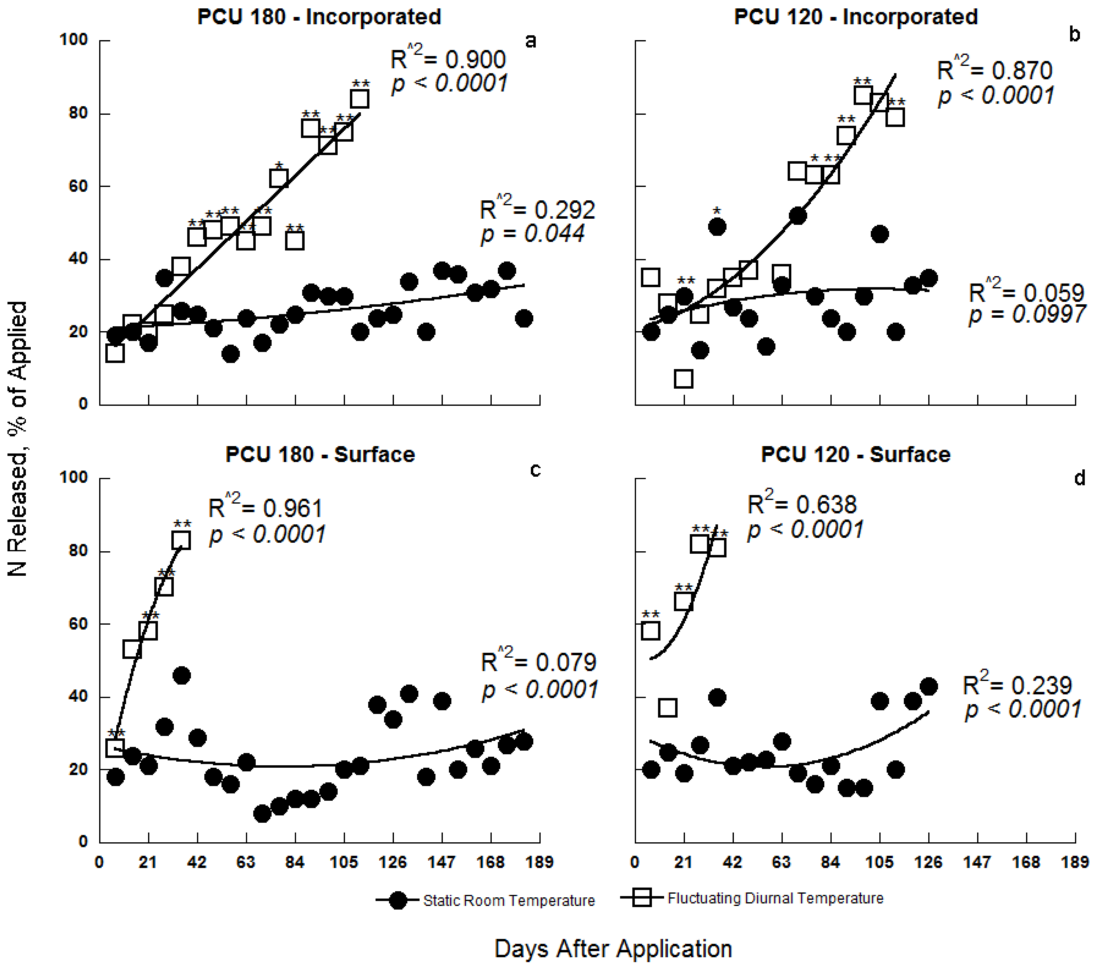

Figure 2: Percent N release from prills of PCU 180 and PCU 120 over time comparing diurnal fluctuating and static temperature effects. Each graph indicating either surface applied or incorporated treatments with individual fertilizer type. "**" indicate significance between static room and fluctuating diurnal temperatures for that given sampling date ($P < 0.05$ level), "*" indicates slight significance at ($P < 0.1$).

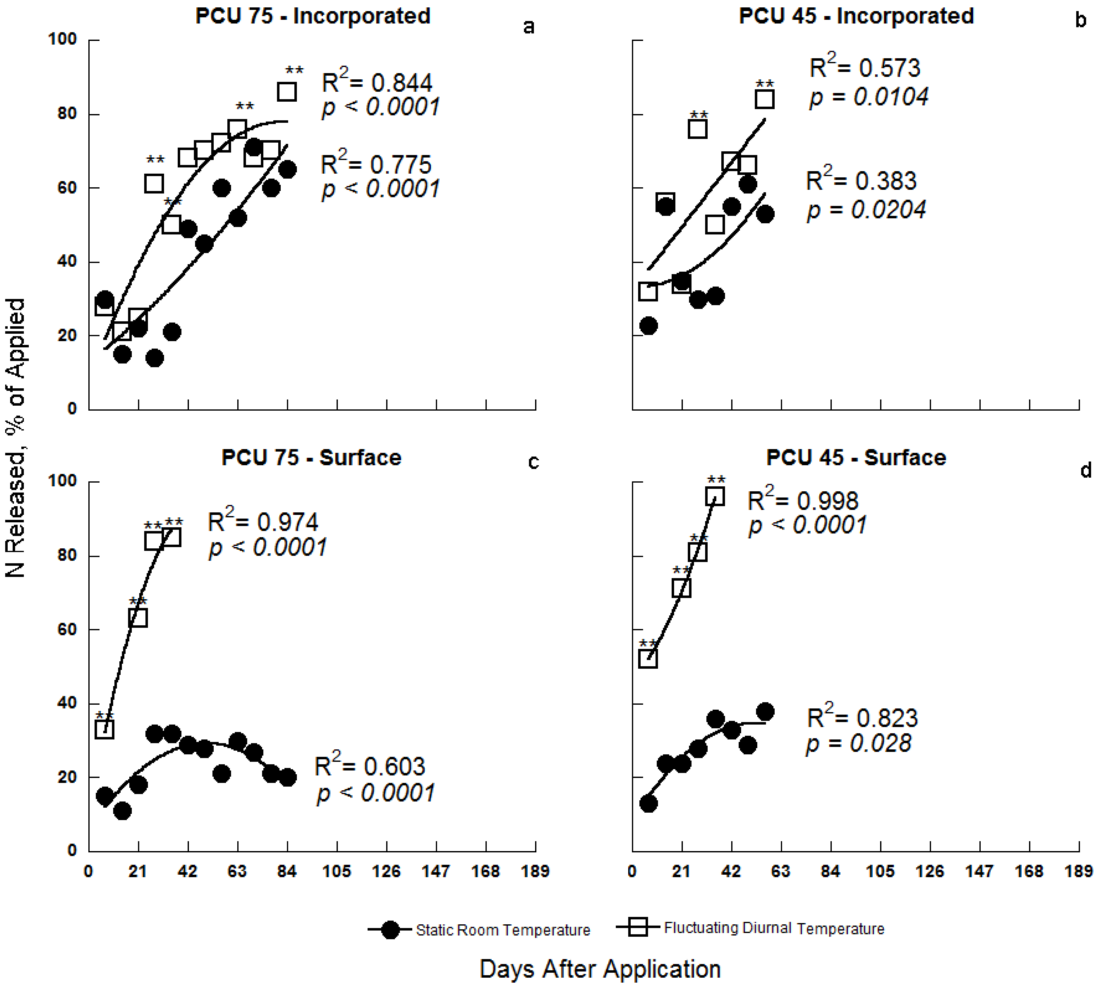

Figure 3: Percent N release from prills of PCU 75 and PCU 45 over time comparing diurnal fluctuating and static temperature effects. Each graph indicating either surface applied or incorporated treatments with individual fertilizer type. "**" indicate significance between static room and fluctuating diurnal temperatures for that given sampling date (P < 0.05 level), "*" indicates slight significance at (P < 0.1).

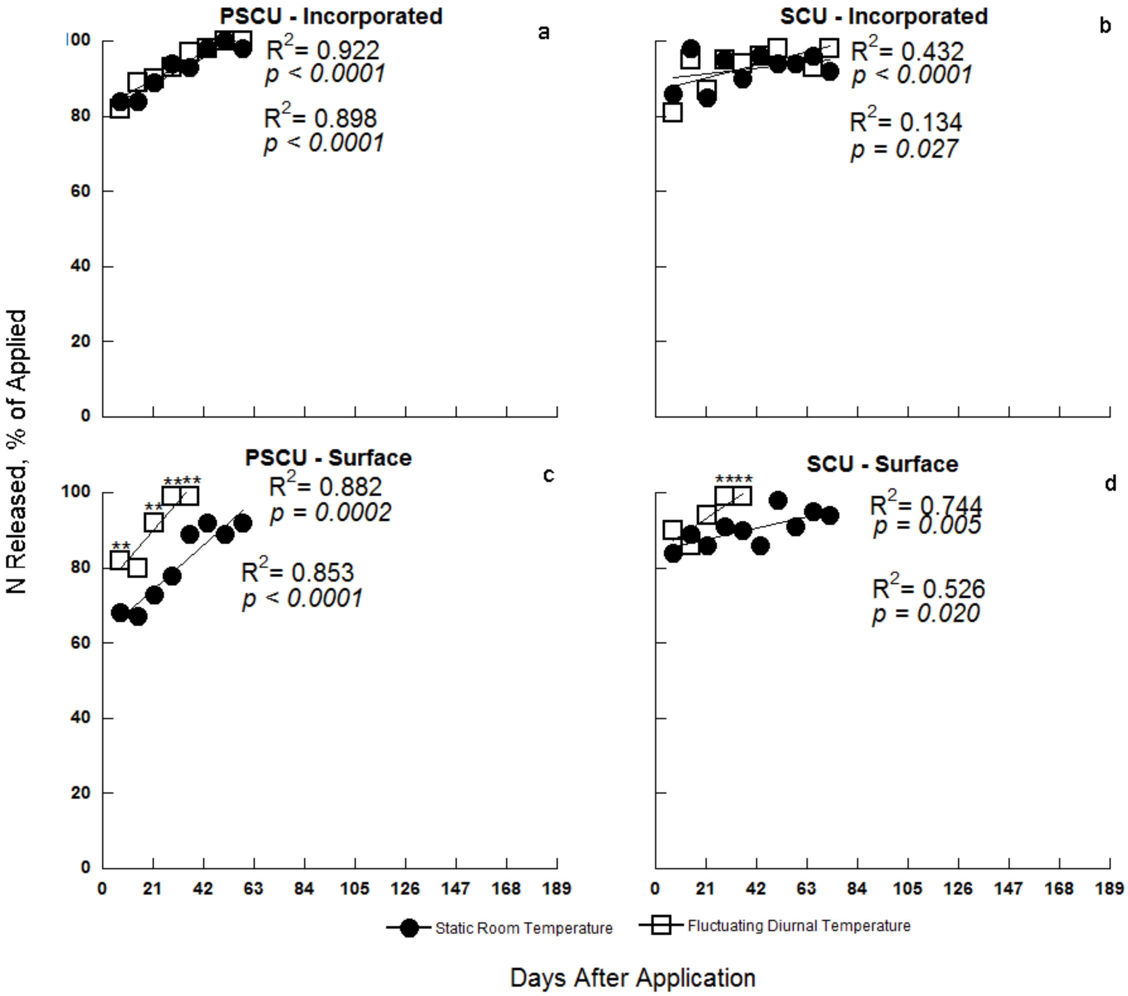

Figure 4: Percent N release from prills of PSCU and SCU over time comparing diurnal fluctuating and static temperature effects. Each graph indicating either surface applied or incorporated treatments with individual fertilizer type. "**" indicate significance between static room and fluctuating diurnal temperatures for that given sampling date (P < 0.05 level), "*" indicates slight significance at (P < 0.1).

Chapter 2

Turf Response to Reduced Rates of Polymer-coated Urea

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ABSTRACT

Polymer-coated urea (PCU) is a controlled-release fertilizer which can enhance nitrogen (N) use efficiency (NUE), reduce N pollution, reduce the need for repeated fertilizer applications, and reduce turfgrass shoot growth and associated costs. Spring applied N fertilizer trials were conducted over two years to determine the optimal N rate for Kentucky bluegrass. A PCU fertilizer rated for 120 d was applied at 50, 75, and 100% of the recommended full rate and compared to an unfertilized control and urea, applied either all at once or split monthly at the full recommended rate. Spring applied PCU showed no initial response until 42 d after application. After which, the 75 and 100% rates were equivalent to urea split monthly for biomass growth, verdure, and shoot tissue N. At the 50% rate, there was reduced growth and shoot tissue N, and consequently reduced mowing expense but also a 4% reduction in verdure. This PCU is effectively applied as a fertilizer at a reduced rate between 50 and 75%, although an additional application of quick release N is recommended to compensate for the early season lag in N release. More research is required to reach the goal of uniform seasonal growth with adequate verdure and to better quantify reduction of N pollution.

Keywords: polymer-coated urea (PCU), control release fertilizer (CRF), urea, turfgrass, Kentucky blue grass (KBG)

INTRODUCTION

All plants require nitrogen (N) to complete their life cycle and to play vital roles in various biochemical processes. Chlorophyll molecules, which facilitate photosynthesis and produce the green color in leaves, requires N to function properly (Marshchner, 2012). Furthermore, the biosynthesis of nucleotides found in deoxyribonucleic acid (DNA) and ribonucleic acid (RNA), and in the biosynthesis of amino acids (R-NH_2) used for protein/enzyme production all require N. As such N is often the primary limiting factor for plants growing in soil based ecosystems, due to high plant demand and the mobile characteristics of N resulting in N being easily lost from the lithosphere (Chatterjee, 2012).

Hydrolysis of urea fertilizer and decomposition of soil organic matter and organism residues results in ammonification—conversion of R-NH_2 to ammonia [NH_3 (g)] and then to ammonium (NH_4^+). However, the gaseous form volatilizes quickly into the atmosphere, especially if the ammonification occurs at or near the soil surface (Schlesinger and Harley, 1992). If the NH_4^+ is formed and captured by soil, it can be retained relatively well. However, under typical soil conditions, NH_4^+ is rapidly nitrified—oxidation to nitrate (NO_3^-). Nitrate is easily lost by leaching due to its high solubility and anionic repulsion from similarly charged soil colloids. It can also be denitrified into the nitrous oxide [N_2O (g)] form and subsequently lost to the atmosphere, especially under anaerobic conditions. A portion of the N is also lost as N_2O during nitrification.

