IN-SEASON SOIL NITROGEN AS A PREDICTOR OF CORN GRAIN YIELD

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ABSTRACT

Corn (Zea mays L.) grain yield is closely linked to plant available soil nitrogen (N). Our objectives were to (i) examine the influence of N rate, source, and time of application on N use efficiency with relation to grain yield and total plant N uptake, and (ii) evaluate in-season soil N testing as a tool to determine N rate needs and predict grain yield. During the 2014-2015 growing seasons, 12 fields across Minnesota varying in soil and climate conditions received 1) pre-plant urea (0 to 204 or 315 kg N ha^{-1} in 34 or 45 kg N ha^{-1} increments); 2) pre-plant (102 or 135 kg N ha^{-1}) N sources including anhydrous ammonia with and without nitrapyrin [2-chloro-6(trichloromethyl) pyridine], polymer coated urea (PCU), and PCU-urea blends; 3) split-applications with urea ammonium nitrate at planting (34 or 45 kg N ha^{-1}) and urea with N-(n-butyl) thiophosphoric triamide (NBPT) (68 or 90 kg N ha^{-1}) at V2, V4, V6, V8, or V12 developmental stages. Soil texture and the two-tailed log likelihood test were used to group fields by grain yield response to N rate. Group1 (loamy sand) and Group2 (silty-clay loam or finer) were linear, Group3 (loam or finer) was quadratic plateau with the plateau occurring at 182 kg N ha^{-1} and 11 Mg grain ha^{-1}, and Group4 (loam) was non-responsive. Soil (0-30 cm) nitrate at V4 predicted yield as well or better than any other combination of N species, depth, or time of sampling across all groupings. In Group1 anhydrous ammonia with and without nitrapyrin and PCU outperformed urea by 58% on average and split applications increased yields by an average of 97% compared to single pre-plant application. Overall, there were no differences in grain yield due to N source or timing for Groups 2-4. Using soil N testing at V4 development stage showed promise as a tool to improve N management for corn.

INTRODUCTION

Corn often requires nitrogen (N) fertilizer applications to achieve optimal grain yields. A recent survey found that 59% of Minnesotan farmers apply N fertilizers in the spring as urea or anhydrous ammonia and 9% applied N fertilizer as side-dressed liquid fertilizer (Bierman et al., 2012). While a single pre-plant N application may provide logistical and time management advantages to farmers, the period between application and rapid crop N uptake (approximately the V6 growth stage) can leave N exposed to N loss. This is because typically during that period, much of the Midwest receives excess precipitation (Bender et al., 2013; Dinnes et al., 2002; Ritchie and Hanway, 1989). The warm and wet conditions can result in 50% of N fertilizer to be lost through leaching, volatilization, and denitrification, which not only reduces farmer's profitability, but also can detrimentally affect water and air quality (Jones et al., 2013; Karlen et al, 1998).

An alternative to reduce N loss from single pre-plant applications early in the spring, when N loss potential is highest, is to use enhanced efficiency N products (Venterea et al., 2016). These products include stabilized fertilizers and slow- and controlled-release fertilizers. Stabilized fertilizers have nitrification and/or urease inhibitors that delay the nitrification of ammonium or ammonification of urea (Trenkel, 2010). Vetsch and Randall (2004) found that without a nitrification inhibitor, spring applied anhydrous ammonia treatments lost approximately 10 ppm of nitrate between mid-May and V6 (mid-June) which they attributed to leaching. Slow- and controlled-release fertilizers are designed to release nutrients over a period of time in response to soil and climatic conditions through a variety of mechanisms including semi-permeable membranes, occlusion, and slow hydrolysis (Trenkel, 2010). While each of these N sources have potential for improving yield and fertilizer use efficiency, further investigations are needed to better identify corn responses to varying N sources and application timings.

Another potential strategy to reduce N fertilizer rates and losses is to apply N when it is needed. Delayed or split N application may improve yield and N use efficiency by supplying N closer to the time when crop N demands increase. However, in-season applications can be more labor intensive and costly than single pre-plant applications. Further, this application relies on weather and field conditions that allow equipment traffic in the field. If conditions are not fit, a delay in application can result in crop N stress and reduced yield potential (Trenkel, 2010). Additionally, if the application is not incorporated into the soil by precipitation or mechanical means, reduced yields and significant N loss is possible (Venterea et al., 2015). If in-season N applications are a preferred alternative, it would be important to determine when during the growing season the application(s) should be done to minimize N loss potential and ensure timely N availability for the crop.