Due to these many loss mechanisms or as a result of insufficient fertilization, plants can easily become N deficient. Without adequate N, plants produce less chlorophyll and proteins, becoming chlorotic—which results in decreased growth and increased susceptibility to pathogens (especially saprophytes) and pests and ultimately plant death (Marschner, 2012). With high value crops, such as turfgrass, this becomes a major problem as N is needed to maintain all the services provided by turfgrass. When well maintained, turfgrass reduces water and nutrient loss through leaching, soil erosion, dust and mud problems, noise and air pollution, heat dissipation, glares, and runoff to surface water (Beard and Green, 1994). It is also effective at sequestering carbon dioxide, capturing water, and producing O_2 (Stier et al., 2012), and it provides a low cost recreational surface that can be physically safer than other playing surfaces or poorly maintained turfgrass. Turfgrass has also been attributed to improved mental health and increased quality of life, community pride, social harmony, and value of properties (Beard and Green, 1994).

To maintain these benefits, turfgrass requires a consistent supply of N. However, excessive N is often applied by homeowners and turfgrass managers in an effort to maximize benefits—operating under the concept of “if a little is good, more must be better” or simply due to lack of precision or ignorance. Excessive N applied to turfgrass can result in immense increases in biomass—requiring more frequent mowing, which increases labor and other related costs. Furthermore, application of excessive N fertilizer can be a waste of natural resources and can result in N pollution when it becomes lost to the environment through naturally occurring soil processes.

Nitrogen lost to the environment contributes to N pollution in the atmosphere, hydrosphere, and lithosphere. High concentrations of N in the atmosphere contribute to global warming, especially in the form of N_2O (IPCC, 2007), and photochemical smog, increasing particulate matter, strong odors, and acid rain when NH_3 reacts in the atmosphere (Fenn et al., 1998; Erisman and Shaap, 2004; Zhang et al., 2011). Furthermore, NH_3 deposition and NO_3^- leaching lead to N accumulation in sensitive soil based ecosystems and in the hydrosphere (Sutton et al. 2008). The N pollution in water can cause eutrophication due to promotion of algae growth and subsequent death followed by anaerobic conditions during microbial decomposition (Cameron et al., 2013). The reduced dissolved O_2 levels can result in the death of aquatic organisms, leading to decreased biodiversity, strong odors, and unsightly water bodies, economic losses, decreased harvestable food in the form of fish and shrimp, and decreased recreational use (Fangmeier et al., 1994; Mulvaney et al., 2009). In addition, high concentrations of NO_3^- in drinking water have been related to health problems, such as methemoglobinemia (baby blue syndrome) in mammalian infants (Olson et al., 2009).

These issues have been connected to both field crop and turfgrass systems, and the latter accounts for about 10% or more of total N fertilizer applied in the United States (Galloway et al., 2008; Zhang et al., 2013). The high rate of N applied, comes from the large surface area of turfgrass—about 20 million ha (Zhang et al., 2013) or 1.9% of the total surface area in the United States (Milesi et al., 2005). This is particularly a problem since the greatest percentage of turfgrass is comprised of lawns (Beard and Green, 1994; Walker, 2007).

To minimize N pollution while optimizing turfgrass benefits, best management practices (BMPs) for N fertilization are needed. One approach is consistent application of N fertilizer or "spoon feeding", to maintain shoot N concentrations between 28 and 42 g kg^{-1} dry biomass of turfgrass (Marshchner, 2012). Maintaining this adequate tissue N concentration differs among species of turfgrass. For warm-season turfgrass, it is often recommended to supply 50 kg N ha^{-1} for each month of active growth (Christians, 2007). For cool-season turfgrass, it is generally accepted to supply a total of 150-250 kg N ha^{-1} over the active growing season (Christians, 2007). The availability of the N needs to be somewhat consistent throughout the growing season, although a relatively greater amount during late fall is beneficial to allow for extended production of photosynthates to draw on when coming out of dormancy in the spring (Christians, 2007). This "spoon feeding" approach is effective, but it often results in spikes of excessive tissue N and biomass proliferation (Mangiafico and Guillard, 2007). This practice is also still prone to loss due to N_2O formation, volatilization of NH_3, and NO_3^- leaching (Osmond and Platt, 2000; Knight et al., 2007; Hochmuth et al., 2011).

Controlled-release fertilizers (CRF) and/or slow-release fertilizers (SRF) are often used to increase nitrogen-use efficiency (NUE) and allow for the provision of N over extended periods of time. As compared to “quick release” fertilizers, CRFs and SRFs are designed to release N over an extended period of time, rather than all at once, in an attempt to better match plant N needs throughout the growing season and to reduce time of exposure for N losses to the environment. Controlled-release fertilizers and SFRs primarily differ in their mode of release. Slow-release fertilizers release through a variety of methods including microbial processes, chemical reactions, or bursting of a coating due to water vapor infiltration, resulting in high internal pressures. Once a point of the coating breaks, the urea becomes exposed and is accessible to be hydrolyzed and further converted to other N forms. This process is relatively more unpredictable compared to CRFs, making additional applications necessary during growing seasons and decreasing N use efficiency (Ellison et al., 2013). This group of fertilizers includes denitrification/nitrification inhibitors, long chain molecules requiring microbial decomposition, and granules coated in a substance to restrict water movement through hydrophobic or hydrophilic attractions (Aviv, 2001).

Control release fertilizers have been developed using a coating around individual granules of fertilizer materials, such as urea. The commonly used polymer coating has micropores which allow soil moisture to diffuse through the coating to dissolve the urea. Urea is a larger molecule than water and, as such, does not immediately cross the membrane into the soil. As temperatures increase, it is thought that the coating warms and expands, increasing the size of the micropores and allowing the urea to eventually reach the soil solution through diffusion. The rate of diffusion follows first-order kinetics with an approximate doubling of the diffusion rate for every 10°C increase (Adams et al., 2013; Ellison et al., 2013; Shaviv et al., 2003).

By altering the thickness of the coating, the rate of N diffusion is reduced. Knowing the plant's N needs and the average soil or air temperature, a mixture of different coating thicknesses can be used to match these needs (Ellison et al., 2013; Fujinuma et al., 2009; Olson-Rutz et al., 2009; Shaviv and Mikkelsen, 1993). The use of CRF's has increased plant yields and quality (Cahill et al., 2010; Knight et al., 2007), while decreasing the amount of N lost as NO_3^- (Pack and Hutchinson, 2003; Wilson et al., 2010), NH_3 (Knight et al, 2007; Rochette et al., 2009), and N_2O (Halvorson et al., 2008; Halvorson et al., 2010; Hyatt et al., 2010; Jassal et al., 2008) in both turfgrass and agricultural systems (Ellison et al, 2013; Grant, 2008; LeMonte et al., 2011; Torello et al., 1983).

In an effort to provide a sustainable and more effective management system of N for cool-season turfgrass in the Intermountain West, PCU products will be evaluated in these conditions. The main objectives of this study will be to evaluate PCU products to provide adequate N, similar to traditional grower's standard practice (GSP). Another objective is to determine the optimal N that can be used with PCU to maintain sufficient turfgrass quality in comparison to GSP. The overall reduced rates and better NUE will allow for decreased environmental impacts which are often associated with N fertilizer on turfgrass. We hypothesize that 1) PCU will provide a slow release of N that will maintain turfgrass quality throughout the spring/summer growing months. 2) Rates can be reduced to as much as 50% which will limit excessive growth of turfgrass but still maintain adequate quality color in turf.

MATERIALS AND METHODS

One field study was conducted in 2011 and three studies in 2012 at separate Utah, USA locations with established Kentucky bluegrass (KBG; *Poa pratensis* L.) over 120 d. The 2011 site was conducted at the Brigham Young University (BYU) experimental farm near Spanish Fork, UT (40°4′1.77″ N Latitude 111°37′44.99″ W Longitude) on a Timpanogos clay loam (fine-loam, mixed, mesic Calcic Argixerolls). The 2012 sites were located in the vicinity of the BYU sports turfgrass sod farm (40°16′1.4” N Latitude 111°39′28.59” W Longitude). The 2011 site was established for more than a decade and had no N applied for more than one year. The 2012 sites 1, 2, and 3, were previously established for one, five, and two years, respectively. The 2012 site 1 turfgrass plots were established in manufactured sand soil (>95%) from crushed quartz minerals with 1% (w/w) peat moss. The 23 cm layer of sand lay over a gravel layer for a designed perched water table. The site received no N application after establishment and prior to the start of study. The 2012 site 2 was in close proximity to site 1 and was also a manufactured urban loam soil (composed of a mixture of a variety of local soils derived from various BYU landscaping construction projects). This site received minimal N application in prior years to the use in this study. The 2012 site 3 was also classified as a sandy soil (>95% sand), although different in parent material origin from site 1. Nitrogen management was also more intensive in previous years than the other sites, although no N was applied for eight months prior to the start of study. All soils were alkaline pH (7.5-8.2) and had low organic matter (1-2%) and low to moderate levels of all nutrients and minimal salts.

Air temperature and precipitation for all sites were monitored with nearby weather stations. Best management practices were followed in growing the turfgrass for irrigation, pest management, cultural practices, etc. Applications of phosphorus (0-30-0) and macro and micro nutrients were applied as needed, based on soil test and visual chlorosis symptoms which occurred, (especially for the poorly fertile sand soils).

Plots, 1 m x 3 m, were set up in a randomized block design with four replications of six treatments. Treatments included: 1) an unfertilized control, 2) urea (46-0-0), 3) urea with four equal split applications every 30 d, 4) polymer-coated urea (PCU 100%; Duration 120 CR©; 43-0-0), 5) PCU at a 75% rate (PCU 75%), and 6) PCU at a 50% rate (PCU 50%). The PCU products were supplied by Agrium Advanced Technologies (Loveland, CO, USA). Treatments 2-6 were applied at a "full" rate (100%) at 140 kg N ha^{-1} and the reduced rate treatments, 7 and 8, were applied at 105 and 70 kg N ha^{-1}, respectively. All treatments were broadcast applied evenly to the surface on May, 13 for 2011 and April, 30 for 2012 sites 1, 2, and 3, respectively. The plots were sprinkle irrigated within 12 hours of fertilizer application with a minimum of 1 cm of water.

The overall quality of the KBG (verdure) was measured visually on a weekly basis using a scale from 0 to 5 (0= dead, brown shoots; 5 = dark green, healthy) and Normalized Difference Vegetation Index (NDVI) using a handheld GreenSeeker (Trimble®, Sunnyvale, CA, USA). Measurements for NDVI were not taken on the 2011 site due to instrumentation malfunction. Shoot growth was monitored through bimonthly biomass samples using an 86.6 cm^2 area and cut down to a 1 cm height. Tissue samples were oven dried at 65^{o}C for a minimum of three d and dry biomass recorded and then ground to pass through a 2 mm mesh and analyzed for N and C concentration (TruSpec®; Leco, St. Joseph, MI, USA). A C:N ratio was calculated by dividing C by N concentrations. Average heights were taken weekly by measuring height from the ground in three random areas of each plot. After measurements were taken, turfgrass was mowed to a height of 5 cm. Clippings were removed to avoid cross contamination of plots. In some cases, mowing was unavoidably delayed due to weather etc.—extending mowing time up to 9 d.

Soil samples were taken 7, 14, and 119 d after application for all sites during 2012 (additional composite samples were taken at various other times to monitor the entire study, but individual plot analysis occurred only on these three dates). Samples were taken from three random cores of 5 cm diameter by 10 cm length and then air dried for 24 h. Soil was mixed for uniformity by hand and any plant residue was removed before analysis. Analysis for NO_3^--N was done with 2 N KCl extraction (Kenny and Nelson, 1982), followed by analysis with the salicylate nitroprusside method (Mulvaney, 1996; Lachat QuickChem 8500 Series 2 FIA, Lachat Instruments, Loveland, CO, USA).

Root lengths were taken at the beginning and the end of the study by extracting a 5 cm diameter core and measuring the longest roots at two random locations from each plot. Plant crown density was measured at the end of the study. An 86.6 cm^2 area was cut from each plot and KBG crowns were counted. Root biomass was taken from the same plug, by first washing soil out of the roots, and separating shoots from roots. Roots were dried at 72^oC for 5 d and weighed. Shoot to root ratio was calculated for each plot by taking the final shoot biomass, divided by the final root biomass, all taken from the same plug.

Differences between treatments were determined using an analysis of variance (ANOVA) utilizing R software (R Project for Statistical Computing, http://www.r-project.org/) with significance determined at $P \leq 0.05$. Resulting source X site interactions were analyzed by pooling all sampling dates together and analyzing each site separately. Source X date interactions were further analyzed by pooling all sites together and analyzing each date separately. Significant means were separated using a Duncan mean separation test.

In general, the overall models were significant for measured parameters except the root biomass and shoot:root ratio (Table 1). There were significant differences in response by date and site and their interactions for all measured parameters, but the three-way interaction between fertilizer source, site location, and measurement dates were not significant. As such, the focus was on fertilizer source and its interactions with site and date, which generally were both significant.

RESULTS

Verdure and NDVI

An overall N response for green up was seen over the unfertilized control, with specific differences between N treatments varied by date (Fig 1). Assuming the GSP is the ideal, the results of the other fertilized treatments (not showing the control in an effort to make the graph readable) are shown in relation to this treatment representing the baseline at 0. When sites were pooled and treatments were compared for each sampling date, urea applied all at once had a significant increase in verdure at 35 and 42 d after application over the GSP. After which, there was a decrease at 63 and 117 d after application—being significantly lower than the GSP. In contrast, PCU at the 75 and 100% rates was never significantly different from the GSP. At a reduced 50% rate, PCU showed a decrease of verdure at 42, 47, and 63 d after application, but was the same at all other measured dates.

Response also varied by site due to a source X site interaction. Surprisingly, the 2011 site 1 produced no treatment response over the control. Sites 1 and 2 in 2012, resulted in all N treatments with a significant response higher than the control, while site 3 resulted in only urea,

urea split, and PCU 75% significantly greater than the control (Fig 2). Again assuming the urea split is the “grower standard practice” (GSP) providing the most steady supply of N over the season, note that all three PCU rates provided the same verdure except for the reduced rates at site 2 (Fig. 2).

Unlike verdure, data for taken for NDVI showed no significant difference across time, although source response differed by site (Table 1). When pooled across dates, NDVI measurements showed no response for 2012 site 3 (Fig. 3). The other two sites showed N response, which is similar to the visual verdure ratings (Figs. 2 and 3). Interestingly, NDVI showed no significant difference between N sources on either 2012 site 1 and 2 (Fig. 3), although similar decrease in greenness for PCU 50% was measured on 2012 site 2. This data matches verdure ratings for the same site and provides further confirmation to a significant difference between GSP and PCU 50% on 3 of the 17 sampling dates (Figs. 1, 2, 3).

Plant Growth

No differences were measured for root biomass or length for any treatments (Table 1). Surprisingly, there were no significant differences in shoot biomass among fertilizer sources (Table 1). However, there were significant differences as a function of fertilizer source, for shoot height, with significant source X date and source X site interactions (Table 1).

When pooled across dates, there was an N response for height for all treatments over the control for all sites except for the 2011 site (Fig. 4). In 2012, all treatments produced taller plants than the control for sites 1 and 2, but only PCU 100 consistently produced taller plants than the control at all three sites. All three PCU treatments were similar to the urea split treatment at every site in 2012, but the reduced rates of PCU in 2012 site 3 did not have significantly greater height than the control (Fig. 4) despite having better verdure (Fig. 1) and NDVI readings (Fig. 3). It is noteworthy that the height of turfgrass with PCU 100% rate was greater than with urea applied all at once at site 1 in 2012.

When combined across sites and all fertilizer treatments and when made relative to the GSP, urea applied all at once produced an increased height at 28 d after fertilization with non-significant trends in that same direction during the entire first phase of the study (5 d-45 d; Fig. 5). However, after 49 d after application to the end of the study, urea applied all at once produced a trend for a decrease in height measurements, but only 77 d measurements were significantly less than GSP. As hoped for from a management standpoint, the PCU treatments did not result in significantly greater heights than the GSP and, in fact, the trend was for lower height during from 5 to 50 d for all PCU treatments and the PCU 50% rate was significantly less than GSP at 49 d after application.

Shoot Nitrogen and Carbon

Shoot N concentrations showed a significant N response over the control for all treatments in two of the four sites, 2012 sites 1 and 2 (Table 1 and Fig. 6). The least responsive treatment, PCU 50%, averaged a factor of 1.25 and 1.32 higher than the control, for sites 1 and 2, respectively. However, there were no significant differences between GSP and any other fertilizer treatments. There were no significant differences among any N source and rate treatments for 2011 site 1 or 2012 site 3 (Fig. 6).

When sites were pooled, turfgrass shoots contained higher concentrations of N for urea, relative to GSP, for the first three sampling periods (statistically significant for d 7 and d 28; Fig. 7) followed by a steady decline for the remainder of the study with shoot N being lower than

GSP on d 70 and thereafter (significantly lower than GSP at 98 and 119 d after application; Fig. 7). The PCU treatments tended to produce lower initial shoot N concentrations (d 5 – d 40) compared to GSP with PCU 50% being significantly lower than GSP 42 d after application with shoot N increasing to be near or above GSP for all PCU treatments thereafter—with the PCU 100% rate and source application consistently resulting in shoot N above GSP (not statistically significant). Both PCU 100% and PCU 75% were not different from GSP, while PCU 50% showed a significant decrease at 98 d after application.

Whereas Shoot C concentrations were not significantly impacted by fertilizer source; the overall average when pooled across all treatments, sites, and dates was 45.7%. The effect generally was related to the N concentrations changing while C concentrations held steady.

Soil Nitrate

Because of significant two-way (source X site, source X date and site X date) and three-way interactions (source*site*date; Table 2), soil NO_3-N data are shown for each site, source, and sampling date (Table 2). The three 2012 sites showed significant increases in NO_3-N for urea applied at once 7 d after application (Table 2) and two (site 2 and 3) showed increases14 d after application., 2012 site 2 and 3 had a significant increase of urea over all of the treatments. By the end of the study (119 d after application), all treatments were equally low in NO_3-N. Averaging NO3-N values shows site 3 having the highest average NO_3-N and site 1 with the lowest NO_3-N.

DISCUSSION

Nitrogen Response

As expected, a N response in terms of verdure, NDVI, height, and shoot N was observed for all fertilizer sources. The response varied by site; with sites that had initially high initial shoot N concentrations showing the least response. This has been seen in previous research, with turfgrass having high shoot N concentrations at the start of spring, having a minimal increase with further N application (Zhang and Nyborg, 1998). On the other hand, fertilizers did not impact crown density, shoot C, root length, root or shoot biomass, or the shoot:root ratio. However, the shoot biomass results were likely impacted in the current study by variation associated with too small of a sampling area. Future studies would likely have greater sensitivity by harvesting a larger area. While results were not conclusive for biomass, there were significant height differences among treatments and we would expect an increase of biomass for higher rates of N applied, as previous research has shown (Walker et al., 2007).

Source of N fertilizer resulted in differing results, with urea applied at the full rate (140 kg ha^{-1}) in early spring resulting in a temporary increase in plant growth and verdure—with the downside being a need for increased mowing times and associated costs. The lack of long-term N availability was expected as N in this form of fertilizer is quickly utilized or lost through clipping removal, leaching, volatilization, or denitrification (Zhang and Nyborg, 1998; Knight, et al., 2007). In comparison to split application, this type of application is ineffective, although differences were not as great as expected. An application of urea on sandy soils has been shown to result in high levels of leaching (Unruh et al., 2013), especially after rain events that are common in early spring in the Intermountain West. Such rainfall events would likely reduce available N supplied by unprotected urea applied all at once. Splitting the urea applications reduces these losses due to spreading the supply of N over a longer period and, thus, increasing the plant's ability to utilize it and also due to a lack of natural precipitation during summer months (assuming non-excessive irrigation).

Polymer-Coated Urea Rates

Compared to urea-N, PCU products produced a more controlled response that resulted in a better-maintained turfgrass quality through the end of summer (~120 d—as suggested as the N release from the Duration 120 CR ©). In comparison to GSP, PCU had similar turf quality. This currently matches previous research which even indicated that PCU applied to tall fescue in the spring, resulted in less clipping production and a greater uniformity of growth, while still matching the quality of traditional quick release fertilizers (JiaLin et al., 2009).

An increased N response was seen with increasing N applied. Although when taking into account key variables that were measured (shoot N, verdure and NDVI, and growth), the controlled release effect from PCU showed that a reduced rate of 70 kg N ha^{-1} (PCU 50%) applied early in the spring, resulted in similar quality turfgrass as GSP. Although a few sampling dates showed significant difference in verdure between GSP and the lowest rate of PCU there were also a few sampling dates with reduced growth. If even higher verdure rating were desired, a rate of 105 kg ha^{-1} (PCU 75%) would better match GSP at a tradeoff of slightly more growth. Overall applying a reduced rate would help in reducing labor costs associated with clipping removal as well as reduce N inputs into the environment (Cisar, 2004; Walker 2007).

When compared to other studies, PCU applied at a similar reduced rate (72 and 96 kg N ha^{-1}) to Zoysiagrass (*Zoysia matrella* L. Merr.) resulted in no significant improvement in visual ratings 44 d after application (Karcher and Richardson, 2003). Polymer-coated urea was also found to have significantly less visual and quality ratings over four years of application, with N applied at a rate of 49 and 98 kg ha^{-1} mo^{-1} to warm-season turfgrasses, St. Augustinegrass (*Stenotaphrum secundatum*) and Centipedegrass (*Eremochloa* ophiuroides; Unruh et al., 2013). On Bermudagrass (*Cynodon datyol* L. Pers.) that was recently seeded, there was a reduced rate in plant establishment, visual, and quality differences with PCU applied at a high rate of 62 kg ha^{-1} mo^{-1} compared to reduced rates of urea (Briscoe et al., 2012).

The limited response to PCU seen on Zoysiagrass by Karcher and Richardson (2003) was hypothesized as the lack of available N due to the slow release of PCU. In contrast to our PCU application, N was initially delayed in getting into the plants by about 14 d after application, although not significant from GSP, the remainder of the study provided consistent N for turfgrass growth. The difference in results may be due to variation seen within PCU products, as they often differ according to manufacturing process, coat thickness, and material resulting in different release rate (Adams et al., 2013).

Results seen also depend on previous N levels in the soil and turfgrass (Zhang and Nyborg, 1998). Current research shows that some field sites that were initially high in N showed minimal difference in rates and source applied, while those that had minimal N concentrations showed the greatest difference between N sources. Regardless of previous N concentrations, a onetime application at the beginning of spring will not sustain turfgrass over time. This was seen with warm-season turfgrass, with a decrease in visual ratings after 4 years with constant PCU application (Unruh et al., 2013). With cool-season turfgrass this is often remedied with a second application in the fall. Our current research indicates that PCU treatments were starting to decline in terms of shoot N, verdure and NDVI, and heights by the end of summer in comparison to GSP. A second application of PCU in the fall would help maintain N concentrations in the fall and subsequent spring. In conditions where fall applied N was not applied or not enough N is available, it is recommended to mix a quick release N, like urea, with PCU to help compensate for the lag time seen with PCU products in the spring.

CONCLUSION

Urea that was applied all at once resulted in initial spike of N concentrations and subsequent growth which declined towards the end of summer compared to GSP (grower standard practice). This method is more prone to N lost to the environment as well as increased labor from increased growth. Split application of urea overcame these issues. However, a reduced rate of PCU applied at 50 and 75% (70 and 105 kg N ha^{-1}) of recommended rates, results in similar verdure and growth as GSP (140 kg N ha^{-1}) for spring application to KBG (Kentucky bluegrass). The PCU at the low rate of 50% of GSP (70 kg N ha^{-1}) showed sampling dates that had a slight but acceptable decrease in verdure as well as slightly slower growth. In comparison to GSP and urea, PCU products had a slight lag time before N was uptake by plants. Based on verdure, N concentration, and height data, PCU could be recommended at 50% GSP with a low supplemental application (rate to be determined) in the early season (before temperature rises to release N). Future studies will include monitoring using PCU 50% in combination with small amount of quick release N during lag periods observed in this study in an effort to better match the GSP verdure and growth patterns.

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TABLES

TABLE 1: P-values of analysis of variance (ANOVA) on twelve parameters of the study. Statistically significant values (P ≤ 0.05) are in bold.

	Verdure	NDVI	Average Height	Shoot N	Shoot C	Soil Nitrate	Shoot Biomass	Crown Density[†]	Shoot C:N	Root Biomass[†]	Root Length	Shoot: Root[†]
Source	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	0.103	**< 0.001**	0.796	0.561	**< 0.001**	0.177	0.270	0.054
Site	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	0.209	**< 0.001**	0.194
Date	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**		**< 0.001**		0.143	
Source X Site	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	0.616	**< 0.001**	0.444	0.491	**< 0.001**	0.489	0.951	0.556
Source X Date	**< 0.001**	0.994	**< 0.001**	**< 0.001**	0.403	**< 0.001**	0.990		**< 0.001**		0.567	
Site X Date	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**		**< 0.001**		0.019	
Source X Site X Date	0.590	1.00	0.175	0.054	0.545	**< 0.001**	1.00		0.354		0.133	
Overall Model	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**0.013**	**< 0.001**	0.122	< 0.001	0.070

[†] Indicates parameters that were only measured only 1 sampling date.

TABLE 2: Average soil NO_3-N (g kg^{-1}) taken 7, 14, and 119 days after application of five sources. Means for a given day and site with the same letter are not significantly different at $P < 0.05$, using Duncan means separation. Significant p values are in bold.

Site	**N Source**	**Days After Fertilizer Application**					
		7		**14**		**119**	
2012 Site 1	Control	2.2	b	4.1	a	2.4	a
	PCU 100%	2.1	b	4.3	a	8.3	a
	PCU 75%	2.7	b	5.3	a	4.*	a
	PCU 50%	2.6	b	5.1	a	2.7	a
	Urea	4.2	a	8.5	a	2.9	a
	Urea Split	3.1	ab	4.3	a	3.5	a
	P value	**0.033**		**0.16**		**0.328**	
2012 Site 2	Control	2.5	b	7.6	b	6.2	a
	PCU 100%	2.7	b	8.8	b	7.7	a
	PCU 75%	3.0	b	10.3	b	9.9	a
	PCU 50%	2.9	b	8.5	b	7.4	a
	Urea	5.6	a	47.6	a	8.1	a
	Urea Split	4.6	ab	13.2	b	7.6	a
	P value	**0.024**		**< 0.001**		**0.432**	
2012 Site 3	Control	6.3	b	6.1	b	3.62	a
	PCU 100%	3.6	b	20.0	b	3.15	a
	PCU 75%	6.7	b	5.9	b	3.28	a
	PCU 50%	5.9	b	11.9	b	3.59	a
	Urea	20.6	a	76.1	a	3.34	a
	Urea Split	11.7	ab	40.0	b	3.27	a
	P value	**0.012**		**0.002**		**0.849**	

FIGURES

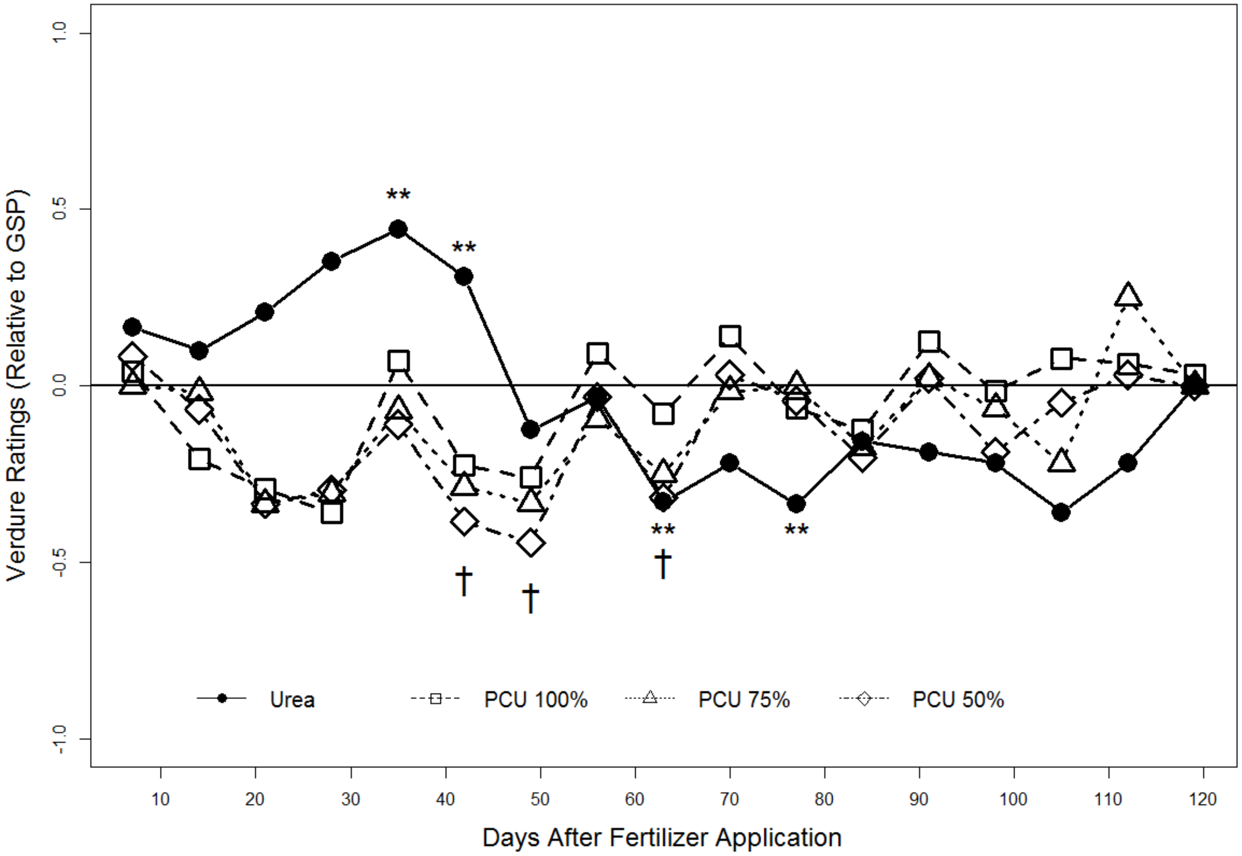

Figure 1: Relative verdure measurements with all 2011 and 2012 sites pooled together. Verdure was measured on a scale from 1-5 (1=dead brown turfgrass, 5=dark green healthy turfgrass). All treatments were expressed relative to GSP which is the urea split applied monthly. "**" indicates when urea is signficantly different from GSP ($P < 0.05$), "†" indicates when PCU 50% is significantly different from GPS ($P < 0.05$). Unfertilized control treatments are not included to simplify presentation of data.