Finally, an additional alternative to improve N management is through soil testing. Failure to account for residual soil N can result in excessive N applications, economic loss, and environmental waste (Dinnes et al., 2002). The pre-sidedress nitrate test (PSNT) is a tool that may help predict whether a soil will provide sufficient N for optimal grain yield. Typically, soil samples are collected from the top 30 cm and analyzed for nitrate-N (Magdoff, 1991). Soil nitrate values that fall beneath a certain threshold indicate a greater likelihood of benefit from additional N. While the test helps to identify soils that may need N, in Minnesota previous efforts have not been successful at predicting how much additional N should be applied. This test often works best when little or no N has been applied before sampling or in fields with substantial potential for mineralization. While in-season soil N measurements may help us improve N management, additional work is needed to quantify crop response to soil N at various development stages and under different soil and environmental conditions.

Our objectives were to (i) examine the influence of N rate, source, and time of application on N use efficiency with relation to grain yield and total plant N uptake, and (ii) evaluate in-season soil N testing as a tool to determine N rate needs and predict grain yield.

MATERIALS AND METHODS

Field trials were conducted in 2014 and 2015 on twelve field sites that represent major soils and agricultural regions across Minnesota. Field sites were located at the Sand Plain Research Farm in Becker, the University of Minnesota research stations at Lamberton and Waseca, and on farmers' fields near Theilman and Clara City, MN. General site descriptions and soil conditions for the top 15 cm of the soil are presented in Table 1 and Table 2. All sites were in a continuous corn (CC) cropping rotations except for Waseca1 which had a soybean corn (SbC) rotation. All locations were dryland, except for those at Becker that were irrigated.

Pre-plant treatments consisted of granular urea (46-0-0) (N-P-K) applied at 34/45 kg N ha^{-1} rate increments from 0 to 204/270 kg N ha^{-1} for SbC and CC systems respectively. A pre-plant urea (PPU) treatment of 315 kg N ha^{-1} was also applied at each of the Becker sites. Additional pre-plant treatments applied at all locations consisted of: 102/135 kg N ha^{-1} as polymer-coated urea, PCU (44-0-0) (Agrium Advanced Technologies, Loveland, CO); PCU-urea blends of 34/45-70/90 (PCU-urea 1:2) and 70/90-34/45 (PCU-urea 2:1) kg N ha^{-1}; and anhydrous ammonia (82-0-0), applied with (AAI) and without (AA) the nitrification inhibitor 2-chloro-6-(trichloromethyl) pyridine (N-Serve®, Dow Agrosciences LLC, Indianapolis, IN) at a rate of 102/135 kg N ha^{-1}. All pre-plant granular fertilizer treatments were incorporated into the soil by shallow tillage or 6 mm of irrigation within two days of broadcast application. Six additional treatments were split-applied with 34/45 kg N ha^{-1} applied as urea ammonium nitrate UAN (28-0-0), dribbled on the crop-row as a starter within 8 days of planting and side-dressed with 70/90 kg N ha^{-1} as urea with N-(n-butyl) thiophosphoric triamide (NBPT), Agrotain (46-0-0) (Koch Fertilizer LLC, Wichita, KS) broadcast applied at V2, V4, V6, V8, or V12 corn development stage (Ritchie and Hanway, 1989). On irrigated sites, the side-dressed treatments were incorporated into the soil with 6 to 20 mm of water, except for a single rain event in 2014 where 40 mm of rain incorporated the V4 side-dress fertilizer. Treatments were arranged in a randomized, complete block design with four replications. At the irrigated sites N rates were not adjusted for nitrate contributions from the irrigation water because the total amount was small. Irrigation was applied 17 times in 2014 (266 mm) and 12 times in 2015 (188 mm). Nitrate concentrations in irrigation water were low (<10 mg L-1) and are considered normal background levels. Other than N management, each location was managed to maximize corn yield (hybrid selection, planting date, population, herbicides, pesticides, etc.).