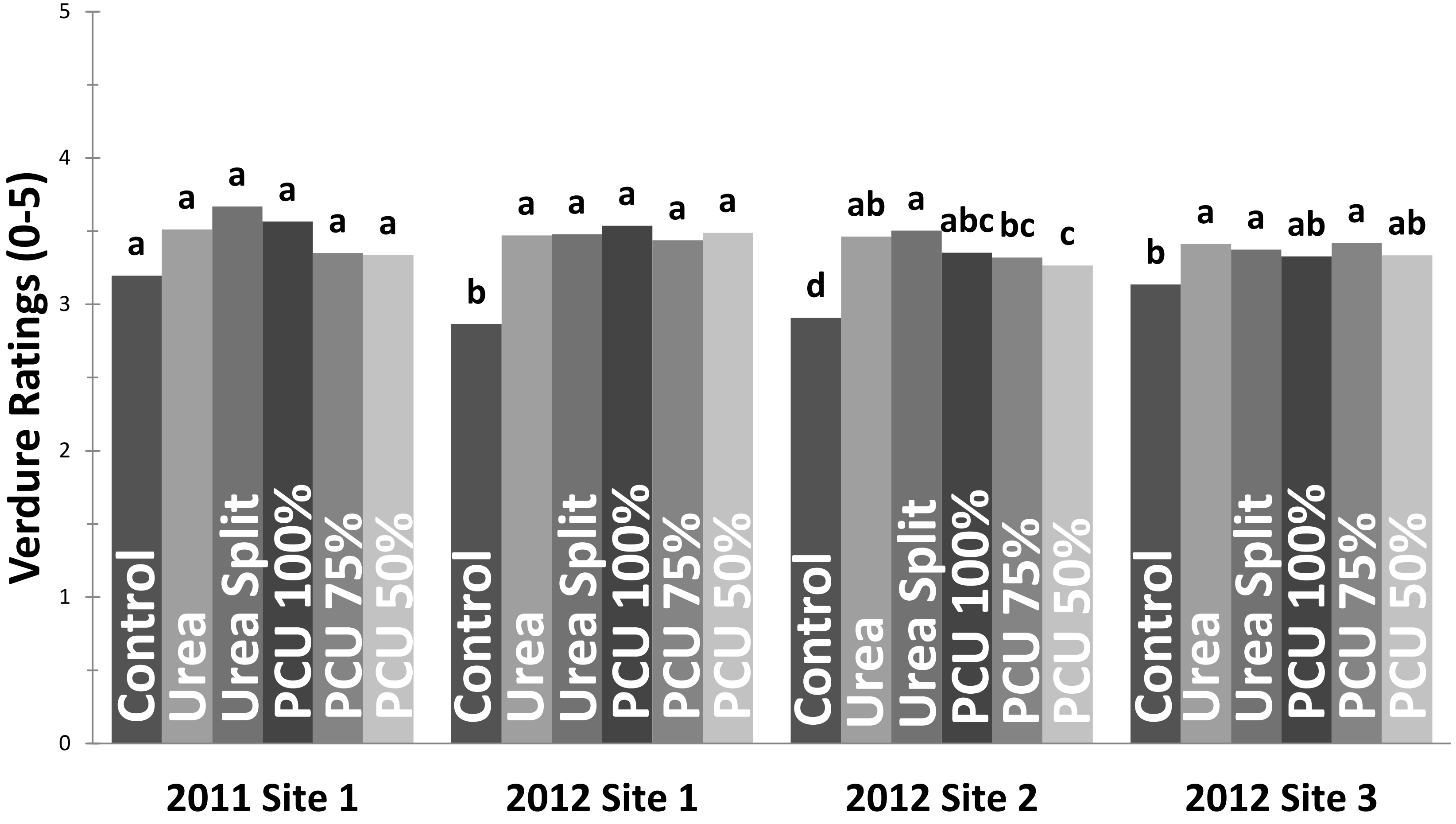

Figure 2: Verdure measurements averaged across sampling dates. Verdure measured on a scale from 1-5 (1=dead brown turfgrass, 5=dark green healthy turfgrass). Treatments within a given site with the same letter are not significantly different ($P < 0.05$).

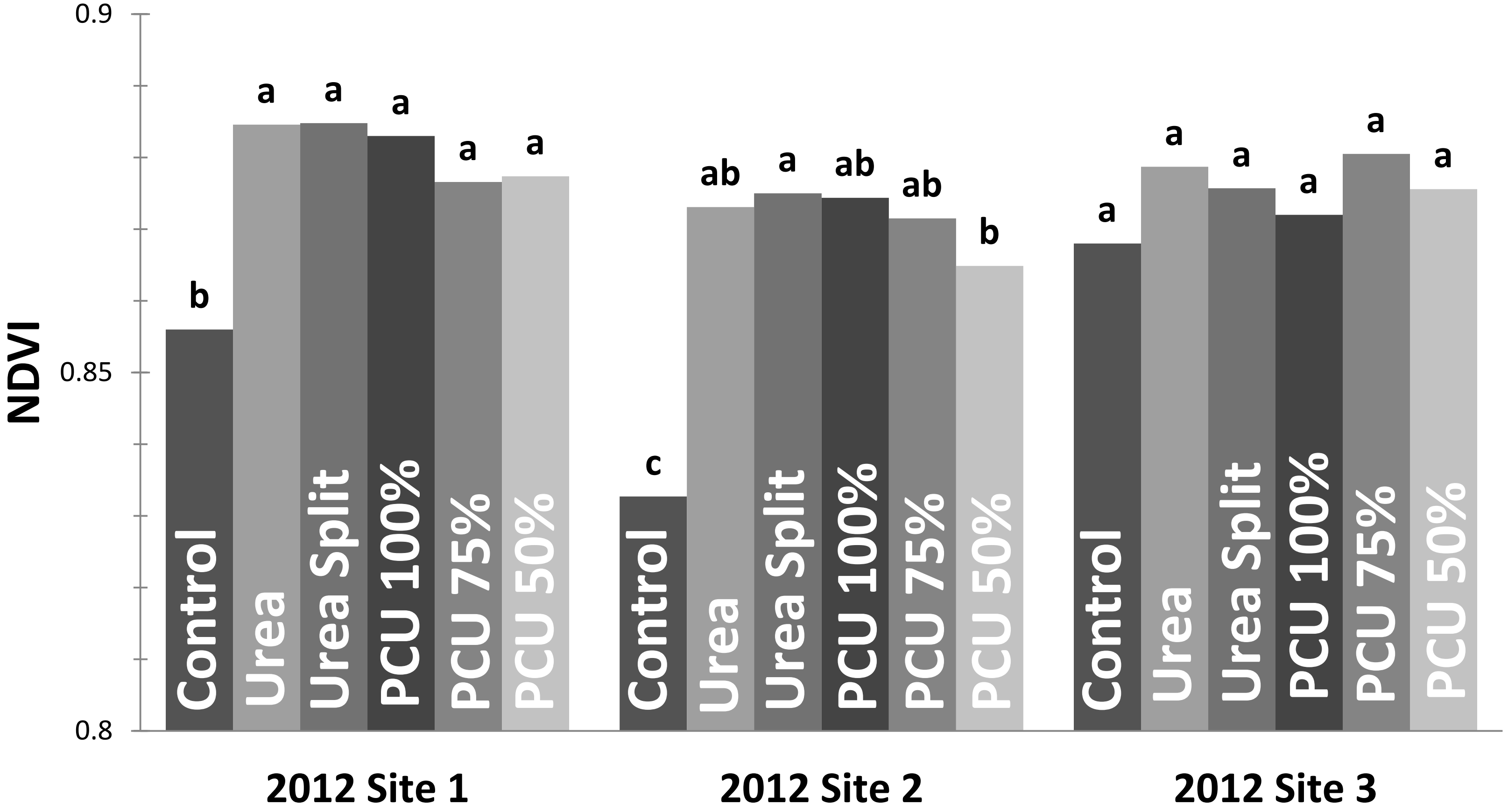

Figure 3: Average of weekly NDVI measurements averaged across sampling dates for each of the 2012 sites. Means within a given site with the same letter are not significantly different at $P < 0.05$, Duncan means separation.

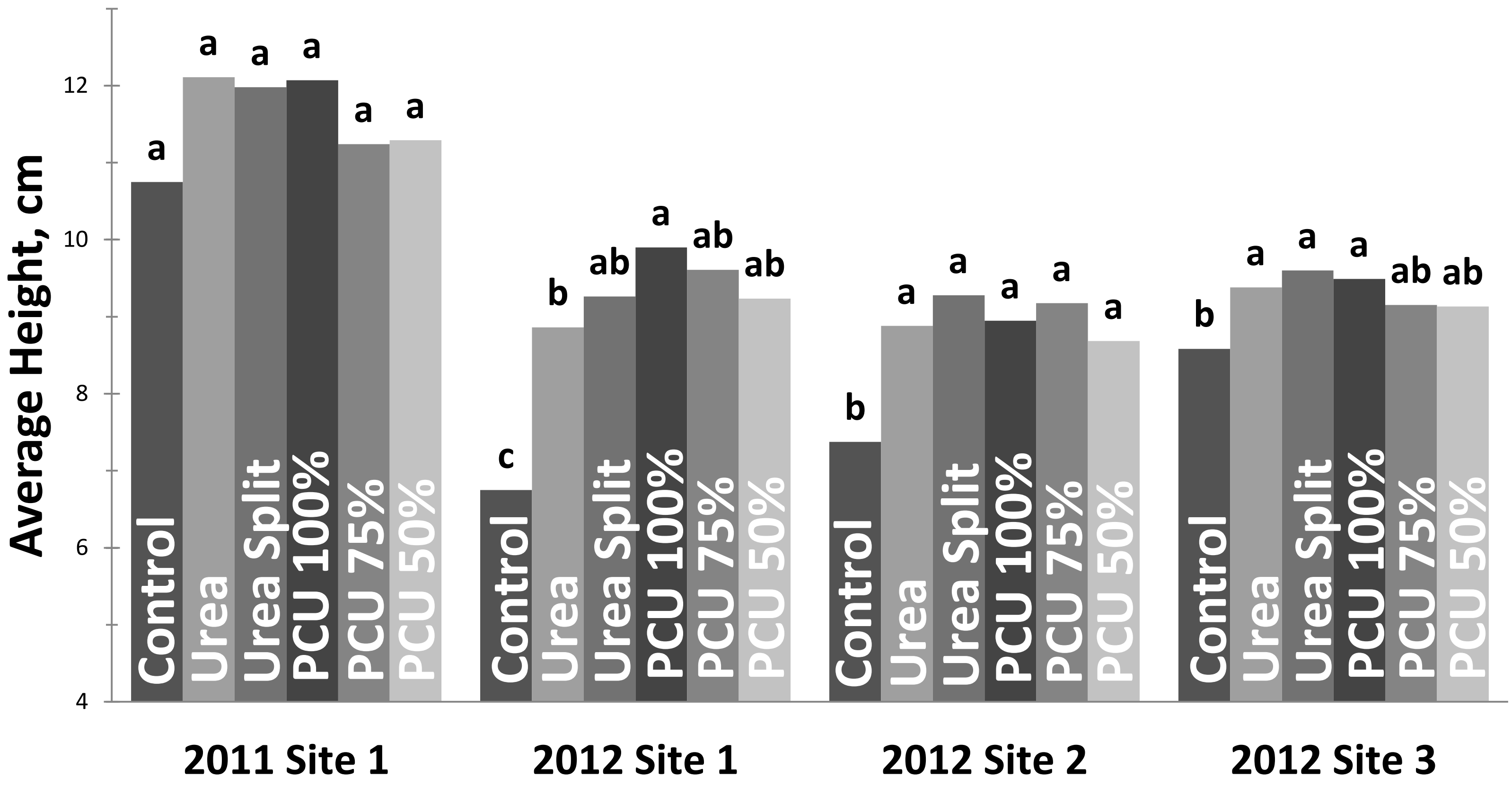

Figure 4: Average of weekly measured heights for all sites, averaged across all sampling dates, measured from the soil surface to tip of blades. Means within a given site with the same letter are not significantly different at $P < 0.05$, Duncan means separation.

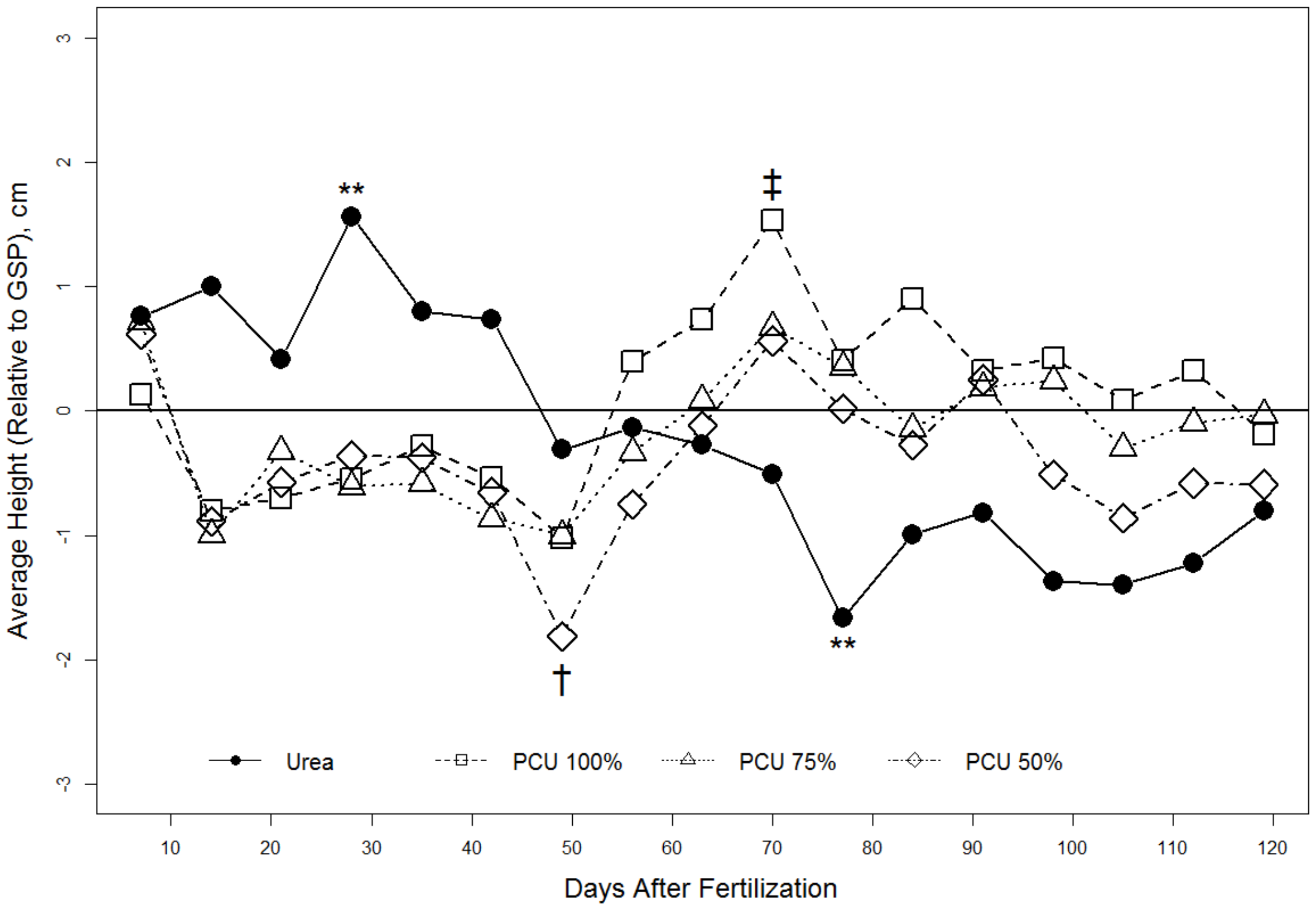

Figure 5: Average heights, pooled across all sites, taken weekly and measured from the soil surface to tip of blades. All treatments were expressed relative to GSP which is the urea split applied monthly. "**" indicates when urea is signficantly different from GSP ($P < 0.05$), "‡" indicates when PCU 100% is significnatly different from GSP ($P < 0.05$), "†" indicates when PCU 50% is significantly different from GPS ($P < 0.05$). Unfertilized control treatements are not included to simplify presentation of data.

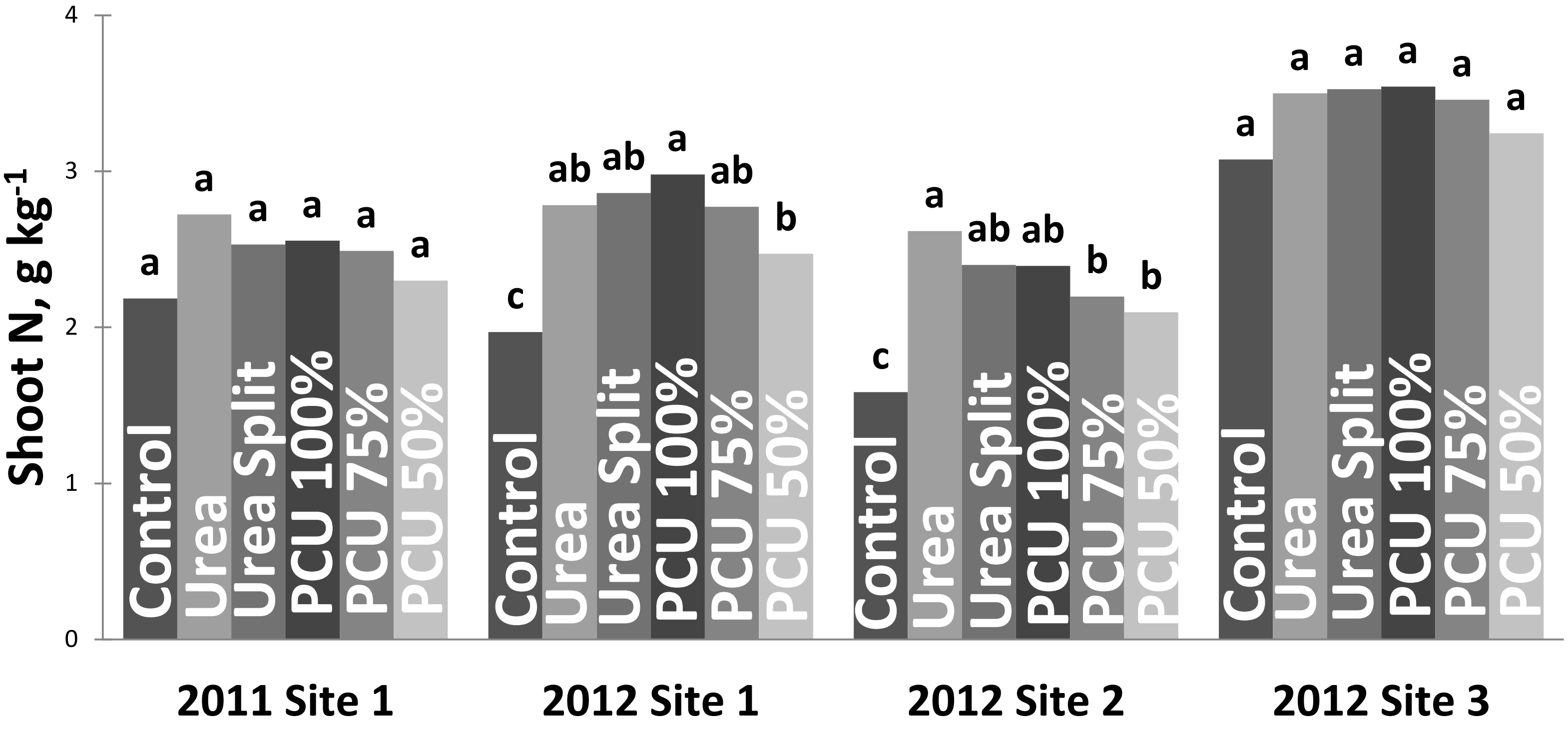

Figure 6: Average of shoot N concentrations (g N kg^{-1}) across all sampling times for all sites. Means with the same letter are not significantly different at $P < 0.05$, Duncan means separation.

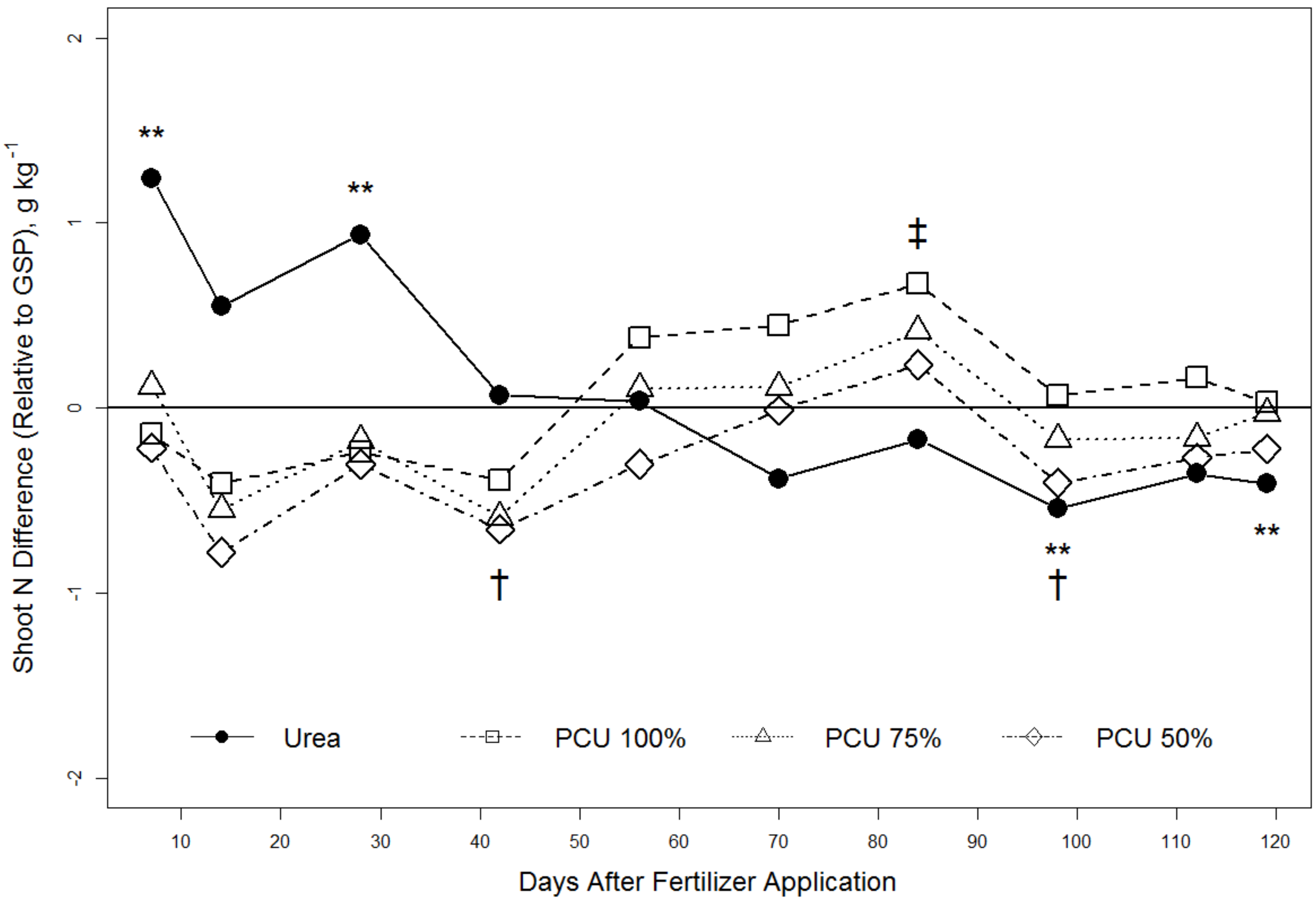

Figure 7: Shoot N concentrations (g N kg^{-1}) taken bimonthly and averaged across all sites. All treatments were expressed relative to GSP which is the urea split applied monthly. "**" indicates when urea is signficantly different from GSP ($P < 0.05$), "‡" indicates when PCU 100% is significnatly different from GSP ($P < 0.05$), "†" indicates when PCU 50% is significantly different from GPS ($P < 0.05$). Unfertilized control treatements are not included to simplify presentation of data.

APPENDIX A

LITERATURE REVIEW

Nitrogen Vital for Life

All plants require nitrogen (N) to complete their life cycle. Nitrogen is vital to various biochemical processes. It is a major factor in the formation of chlorophyll molecules, which facilitate photosynthesis and produce the green seen in leaves (Marshchner, 2012). Nitrogen is also essential in the biosynthesis of nucleotides found in deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) and in the biosynthesis of amino acids used for protein/enzyme production. Nitrogen is often the primary limiting factor for plant growth due to high demand and the fact that soil N is easily lost to the surrounding environment (Chatterjee, 2012). Without adequate concentrations of N, plants produce less chlorophyll and proteins—which results in decreased growth and increased susceptibility to pests and diseases (Marschner, 2012).

To prevent N deficiency, it is important to understand the interactions between N forms and plant uptake—as described by the N cycle. Plants depend on these interactions to obtain needed N in the forms required for uptake, namely, nitrate (NO_3^-) and ammonium (NH_4^+). The plant assessable forms make up a minimal percentage of the N in the environment as the largest pool of N is found as biologically inert N_2 gas, making up about ~78% of the atmosphere. Fixation of N from the atmosphere is dependent on lightning, in small amounts, and diazotroph soil microorganisms (eg. cyanobacteria, green sulfur bacteria, and *Azotobacteraceae)* to convert N_2 gas to biologically accessible forms. Nitrogen fixed by lightening can be directly used by plants in the form of NH_4^+.While N fixed and utilized directly by soil microorganisms is eventually made available to plants through the conversion of organic N through decomposition. Ammonium made available through decomposition is taken up from the soil solution by plant roots. Fixation of N also occurs directly into certain plants (legumes) which have developed symbiotic associations with microbes (*Rhizobium* and *Frankia*). These associations occur in the roots, where the microorganisms provide NH_4^+ directly into the xylem while receiving simple sugars and nutrients in exchange.

Soil NH_4^+ not taken up by biota is subjected to a chemical conversion to ammonia gas (NH_3). This occurs as NH_4^+ loses a hydrogen ion through chemical reactions. This form of N is highly volatile and highly soluble in water, as such during dry conditions will cause NH_4^+ volatilization. Ammonia volatilization is further increased when the chemical equilibrium is shifted towards the production of NH_3, specifically under high temperatures and with high wind speeds. Furthermore, NH_3 volatilization is dependent on soil conditions such as: soil pH, texture, and exchangeable cations. A high soil pH contains more hydroxyl ions which readily react with NH_4^+ to form NH_3 gas and water (H_2O). Soils with texture that provides adequate drainage helps move urea deeper into the soil, becoming less likely to volatilize (Al-Kanani et al., 1991; Jones et al., 2013b; Kissel, 1988). Soils with higher cation exchange capacity are able to retain NH_4^+ through electrostatic attraction to clay and organic matter, resulting in reduced NH_4^+ concentration in the soil solution and less NH_3 volatilized (Al-Kanani et al., 1991; Cameron et al., 2013). Furthermore, cation exchange sites buffer the soil against pH changes. Urea hydrolysis and NH_4^+ to NH_3 conversation temporarily increase soil pH. A low buffered soil will readily increase in pH during these chemically processes, promoting NH_3 volatilization, especially when soil pH is near or above 7 (Whitehead & Raistrick, 1993).