Stand counts were taken at the V4 development stage by counting the number of plants in 12.2 meters of row. Plant tissue N uptake was measured by collecting six, representative whole plant samples cut at the soil surface at the R6 development stage. Plant samples were chopped, dried at 60°C, and weighed. The dried samples were then mixed, and ground to pass through a 2mm screen with a Thomas Wiley mill. Tissue analysis for total N was determined using a Carlo Erba 1500 elemental analyzer (Horneck and Miller, 1998). Tissue N concentration, dry biomass, and plant population values were used to calculate plant N uptake of aboveground plant biomass in kg N ha^{-1}. Harvest grain yield and moistures were collected and corrected to 155 g kg^{-1} moisture. Grain was then ground using a flour mill and analyzed for total N content via combustion analysis using an Elementar Analyzer.

Soil samples were collected at the V4, V8, V12 and R1 stages using hand probes by collecting four soil cores at depths of 0-30 and 30-60 cm depths from each plot. The cores were mixed, combined, dried at 35°C, and ground to pass through a 2mm sieve. Soil samples were then analyzed for nitrate-N (Gelderman and Beegle, 2012) and ammonium-N (Bremner and Mulvaney, 1982). Air temperature and precipitation data were obtained from the Minnesota Department of Natural Resources weather stations in closest proximity to each site. Agronomic efficiency (AE) was calculated as the yield difference between the unfertilized check plot and an N treated plot divided by the applied N rate (Snyder and Bruulsema, 2007).

STATISTICAL ANALYSIS

Data were analyzed at $P \leq 0.05$ using the MIXED procedure of SAS (SAS Institute, 2012).

Fertilizer N rate was considered a fixed effect while block (nested within location), interactions with block, location and interactions with location were considered random effects. The UNIVARIATE procedure of SAS was used to assess normality of residuals and scatterplots of residuals vs. predicted values were used to verify homogeneity of variance (Kutner et al., 2004). Locations were initially separated into groups of fine and coarse textured soils. The two-tailed log likelihood ratio test was then used to investigate the significance of the location x N treatment interaction with relation to grain yield and create sub-groups of similar responses to N treatments (Neyman and Pearson, 1933). The same groupings were maintained throughout the remainder of the analysis of other dependent variables. Linear and non-linear regressions were performed using the MIXED and NLIN procedures of SAS when the main effect of N rate was significant at $P \leq 0.05$. Mean comparisons of dependent variables associated with time of N application or N source were performed using the PDIFF option of the MIXED procedure at $P \leq 0.05$.

RESULTS AND DISCUSSION

Weather

The 2014 growing season was marked by wetter than the 30-yr normal rainfall and cooler than normal temperatures in the months of April and June at all locations. For the period of April to June in 2014 we had 52% (range of 45-60%) of the yearly annual precipitation. This delayed planting and may have reduced available soil N via denitrification and leaching. Later in the season, drier than normal conditions may have resulted in water stress and reduced mineralization rates. In contrast, 2015 spring temperatures were warmer than normal and precipitation events were more evenly distributed across the growing season with only 36% of the annual precipitation falling in the months of April to June, which allowed for earlier planting than 2014.

Plant Components

Locations were grouped based on similar soil characteristics and by using the two-tailed log-likelihood test for response of grain yield to N rate. Group1 (Becker1, Becker2, Becker3) had loamy sands, Group2 (Clara1, Waseca1, Waseca2, Waseca3, Waseca4) had silty-clay loam or finer soils, Group3 (Clara2, Lamberton1, Theilman) had loam or finer soils, and Group4 (Lamberton2) had a loam soil. Groups 1 and 2 had linear yield responses to N fertilizer (Fig. 1). The highest applied N rate was considered the agronomic optimal N rate (AONR) for Groups 1 and 2 with yields of 8.9 and 11.5 Mg ha^{-1} respectively (Fig. 1). Group3 had a quadratic plateau response with an AONR of 182 kg N ha^{-1} and yield at AONR of 11.1 Mg ha^{-1}. Group4 was non-responsive to N fertilizer with an overall average grain yield of 12.6 Mg ha^{-1}.

In Group1, grain yields of PCU, AA, and AAI treatments were greater than PPU by 158% (averaged across the three sources), but the PCU-urea blends were not different than PPU (Table 3). Similar results were observed for AE where PCU, AA, and AAI increased AE by 118% (averaged across the three sources) compared to PPU. These results indicate that pre-plant N applications of urea should be avoided in coarse textured soils. While some N sources may be better than urea for single pre-plant applications, our data also showed that split-N applications are superior. In Group1, delaying N application until V4 or later, on average, increased yield by 107% and AE by 216% compared to PPU (Table 4). Even a delay until V2 was better than a single pre-plant application. Except for a yield increase with PCU-urea blends compared to PPU in Group2 (Table 3), there were no differences in grain yield due to N source or timing of application for Groups2 and 3 (Table 3 and Table 4). Similarly, except for the PCU-urea 2:1 blend that improved AE by 58% compared to PPU, there were no differences in AE due to N source or timing of application for Groups 2 and 3 (Table 3 and Table 4). Despite the potential for greater N loss in early spring, our data show that split-N applications may provide limited benefits for corn relative to a single pre-plant application on fine textured soils. Some inconsistent yield and AE differences occurred in Group4 due to timing of application and N source, but at present, given that the site was clearly not responsive to N, our preliminary analysis has not helped us obtain a clear explanation beyond possible random variability.