Ammonium not lost from soil solution due to NH_3 volatilization can undergo further chemical changes through nitrification processes. This change occurs as ammonia-oxidizing bacteria, specifically chemoautotrophic *Nitroso*–genera, oxidize NH_4^+ under aerobic conditions to nitrite (NO_2^-). Nitrite is than converted by *Nitro*-genera bacteria to NO_3^-. This conversion process is mainly dependent on conditions ideal for microbial activity, with optimal conditions being between: 46-80°F, pH 6-8, and water content 0.26-0.42 $m^3 m^{-3}$ (Frederick, 1954; Kyveryga et al., 2004; Schjønning et al., 2003).

Once NO_3^- is produced, this negatively charged N form is highly soluble in water and repelled by negatively charged soil particles. This repulsion of charges allows for relatively easy movement through the soil and into ground water. Conditions that facilitate increased NO_3^- loss are large pore spaces (especially sandy and gravely soils), excess water, and a shallow rooting zone (Easton and Petrovic, 2004). Large pore spaces and excessive water cause NO_3^- to infiltrate and percolate through the soil more quickly. Rapid percolation decreases the amount of NO_3^- available in the rhizosphere and availability for plant uptake. Nitrate taken up by the plants through mass flow, is reduced inside the plant to NH_4^+ before being integrated into molecules.

Nitrate still in soil solution is subjected to further conversion back to N_2, to complete the N cycle. This denitrification process occurs as a four step procedure when soils are anaerobic and bacteria containing the necessary enzymes are present. The process begins as bacteria utilize NO_3^- as an electron acceptor due to the limited oxygen (O_2) supply (Goodroad and Keeney, 1984). Nitrate is reduced to NO_2^- with the use of nitrate reductase. Following which NO_2^- is further converted with the same enzyme to nitric acid (NO). Nitric oxide reductase then converts NO to N_2. Similar to nitrification, denitrification rates depend on environmental factors that optimize bacterial activity. Denitrification occurs under anaerobic conditions, with water filled pore space (WFPS) at 80%, a neutral pH, and high temperatures. The process is further limited by the concentration of NO_3^- in soil solution, or the rate of nitrification (Goodroad and Keeney, 1984).

Denitrification also produces a few intermediates with nitrous oxide (N_2O) being noteworthy as it is a potent greenhouse gas. The amount of N_2O produced is dependent on soil conditions less than optimal for denitrification. Under normal denitrification conditions about 2% of N is lost as N_2O, under less than ideal conditions, as found in a temperature forest, as much as 52% of the NO_3^- converted into N_2O (Sorai et al., 2007). Conditions ideal for N_2O production are soils with: WFPS at 60%, pH between 6 and 8, soil temperatures between 59 and 95^{o}F, and high N availability (EPA, 2010; Chatterjee, 2012; Goodroad and Keeney, 1984).

The N cycle provides input into native ecosystems in amounts adequate to sustain life. However, the naturally occurring N cycle is insufficient in relatively intensive agricultural systems—requiring additional N inputs in order to avoid N deficiency and crop losses. Historically, N was provided via rotation with leguminous crops and/or application of livestock manure and other biomass source fertilizers, such as bat guano. Although crop rotation and effective recycling of wastes are best management practices, this approach to fertilization would not be sufficient to produce the needed food, fuel, and fiber to maintain the current world population of seven billion and growing. There is not enough manure and biosolid waste to meet demand and meeting the remaining demand with legumes would require development of large tracts of additional acreage in order to maintain current crop production levels.

The ability to enhance the amount of N fixation to supply this essential life giving nutrient to growing crops was facilitated at the beginning of the 20th century with the development of the Haber-Bosch process. This process uses methane to fix N_2 gas into fertilizer products. This process has provided worldwide access to N fertilizer produced in a form which is concentrated—allowing transport using less energy and greater efficiency and without the negative aspects of manure (presence of weed seeds, disease, inclusion of nutrients and other elements at levels not needed or toxic to plants). The use of manufactured fertilizers is one of the important factors leading to the green revolution which has increased plant yields around the world—resulting in reduced starvation and malnutrition and increased lifespan and quality of life in areas of the world where these fertilizers are readily accessible.

Nitrogen in the Environment

Although fertilization is essential, the increase of fertilizer use can result in increased damage to the environment due to the "leaky" N cycle. With a growing population there is a continual increase in demand for N fertilizers to be used around the world. As N undergoes a change in form through the N cycle it is easily lost to the atmosphere or hydrosphere (LeMonte et al., submitted 2012; Schlesinger and Hartley, 1992; USEPA, 2007).

Research indicates that as much as 100% of broadcasted liquid urea fertilizer applied to a residue rich surface volatilized under extreme conditions of temperature (>30^{o}C), humidity (>95%), soil moisture (field capacity), and wind (>8.3 m s^{-1}). Other studies showed surface application of N fertilizers exceeded 60% lost as a gas over the first 10 days following application (Bremer, 2006; Cameron et al., 2013; Knight et al., 2007). An early estimate of volatilization from manufactured N fertilizers was marked at 10% (Schlesinger and Harley, 1992), while more updated studies indicate as much as 20% from developed countries, or even 50% in developing countries (Zhang et al., 2011). In terms of N_2O, a conservative estimate indicates about 1.25 +/- 1.0% of all N fertilizer applied is lost as N_2O (Aneja et al., 2012; GHG Working Group, 2010). This adds up to being about 78% of N_2O produced for agricultural practices (USEPA, 2007) or about 49% of the total anthropogenic production in the world (Cameron et al., 2013; EPA, 2007).

With huge losses of gaseous NH_3 and N_2O to the atmosphere, they are contributing to a variety of environmental problems. Specifically N_2O is a major cause for concern as the molecule is a potent greenhouse gas that affects global warming potential. It has approximately a

310 times greater warming potential than carbon dioxide, due it being less reactive (USEPA, 2007). Nitrous oxide catalytically destroys ozone in the troposphere, allowing for an increased UV radiation exposure and warming effect on the Earth's surface (IPCC, 2007; LeMonte et al., Submitted 2012). Atmospheric issues steaming from NH_3 accumulation include: photochemical smog, increasing particulate matter, and strong odors, all of which are adverse to human health (Erisman and Shaap, 2004; Zhang et al., 2011).

Furthermore, NH_3 is highly reactive with water in the atmosphere and forms acid rain. In conjunction with dry and wet deposition results the saturation of watersheds which leads to soil acidification (Fenn et al., 1998). Due to the additional input of N, sensitive ecosystems have been shown to have a decrease in biodiversity as some species are able to utilize the additional N more effectively, helping to outcompete species that are less effective (Sutton et al., 2008).

The hydrosphere is also highly affected by N pollution, resulting in even more economical and health problems. Nitrogen accumulation in water systems commonly occurs due to NH_3 wet or dry deposition, NO_3^- leaching to ground water, surface runoff, and erosion of soils high in NH_4^+ or NO_3^- (Hochmutch et al., 2010; Osmond and Platt, 2000). Water eutrophication in N limited water systems (especially in saline waters), promotes algae and other N limited plants to bloom (Cameron et al., 2013). Microbial decomposition of these organisms requires the use of water dissolved oxygen O_2, ultimately resulting in an anaerobic aquatic environment in extreme circumstances. The reduced dissolved O_2 levels limit the future growth of aquatic based organisms resulting in decreased biodiversity, strong odors and unsightly waters bodies, economic losses, decreased harvestable food in the form of fish and shrimp, and decreased recreational use (Fangmeier et al., 1994; Mulvaney et al., 2009).

Furthermore, high concentrations of NO_3^- in drinking water have been related to health problems such as methemoglobinemia (baby blue syndrome) in mammalian infants (Olson et al., 2009) and linked to cancer and heart disease in Europe, although still speculative as limited research has been available to confirm in other regions of the World (Grizzetti et al., 2011).

Turfgrass Nitrogen Management

As N is often the most limited nutrient for plant growth, excessive fertilizers are often added when adequate information is unavailable. This damage is more likely if fertilizer is mismanaged, especially with application of excessive N or use of inefficient fertilizer types (Cameron et al., 2013; Zhang et al., 2011). Mismanagement is a high concern for turfgrass systems. This is primarily due to the large surface area that it covers in the United States, 1.9%, and areas are divided into small properties each being managed differently (Milesi et al., 2005). While some homeowners do not apply adequate levels of N others operating under the concept of "little is good, but more is better". This often results in high N potential loss to the environment.

To maintain a balance of healthy turf and limited N loss to the environment, best management practices (BMP) are needed. When BMP are implemented turfgrass will be more effective at reducing: water and nutrient loss through leaching, soil erosion, dust and mud problems, noise and air pollution, heat dissipation, glares, and runoff to surface water (Beard and Green, 1994). It will also become more effective at: sequestering carbon dioxide, capturing water, and producing O_2 (Stier et al., 2012). Well maintained turfgrass also provides a recreationally function by providing a low cost surface that is physical safer than other playing surfaces. Turfgrass has also been attributed to increased mental health and increasing the quality of life, community pride, social harmony, and increasing the value of properties (Beard and Green, 1994).

In order to optimize these services, consistent application of N is required to maintain a good density, color, and increase resistance to pests and environmental stresses. Nitrogen usually makes up about 2.8 to 4.2 % dry biomass of turf (Marshchner, 2012). To maintain N biomass concentrations in that range N fertilizer is traditionally applied in split applications throughout the active growth portion of the year. For warm-season turfgrass, it is often recommended to supply 50 kg N ha^{-1} for each month of active growth. For cool-season turfgrass, it is generally accepted to supply a total of 150-250 kg N ha^{-1}. The availability of the N needs to be somewhat consistent throughout the growing season, although a relatively greater amount during late fall is beneficial to allow for extended production of photosynthates to draw on when coming out of dominancy in the spring.

With each N application there is a chance of N lost to the environment. To limit N pollution and increase the effectiveness of fertilizer applied to maximize nutrient use efficiency (NUE) recommended BMP should be followed. Generally recommendations indicate that not applying fertilizer in close vicinity to water bodies, streams, or on high slopes. It is also recommended to sweeping granules off of sidewalks and driveways, which are more likely to move latterly on smooth urban surfaces ending up in water systems (Hochmuth et al., 2011; Osmond & Platt, 2000). Additionally it is recommended to not over apply N fertilizer as this will readily lead N lost to the environment through NO_3^- leaching and NH_3 volatilization (Guertal and Howe, 2012). Not over irrigating is also crucial to limiting NO_3^- leaching, while a slight irrigation event will help hydrolyze and move N into the root zone, reducing NH_3 volatilization (Hochmuth et al., 2011; Jones et al., 2013a; Osmond & Platt, 2000).

Some more extreme BMP are being implemented to curb nutrient pollution problems associated with N application to turfgrass. They are being implemented in the form of bans on N fertilization. A recent example being: New Jersey banning N fertilizer application between the summer months of April to September. The intent being to limit N volatilization, surface runoff, and NO_3^- leaching that would usually occur during the hottest and rainiest months of the year. The effectiveness of this practice is debatable as some studies have suggested that about 5% of nitrogen applied is moved laterally through runoff into aquatic systems (Stier et al., 2012). While other studies have shown BMP reduces runoff from well-maintained turfgrass close to zero (King et al., 2007; Stier et al., 2012).

Other BMP include increasing the amount of N from fertilizer used by the plants and decreasing the N lost to the environment. This can be done by increasing N use efficiency (NUE) of fertilizers applied. To maximize NUE, applying the right fertilizer at the right time and rate is essential. Overall, including all crop types, NUE is estimated to be about 50% at optimal conditions when using traditional types of fertilizer (urea and ammonium sulfate being the most common for turfgrass) (Ellison et al., 2013; Marshchner, 2012). The low NUE is dependent on the plant's ability to uptake N, environmental and soil factors, and time and rate of fertilizer application, as well as BMP applied as previously mentioned (Snyder et al., 2007).

Controlled-Release Fertilizers

A relatively new solution to increase NUE includes the use of controlled-release fertilizers (CRF) and slow-release fertilizers (SRF). In contrast with standard "quick release" fertilizers, CRFs and SRFs release N over time rather than all at once in an attempt to better match plant N needs through the growing season and to reduce time of exposure for N loss to the environment. The difference between the SRF and CRF is the mode of release. The former are subject to soil microbial processes such as the breakdown of wax or sulfur coatings. Once an area of the coating is broken down, the urea is left accessible to be hydrolyzed and further converted to other N forms. This process is more unpredictable, making additional applications necessary during growing seasons (Ellison et al., 2013). This group of fertilizers also includes denitrification/ nitrification inhibitors, long chain molecules that require further break down, or granules coated in a substance to restrict water movement through hydrophobic or hydrophilic attractions (Aviv, 2001). On the other hand CRFs are developed using an organic coating around a granule of standard fertilizer, such as urea. The polymer coating has micropores that allow soil moisture to diffuse through the coating to dissolve the urea. Urea is a larger molecule than water and, as such, does not immediately cross the membrane into the soil. We hypothesize that, as the coating warms along with increasing soil temperatures, it expands and the size of the micropores increase—allowing the urea to eventually reach the soil solution through diffusion. The rate of diffusion is based on the concentration gradient with temperature being the primary regulator (Ellison et al., 2013; Shaviv et al., 2003).

The Polymer coating of CRF provides a protective barrier for various lengths of time depending on coating properties and thickness—allowing for release rates of N to correctly match plant nutrient needs (Ellison et al., 2013; Fujinuma et al., 2009; Olson-Rutz et al., 2009; Shaviv and Mikkelsen, 1993). This coating is resistant to microbial breakdown, although it is eventually decomposed. It is also resistant to physical damage inflicted by abiotic conditions, but aggressive handling can catastrophically disrupt the membrane. Research has shown that CRF has increased plant yields and quality (Cahill et al., 2010; Knight et al., 2007), while decreasing the amount of N lost as NO_3^- (Pack and Hutchinson, 2003; Wilson et al., 2010), NH_3 (Knight et al, 2007; Rochette et al., 2009), and N_2O (Halvorson et al., 2008; Halvorson et al., 2010; Hyatt et al., 2010; Jassal et al., 2008) in both turf and agricultural systems (Ellison et al, 2013; Grant, 2008; LeMonte et al., Submitted 2012; Torello et al., 1983). The use of this technology allows for an extended application up to three or four months in a single application at the beginning of the growing season. Thus improving cost benefits by eliminating additional N applications seen with traditional fertilizer and SRFs (Ellison et al., 2013; Hyatt et al., 2010). The potential use of CRF for turfgrass is warranted as increasing NUE has been seen in other crops (Ellison et al., 2013).

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APPENDIX B

DATA TABLES

VERDURE

Location	N Source	Julienne Day (Weeks After Application)									
		139 (1)	148 (3)	159 (4)	167 (5)	173 (6)	181 (7)	187 (8)	196 (9)	202 (10)	229 (12)
2011- Site	Control	1.7	1.7	2.2	2.0	2.8	2.8	4.1	2.6	3.5	3.5
	PCU 100%	1.5	1.7	2.3	2.4	3.0	3.2	4.3	3.9	4.4	4.1
	PCU 75%	1.7	1.7	2.2	2.1	3.0	3.1	4.1	3.4	3.9	4.3
	PCU 50%	1.8	1.8	2.1	2.0	2.8	3.0	4.1	3.3	4.0	4.1
	Urea	1.8	1.8	2.9	3.2	3.8	3.5	4.3	3.4	3.6	4.3
	Urea Split	1.9	1.9	2.9	2.7	3.5	3.8	4.5	4.4	4.3	4.1

N Source	Julienne Day (Weeks After Application)			
	243 (14)	251 (15)	258 (16)	251 (17)
Control	4.4	4.1	3.6	4.3
PCU 100%	4.6	4.4	3.9	4.4
PCU 75%	4.4	3.5	3.6	4.5
PCU 50%	4.4	3.9	3.4	4.4
Urea	4.5	3.1	2.8	4.6
Urea Split	4.6	3.8	3.1	4.3

Verdure ratings (0-5) averaged across four replications for each sampling date for the 2011 site.

Location	N Source	Julienne Day (Weeks After Application)											
		123 (1)	130 (2)	137 (3)	144 (4)	151 (5)	158 (6)	165 (7)	172 (8)	179 (9)	187 (10)	193 (11)	200 (12)
2012- Site 1	Control	2.5	2.8	2.8	2.4	2.6	2.8	2.6	2.8	2.7	2.6	3.0	3.1
	PCU 100%	2.8	2.6	3.0	2.6	3.5	3.6	3.8	4.0	3.8	3.6	3.7	3.9
	PCU 75%	2.8	2.8	3.1	3.2	3.1	3.7	3.4	3.8	3.3	3.6	3.9	3.6
	PCU 50%	2.9	3.1	3.1	3.1	3.3	3.8	3.3	3.9	3.5	3.8	3.8	3.8
	Urea	3.0	3.4	4.0	3.8	3.6	4.1	3.4	3.5	3.3	3.2	3.4	3.4
	Urea Split	2.8	2.8	3.3	3.0	3.1	3.7	3.4	3.8	3.4	3.4	3.8	4.1
2012- Site 2	Control	3.0	2.9	3.1	2.8	2.9	2.9	3.1	2.9	2.7	2.8	2.9	2.9
	PCU 100%	3.0	3.1	3.5	3.3	3.3	3.6	3.5	3.8	3.2	3.8	3.4	3.0
	PCU 75%	3.0	3.0	3.1	3.0	3.3	3.3	3.5	3.5	3.1	3.5	3.5	3.3
	PCU 50%	3.0	2.9	3.4	2.9	3.1	3.0	3.4	3.6	3.4	3.5	3.4	3.1
	Urea	3.0	3.0	4.1	3.8	3.6	3.9	3.9	3.9	3.3	3.5	3.3	3.5
	Urea Split	3.0	3.3	3.9	3.4	3.3	3.6	4.3	3.5	3.3	3.5	3.5	3.5
		123	130	137	144	151	158	165	172	179	188	193	200
2012- Site 3	Control	2.5	2.8	2.5	3.1	2.9	3.4	3.1	2.9	3.1	3.2	3.2	3.3
	PCU 100%	2.8	2.5	3.1	3.3	3.1	3.5	3.6	3.5	3.5	3.4	3.6	3.5
	PCU 75%	2.8	3.3	3.3	3.4	3.3	3.5	3.7	3.4	3.6	3.5	3.5	3.3
	PCU 50%	2.9	2.7	3.0	3.5	3.1	3.5	3.6	3.4	3.4	3.4	3.5	3.3
	Urea	3.0	3.0	3.0	3.9	3.4	4.0	3.7	3.4	3.4	3.4	3.3	3.3
	Urea Split	2.8	2.9	3.4	3.6	3.0	3.8	3.6	3.4	3.5	3.4	3.6	3.4

Verdure ratings (0-5) averaged across four replications for each sampling date for all 2012 sites.

Location	N Source	Julienne Day (Weeks After Application)				
		207 (13)	215 (14)	222 (15)	228 (16)	237 (17)
2012- Site 1	Control	3.2	3.2	3.1	3.1	3.5
	PCU 100%	3.9	3.9	3.9	3.6	3.9
	PCU 75%	3.6	3.9	3.6	3.8	3.5
	PCU 50%	3.6	3.6	3.8	3.6	3.6
	Urea	3.4	3.3	3.4	3.3	3.5
	Urea Split	3.7	3.8	4.1	3.6	3.6
2012- Site 2	Control	2.9	2.8	2.8	3.0	3.1
	PCU 100%	3.8	3.3	3.2	3.0	3.5
	PCU 75%	3.6	3.3	3.3	3.4	3.5
	PCU 50%	3.7	3.2	3.4	3.3	3.5
	Urea	3.3	3.2	3.2	3.1	3.4
	Urea Split	3.8	3.4	3.4	3.3	3.8
		207	215	222	228	237
2012- Site 3	Control	3.9	3.9	3.4	3.1	3.1
	PCU 100%	3.8	3.9	3.4	3.0	3.0
	PCU 75%	3.9	3.9	3.4	3.5	3.1
	PCU 50%	3.9	3.9	3.4	3.1	3.1
	Urea	3.8	3.9	3.4	3.3	3.1
	Urea Split	3.7	3.9	3.4	3.3	3.0

Continued verdure ratings (0-5) averaged across four replications for each sampling date for all 2012 sites.

NDVI

Location	N Source	Julienne Day (Weeks After Application)										
		123 (1)	137 (3)	144 (4)	151 (5)	158 (6)	165 (7)	172 (8)	179 (9)	187 (10)	193 (11)	200 (12)
2012 Site 1	Control	0.712	0.786	0.800	0.862	0.830	0.824	0.872	0.898	0.872	0.883	0.901
	PCU 100%	0.776	0.817	0.866	0.895	0.879	0.869	0.904	0.913	0.895	0.896	0.906
	PCU 75%	0.745	0.829	0.841	0.892	0.873	0.860	0.900	0.910	0.891	0.895	0.912
	PCU 50%	0.745	0.809	0.845	0.885	0.870	0.858	0.897	0.912	0.890	0.899	0.909
	Urea	0.782	0.857	0.887	0.903	0.880	0.862	0.900	0.909	0.892	0.889	0.904
	Urea split	0.766	0.831	0.845	0.900	0.880	0.860	0.904	0.914	0.892	0.899	0.913
2012 Site 2	Control		0.816	0.835	0.846	0.815	0.797	0.833	0.845	0.889	0.821	0.802
	PCU 100%		0.837	0.858	0.872	0.858	0.852	0.881	0.895	0.893	0.888	0.874
	PCU 75%		0.831	0.843	0.866	0.844	0.838	0.868	0.885	0.870	0.876	0.867
	PCU 50%		0.847	0.843	0.870	0.853	0.843	0.879	0.892	0.885	0.882	0.880
	Urea		0.851	0.871	0.885	0.855	0.855	0.883	0.890	0.864	0.881	0.865
	Urea split		0.855	0.869	0.879	0.868	0.856	0.880	0.886	0.876	0.875	0.882
2012 Site 3	Control	0.780	0.787	0.837	0.862	0.853	0.860	0.878	0.878	0.886	0.883	0.902
	PCU 100%	0.762	0.772	0.841	0.856	0.873	0.873	0.890	0.886	0.903	0.894	0.899
	PCU 75%	0.760	0.815	0.872	0.881	0.866	0.863	0.896	0.888	0.901	0.890	0.897
	PCU 50%	0.787	0.833	0.875	0.875	0.871	0.878	0.900	0.886	0.903	0.891	0.897
	Urea	0.752	0.822	0.879	0.885	0.878	0.881	0.898	0.889	0.897	0.885	0.897
	Urea split	0.758	0.790	0.858	0.888	0.875	0.877	0.893	0.884	0.902	0.889	0.901

.NDVI measurements averaged across four replications for all 2012 sites.

Location	N Source	Julienne Day (Weeks After Application)			
		207 (13)	215 (14)	222 (15)	237 (17)
2012 Site 1	Control	0.908	0.908	0.888	0.899
	PCU 100%	0.912	0.914	0.898	0.909
	PCU 75%	0.914	0.914	0.885	0.904
	PCU 50%	0.911	0.913	0.891	0.918
	Urea	0.911	0.909	0.887	0.897
	Urea split	0.937	0.917	0.902	0.916
2012 Site 2	Control	0.840	0.845	0.839	0.837
	PCU 100%	0.896	0.885	0.875	0.882
	PCU 75%	0.891	0.885	0.873	0.873
	PCU 50%	0.891	0.881	0.878	0.880
	Urea	0.894	0.880	0.876	0.876
	Urea split	0.886	0.879	0.877	0.886
2012 Site 3	Control	0.908	0.911	0.905	0.890
	PCU 100%	0.913	0.907	0.910	0.903
	PCU 75%	0.908	0.907	0.906	0.884
	PCU 50%	0.910	0.914	0.901	0.888
	Urea	0.910	0.910	0.906	0.893
	Urea split	0.908	0.916	0.904	0.894

Continued NDVI measurements averaged across four replications for all 2012 sites.

AVERAGE HEIGHTS

Location	N Source	Julienne Day (Weeks After Application)												
		148 (3)	159 (4)	167 (5)	173 (6)	181 (7)	187 (8)	196 (9)	202 (10)	216 (11)	229 (12)	236 (13)	243 (14)	251 (17)
2011 Site 1	Control	10.25	9.93	9.93	9.00	8.98	8.23	11.35	10.43	12.65	15.55	14.35	13.68	5.40
	PCU 100%	10.55	9.20	9.33	8.08	9.05	10.10	13.00	13.65	18.00	19.00	16.45	14.75	5.80
	PCU 75%	9.70	9.63	8.75	7.88	9.30	8.90	11.83	12.20	15.58	17.33	15.33	14.18	5.55
	PCU 50%	10.58	9.28	9.18	8.45	8.70	9.15	12.68	13.10	14.80	16.43	14.78	14.28	5.45
	Urea	15.00	13.40	10.43	10.60	11.53	10.13	12.90	11.95	13.95	15.90	14.43	11.85	5.33
	Urea Split	12.18	9.10	9.18	9.05	12.48	10.50	14.00	12.75	15.35	17.23	14.53	14.00	5.38

Heights (cm) averaged across four replications for each sampling date for the 2011 sites.

Location	N Source	Julienne Day (Weeks After Application)												
		123 (1)	**130 (2)**	**137 (3)**	**144 (4)**	**151 (5)**	**158 (6)**	**165 (7)**	**172 (8)**	**179 (9)**	**187 (10)**	**193 (11)**	**200 (12)**	**207 (13)**
2012 Site 1	Control	4.4	6.1	5.9	5.6	5.9	6.2	6.5	7.2	6.1	7.0	7.0	7.1	7.9
	PCU 100%	4.6	6.2	6.8	8.1	7.4	8.0	10.5	11.8	12.2	13.9	11.8	10.6	11.7
	PCU 75%	5.2	6.7	7.2	7.6	7.8	7.7	10.5	10.9	11.5	13.2	11.9	10.0	11.3
	PCU 50%	5.8	6.1	7.2	8.3	7.5	8.0	9.2	9.8	10.7	12.0	11.2	10.7	11.3
	Urea	5.6	7.9	9.2	10.1	9.2	8.6	9.2	10.2	9.4	9.8	8.4	8.2	9.4
	Urea Split	4.3	6.8	7.0	8.1	8.6	7.7	9.7	10.4	9.9	10.3	10.9	10.0	10.3
2012 Site 2	Control	6.0	6.2	6.8	6.7	7.7	7.1	8.0	7.4	6.5	7.6	7.5	6.9	7.8
	PCU 100%	5.2	6.1	6.7	6.5	7.8	8.0	9.0	8.9	9.7	9.8	10.1	9.6	11.9
	PCU 75%	6.2	6.5	7.2	6.4	7.1	7.9	9.4	8.5	9.2	9.4	10.1	9.6	12.0
	PCU 50%	5.7	6.2	6.4	6.9	7.1	7.3	8.1	7.6	8.6	9.4	10.0	9.7	12.0
	Urea	5.4	6.5	7.0	7.7	7.9	9.2	10.0	9.2	9.4	9.3	8.8	9.6	11.1
	Urea Split	5.5	7.3	7.9	8.7	7.7	9.3	9.8	8.5	8.7	8.6	10.2	9.7	12.0
2012 Site 3	Control	7.9	6.6	7.2	7.7	6.9	8.3	8.5	7.8	8.1	8.2	8.7	10.4	11.5
	PCU 100%	7.9	6.9	6.8	8.2	7.6	9.0	9.0	9.9	10.2	10.5	10.7	11.7	12.0
	PCU 75%	8.1	6.1	7.2	8.1	7.3	8.3	8.5	9.5	10.1	9.6	10.4	10.5	11.8
	PCU 50%	7.5	6.5	7.1	8.2	7.9	8.9	8.4	9.5	9.8	9.5	10.2	10.0	12.0
	Urea	8.6	7.6	7.5	9.2	8.9	9.8	9.8	9.0	9.4	8.7	9.2	10.6	11.6
	Urea Split	7.6	6.7	7.6	8.2	7.7	9.2	9.7	9.7	9.6	10.1	10.3	11.3	12.3

Heights (cm) averaged across four replications for each sampling date for 2012 sites.

Location	N Source	Julienne Day (Weeks After Application			
		215 (14)	222 (15)	228 (16)	237 (17)
2012 Site 1	Control	8.5	7.9	7.7	8.0
	PCU 100%	12.4	11.7	10.2	10.5
	PCU 75%	12.0	10.5	8.8	10.8
	PCU 50%	11.0	10.3	7.9	10.1
	Urea	9.4	8.9	8.1	9.5
	Urea Split	11.5	11.5	9.4	11.4
2012 Site 2	Control	8.6	8.3	8.5	7.9
	PCU 100%	12.0	9.9	9.7	11.3
	PCU 75%	13.0	11.5	10.4	11.9
	PCU 50%	12.3	9.7	9.2	10.8
	Urea	10.9	9.6	9.0	10.6
	Urea Split	12.3	11.0	9.6	11.3
2012 Site 3	Control	11.5	9.5	8.0	9.3
	PCU 100%	11.6	11.1	8.5	10.1
	PCU 75%	12.0	10.3	8.0	10.1
	PCU 50%	11.7	10.6	8.1	9.6
	Urea	11.7	10.3	7.9	9.8
	Urea Split	12.4	11.8	8.7	10.4

Continued heights (cm) averaged across four replications for each sampling date for 2012 sites.