Plant N uptake at R6 in response to N rate was linear for all groupings (Fig. 1). The amount of N was, in general, not affected by the N source used except in Group3 where all sources but PCU enhanced plant N uptake relative to PPU (Table 3). Application timing only influenced plant N uptake for Group1 (Table 4). Applying N at V4 or later in development increased the amount of accumulated N in the plant at R6 relative to PPU. Similarly, grain N increased with delayed application from 33 kg ha^{-1} for PPU to 87 kg ha^{-1} at V12 (data not shown). These results follow closely the response of treatment we observed for grain yield.

Yield Prediction from Soil values

Unfertilized (check plot) pre-plant soil nitrate values in the top 30 cm ranged from 1.3 to 3.3 mg kg^{-1} for Groups 1-3 and 11.4 mg kg^{-1} for Group4 (data not shown). At V4, check plot PSNT values ranged from 1.7 to 7.8 mg kg^{-1} across all groups. In most states in the Midwest, fields with PSNT values of 20-25 mg kg^{-1} have a low likelihood of needing additional N. In our study soil nitrate values for all four groups were well below the threshold, indicating that all fields should respond to N fertilizer. Although Group4 had the largest PSNT values, they were still considered very low. Regardless, grain yield in Group4 did not respond to N. It is possible that the lack of response occurred due to regular rainfall throughout the growing season which likely allowed the soil to mineralize organic N at a sufficient rate to meet corn N demands throughout the growing season.

Grain yield was regressed against soil N values [nitrate or total inorganic N (TIN)] collected at V4 and V8 development stage from the 0-30 cm and 0-60 cm depth increments (Table 5). Coefficients of determination for soil nitrate at the 0-60 cm depth increment were, in general, similar or greater than TIN or shallower depths for V4 and V8 (Table 5). However, coefficients of determination for nitrate in the 0-30 cm depth increment at V4 were relatively similar to the measurement with the 0-60 cm depth increment. Since the standard practice of soil sampling for PSNT is around the V4 development stage and, a shallow sampling depth is easier to collect and nitrate less expensive to analyze than TIN, the V4 0-30 cm depth nitrate test may be a good and practical option. This sample would combine the benefits of reliable information with the least amount of effort and expense. It also provides an opportunity to assess soil N early in the season to allow in-season adjustments with N applications if needed. We also found that delaying soil testing past V8 resulted in poorer correlations to accurately predict plant N needs (data not shown).

Our agronomic optimum yield predictions using soil nitrate values in the top 30 cm at V4 development stage were 7.0, 12.1, 11.1, and 12.8 Mg grain ha^{-1} (Table 5), and soil nitrate concentrations at those optimum yields were approximately 25.5, 37.1, 28.7, and 19.7 mg kg^{-1} for Groups 1 through 4, respectively. The values for the first three groups are greater than the PSNT threshold of 20-25 mg kg^{-1} typically used in the Midwest, and possibly indicate that corn in Minnesota may need greater soil nitrate concentrations than previously determined. On the other hand, the PSNT test is typically used in soils that have received little or no N before the soil sampling, whereas we used the test after fertilizer N was applied pre-plant. Likely, greater concentrations in our study may be the result of earlier fertilization.

Grain yields were affected by in-season soil and weather conditions and nutrient availability. Group1 was the most responsive group to N treatments. Depleted initial soil N values combined with low levels of organic matter and mineralization potential and high nitrate leaching losses limited the ability of the soil to supply all corn N needs. Pre-plant fertilizer loss in the form of nitrate was likely excessive, especially during the 2014 growing season when 216mm of rain fell in the months of May and June. Delayed N with the split application past V4 (totaling 135 kg N ha^{-1}) resulted in yields that were equivalent to pre-plant N rates of 316 kg N ha^{-1} while the use of AA, AAI, and PCU at the rate of 135 kg N ha^{-1} produced equivalent yields obtained with 204 kg pre-plant N ha^{-1}. These findings indicate that for sandy soils, PPU results in substantial N leaching loss that may also impact groundwater quality, while the use of controlled release fertilizers, nitrification inhibitors, or split-N applications can result in improved fertilizer use and increased grain yield.