SHOOT N

Location	N Source	Julienne Day (Weeks After Application)						
		159 (4)	173 (6)	187 (8)	216 (12)	229 (14)	243 (16)	251 (17)
2011 Site 1	Control	2.0	1.7	1.9	2.8	2.8	2.8	0.9
	PCU 100%	2.0	1.7	2.5	4.0	3.5	3.3	1.3
	PCU 75%	1.8	1.7	2.4	3.5	3.3	2.9	1.4
	PCU 50%	2.1	1.5	2.1	3.2	3.2	2.9	1.0
	Urea	3.8	2.8	2.7	2.9	3.0	2.8	1.1
	Urea Split	2.2	2.5	2.5	2.8	3.3	3.0	1.1

Average shoot N (g kg^{-1}) measurements taken across four replications for each sampling date for the 2011 site.

Location	N Source	Julienne Day (Weeks After Application)									
		123 (1)	130 (2)	144 (4)	158 (6)	172 (8)	187 (10)	200 (12)	215 (14)	228 (16)	237 (17)
2012 Site 1	Control	1.9	2.4	2.0	1.7	2.2	1.9	2.2	2.1	1.9	1.4
	PCU 100%	2.1	3.1	2.3	3.0	4.2	3.7	3.4	3.2	2.5	2.3
	PCU 75%	2.1	3.1	2.6	2.5	3.8	3.3	3.1	3.2	2.1	1.9
	PCU 50%	1.9	2.8	2.3	2.8	2.6	2.7	3.0	2.6	2.0	2.0
	Urea	3.7	4.7	3.5	2.8	2.8	2.0	2.3	2.3	2.1	1.6
	Urea Split	2.2	4.1	2.5	2.9	3.4	2.6	2.8	3.3	2.8	2.2
2012 Site 2	Control	2.0	1.8	1.8	1.6	1.7	1.3	1.4	1.8	1.3	1.3
	PCU 100%	2.0	3.0	2.4	2.0	2.4	2.2	2.7	3.0	2.3	1.9
	PCU 75%	1.9	2.1	2.2	2.0	2.3	2.2	2.5	2.7	2.1	2.2
	PCU 50%	1.9	2.1	2.2	1.8	2.0	2.2	2.3	2.5	2.1	1.9
	Urea	3.4	3.5	3.3	3.1	2.7	2.2	2.1	2.4	1.8	1.7
	Urea Split	2.3	2.9	2.7	2.9	2.2	1.9	2.2	2.7	2.0	2.1
2012 Site 3	Control	4.0	4.3	3.5	3.0	2.9	2.7		3.0	2.5	1.8
	PCU 100%	3.9	4.4	3.7	3.7	3.7	3.6		3.3	3.2	2.3
	PCU 75%	4.9	4.8	3.9	3.4	3.3	3.0		3.0	3.0	1.8
	PCU 50%	4.0	4.5	3.5	3.2	3.4	3.2		2.9	2.6	1.9
	Urea	5.1	5.1	4.3	3.6	3.3	2.9		2.9	2.6	1.7
	Urea Split	4.0	4.6	3.9	3.6	3.4	3.6		3.4	3.0	2.2

Average shoot N (g kg^{-1}) measurements taken across four replications for each sampling date for all 2012 sites.

SHOOT C

Location	N Source	Julienne Day (Weeks After Application)						
		159 (4)	173 (6)	187 (8)	216 (11)	229 (12)	243 (14)	251 (17)
2011 Site 1	Control	44.9	45.0	45.4	46.1	45.5	46.3	43.9
	PCU 100%	45.2	45.3	45.6	46.3	46.3	45.8	44.6
	PCU 75%	44.7	45.6	45.9	46.4	45.9	46.0	45.1
	PCU 50%	45.2	44.4	45.6	46.3	45.9	46.0	44.2
	Urea	46.8	46.9	46.5	46.5	46.2	46.4	43.6
	Urea Split	45.5	46.0	46.0	46.0	46.5	46.4	40.0

Average shoot C (g kg^{-1}) measurements taken across four replications for each sampling date for the 2011 site.

Location	N Source	Julienne Day (Weeks After Application)									
		123 (1)	130 (2)	144 (4)	158 (6)	172 (8)	187 (10)	200 (12)	215 (14)	228 (16)	237 (17)
2012 Site 1	Control	44.2	45.7	45.0	44.8	46.0	45.1	44.5	44.8	42.6	44.3
	PCU 100%	45.1	46.6	45.4	45.6	46.7	42.5	44.8	44.8	44.1	42.8
	PCU 75%	43.6	46.3	44.8	45.3	47.2	44.8	44.4	44.5	43.4	42.6
	PCU 50%	45.4	46.4	45.7	45.8	46.8	43.9	44.2	43.5	42.4	43.3
	Urea	45.2	47.0	46.3	45.3	46.1	42.2	44.8	43.3	43.1	44.1
	Urea Split	45.1	47.0	45.7	45.4	47.7	44.9	43.1	43.8	43.7	43.7
2012 Site 2	Control	43.6	42.1	45.5	44.5	44.1	45.1	44.4	45.1	44.8	43.9
	PCU 100%	45.0	50.4	45.2	45.1	45.8	43.5	45.8	45.8	44.4	41.4
	PCU 75%	46.0	45.2	45.3	45.2	45.2	46.0	45.3	44.6	44.9	43.6
	PCU 50%	45.7	43.8	44.8	44.8	37.9	45.7	45.4	44.2	44.5	44.6
	Urea	47.9	44.4	45.8	46.1	45.6	45.8	44.9	45.7	45.0	44.7
	Urea Split	45.5	51.6	44.6	46.1	45.3	44.6	45.2	45.3	44.7	43.8
2012 Site 3	Control	48.7	49.1	48.4	48.0	48.2	46.8		46.5	45.7	45.7
	PCU 100%	47.8	48.3	48.8	48.4	48.5	47.6		47.2	46.5	45.7
	PCU 75%	47.2	50.1	49.0	48.1	48.7	46.8		44.5	47.6	45.3
	PCU 50%	47.9	49.1	47.9	48.1	48.5	46.8		45.8	47.0	45.8
	Urea	47.8	48.7	48.5	48.1	48.2	47.0		46.2	47.5	45.4
	Urea Split	47.6	49.2	48.4	48.3	48.2	47.1		46.2	47.2	45.7

Average shoot C (g kg^{-1}) measurements taken across four replications for each sampling date for all 2012 sites.

C:N RATIO

Location	N Source	Julienne Day (Weeks After Application)						
		159 (4)	173 (6)	187 (8)	216 (11)	229 (12)	243 (14)	251 (17)
2011 Site 1	Control	22.5	27.2	23.5	16.6	16.5	16.6	48.1
	PCU 100%	22.6	27.2	18.7	11.6	13.3	13.9	35.9
	PCU 75%	25.1	26.8	19.1	13.1	14.1	16.0	33.8
	PCU 50%	21.9	29.6	21.8	14.3	14.6	16.1	44.1
	Urea	12.2	17.0	17.6	16.1	15.6	17.0	43.2
	Urea Split	21.4	18.7	18.7	16.5	14.1	15.6	37.8

Average shoot C:N ratio taken across four replications for each sampling date for the 2011 site.

Location	N Source	Julienne Day (Weeks After Application)									
		123 (1)	130 (2)	144 (4)	158 (6)	172 (8)	187 (10)	200 (12)	215 (14)	228 (16)	237 (17)
2012 Site 1	Control	24.1	19.0	23.0	26.7	20.7	24.4	20.0	21.9	23.4	33.6
	PCU 100%	22.3	15.4	20.9	15.5	11.3	11.8	13.8	14.1	18.8	19.8
	PCU 75%	22.1	15.7	17.6	18.7	12.7	13.8	14.7	14.6	21.8	21.9
	PCU 50%	23.8	17.1	21.3	17.0	17.9	16.5	14.9	17.1	21.2	22.9
	Urea	12.4	10.4	13.3	16.7	16.8	21.6	19.3	19.6	21.3	27.1
	Urea Split	21.7	11.5	19.4	16.0	14.2	17.2	15.8	13.2	16.4	20.4
2012 Site 2	Control	24.5	24.0	25.9	28.7	28.8	36.6	32.4	26.1	35.8	35.3
	PCU 100%	22.5	18.5	19.8	22.5	18.9	20.9	17.6	15.4	19.2	21.9
	PCU 75%	24.2	22.0	21.0	23.5	20.2	23.1	19.0	17.1	21.6	20.3
	PCU 50%	24.5	21.4	21.5	26.5	20.1	21.0	20.3	18.1	21.1	23.7
	Urea	14.2	13.2	14.0	15.1	16.6	21.2	21.6	19.1	24.7	27.1
	Urea Split	21.1	17.8	16.9	16.2	21.2	23.7	20.9	17.1	22.4	21.4
2012 Site 3	Control	12.3	11.4	14.3	16.3	16.7	17.5		15.6	18.7	26.5
	PCU 100%	12.2	11.1	13.6	13.2	13.1	13.3		14.3	14.5	20.3
	PCU 75%	10.0	10.4	12.8	14.4	15.0	15.5		14.9	16.0	24.7
	PCU 50%	12.0	11.1	14.0	15.4	14.4	15.0		15.9	18.5	24.7
	Urea	9.5	9.5	11.2	13.5	14.8	16.3		15.9	18.8	27.3
	Urea Split	12.0	10.7	12.3	13.3	14.1	13.1		13.6	16.2	21.3

Average shoot C:N ratio taken across four replications for each sampling date for all 2012 sites.

BIOMASS

Location	N source	Julienne Day (Weeks After Application)									
		123 (1)	130 (2)	144 (4)	158 (6)	172 (8)	187 (10)	200 (12)	215 (14)	228 (16)	237 (17)
2012 Site 1	Control	0.76	1.23	0.74	1.06	0.68	1.05	0.82	1.02	1.53	2.51
	PCU 100%	0.79	0.97	0.78	1.03	1.07	1.65	0.92	1.01	1.11	1.77
	PCU 75%	0.75	1.05	0.91	1.07	1.28	1.57	1.04	1.43	1.58	2.07
	PCU 50%	0.80	1.23	0.89	0.91	0.94	1.18	1.09	1.22	1.65	2.29
	Urea	0.74	0.91	0.99	1.26	1.02	1.44	1.01	1.10	1.41	1.84
	Urea Split	0.97	1.11	0.75	0.94	0.71	1.29	1.08	1.21	0.98	1.88
2012 Site 2	Control	0.67	1.21	0.68	0.60	0.57	0.70	0.82	0.82	1.01	1.18
	PCU 100%	0.66	0.84	0.55	0.65	0.71	0.82	0.99	0.89	0.99	1.61
	PCU 75%	0.67	0.78	0.54	0.56	0.41	0.73	0.94	0.86	1.07	1.33
	PCU 50%	0.51	0.97	0.60	0.58	0.70	0.57	0.86	0.90	1.00	1.56
	Urea	0.71	0.96	0.74	0.57	0.69	0.84	1.05	0.80	0.96	1.51
	Urea Split	0.77	1.06	0.59	0.77	0.66	1.19	1.40	1.15	0.99	1.35
2012 Site 3	Control	0.86	0.85	0.97	0.72	1.20	1.36		1.50	1.36	2.65
	PCU 100%	0.84	0.76	1.20	0.89	1.10	1.60		1.53	0.98	2.63
	PCU 75%	0.88	0.72	0.99	0.94	1.43	1.49		1.74	1.10	2.74
	PCU 50%	0.54	0.86	1.06	0.95	0.99	1.39		1.36	1.49	2.75
	Urea	0.84	0.90	1.27	0.86	1.34	1.66		1.62	1.04	2.80
	Urea split	0.88	0.69	1.29	0.99	1.11	1.45		1.57	1.37	2.81

Biomass (g) taken from subsamples from each plot, averaged across four replications for all 2012 sites.

ROOT BIOMASS

Location	N Source	Julienne Day (Weeks After Application) 237 (17)
2012 Site 1	Control	8.9
	PCU 100%	4.8
	PCU 75%	5.3
	PCU 50%	4.6
	Urea	6.1
	Urea split	6.3
2012 Site 2	Control	6.2
	PCU 100%	4.8
	PCU 75%	4.1
	PCU 50%	5.6
	Urea	5.2
	Urea split	4.8
2012 Site 3	Control	8.0
	PCU 100%	4.4
	PCU 75%	10.0
	PCU 50%	7.4
	Urea	7.5
	Urea split	6.7

Root biomass (g) taken from a 78 cm^2 cut of each plot, averaged across four replications for all 2012 sites.

CROWN DENSITY

Location	N Source	Julienne Day (Weeks After Application) 237 (17)
2012 Site 1	Control	1.4
	PCU 100%	1.1
	PCU 75%	1.2
	PCU 50%	0.9
	Urea	1.1
	Urea split	1.3
2012 Site 2	Control	0.8
	PCU 100%	0.9
	PCU 75%	0.9
	PCU 50%	0.9
	Urea	0.9
	Urea split	0.9
2012 Site 3	Control	1.4
	PCU 100%	1.2
	PCU 75%	1.2
	PCU 50%	1.3
	Urea	1.4
	Urea split	1.3

Crowns counted from a 78 cm^2 cut of each plot, averaged across four replications for all 2012 sites.

ROOT LENGTH

Location	N Source	Julienne Day (Weeks After Application)	
		123 (1)	237 (17)
2012 Site 1	Control	3.6	4.9
	PCU 100%	3.1	2.7
	PCU 75%	2.6	2.9
	PCU 50%	3.3	3.2
	Urea	2.8	3.3
	Urea split	3.3	3.8
2012 Site 2	Control	14.6	10.8
	PCU 100%	10.8	10.8
	PCU 75%	10.9	12.3
	PCU 50%	11.9	11.5
	Urea	13.9	10.7
	Urea split	14.0	10.5
2012 Site 3	Control	12.1	16.7
	PCU 100%	11.1	12.8
	PCU 75%	10.9	12.1
	PCU 50%	11.9	13.3
	Urea	11.6	15.3
	Urea split	11.3	11.9

Root lengths (cm) measured from each plot, averaged across four replications for all 2012 sites.

SHOOT: ROOT

Location	N Source	Julienne Day (Weeks After Application) 237 (17)
2012 Site 1	Control	0.29
	PCU 100%	0.41
	PCU 75%	0.40
	PCU 50%	0.44
	Urea	0.42
	Urea split	0.36
2012 Site 2	Control	0.24
	PCU 100%	0.29
	PCU 75%	0.37
	PCU 50%	0.29
	Urea	0.36
	Urea split	0.28
2012 Site 3	Control	0.34
	PCU 100%	0.66
	PCU 75%	0.37
	PCU 50%	0.42
	Urea	0.40
	Urea split	0.43

Shoot: Root biomass ratio measured from each plot, averaged across four replications for all 2012 sites