Groups 2 through 4 had fine-textured soils that, during the 2014 growing season, experienced periods of standing water or elevated water tables during the months of May and June. Despite these conditions, Groups 2 through 4 check plots consistently had greater yields than Group1. These groups showed limited differences between the various N sources and timing of application relative to PPU for the agronomic parameters we measured. This lack of differences are likely due to greater capacity to retain soil nutrients and greater soil organic matter levels that can replenish soil N via mineralization during the growing season.

SUMMARY

Nitrogen fertilizer management is essential to produce high corn yields with minimal N losses. Individual site characteristics such as soil texture and climate determine which combinations of best management practices are likely to produce optimal yields. Sandy soils significantly benefitted from delayed N application past V4 and the use of nitrification inhibitors or enhanced efficiency fertilizers. Fine-textured soils were less likely to have improved yields when nitrification inhibitors or enhanced efficiency fertilizers were applied or when N was split-applied. The PSNT test accurately predicted 11 of the 12 field sites would likely respond to N fertilizer. Our preliminary analysis indicates that the use of in-season soil N measurements may help us improve grain yield predictions and improve our ability to determine the need for N (and possibly guide N rate decisions), but additional work is needed.

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Table 1. Locations and soil classifications of 12 field sites for the 2014 and 2015 growing seasons in Minnesota.

Location	Year	Coordinates	County	Soil Series (Classification)
Becker1	2014	45˚23’32"N 93˚52’57"W	Sherburne	Excessively drained Hubbard Loamy Sand (Sandy, mixed, frigid Entic Hapludolls)
Clara City1	2014	44˚58’14"N 95˚22’25"W	Chippewa	Very poorly drained Bearden-Quam silty clay loam, depressional, complex, 0 to 2 percent slopes (Fine-silty, mixed, superactive, frigid Aeric Calciaquolls)
Lamberton1	2014	44˚14’50"N 95˚18’37"W	Redwood	Well drained Amiret loam, 2 to 6 percent slopes (Fine-loamy, mixed, superactive, mesic Calcic Hapludolls)
Theilman	2014	44˚16’46"N 92˚12’2"W	Wabasha	Well drained Fayette Silt Loam, benches, 0 to 2 percent slopes (Fine-silty, mixed, superactive, mesic Typic Hapludalfs)
Waseca1	2014	44˚03’40"N 93˚31’26"W	Waseca	Predominately poorly drained Webster clay loam (Fine-loamy, mixed, superactive, mesic Typic Endoaquolls) with poorly drained Canisteo silty clay loam (Fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls)
Waseca2	2014	44˚04’15"N 93˚31’16"W	Waseca	Poorly drained Nicollet clay loam (Fine-loamy, mixed, superactive, mesic Aquic Hapludolls)-Webster clay loam (Fine-loamy, mixed, superactive, mesic Typic Endoaquolls)
Becker2	2015	45˚23’32"N 93˚52’57"W	Sherburne	Excessively drained Hubbard Loamy Sand (Sandy, mixed, frigid Entic Hapludolls)
Becker3	2015	45˚23’31"N 93˚52’57"W	Sherburne	Excessively drained Hubbard Loamy Sand (Sandy, mixed, frigid Entic Hapludolls)
Clara City2	2015	44˚58’14"N 95˚22’25"W	Chippewa	Very poorly drained Bearden-Quam, depressional, complex, 0 to 2 percent slopes (Fine-silty, mixed, superactive, frigid Aeric Calciaquolls)
Lamberton2	2015	44˚14’41"N 95˚18’1"W	Redwood	Moderately well drained Normania Loam, 1 to 3 percent slopes (Fine-loamy, mixed, superactive, mesic Aquic Hapludolls)
Waseca3	2015	44˚04’15"N 93˚31’16"W	Waseca	Poorly drained Nicollet clay loam (Fine-loamy, mixed, superactive, mesic Aquic Hapludolls)-Webster clay loam (Fine-loamy, mixed, superactive, mesic Typic Endoaquolls)
Waseca4	2015	44˚03’35"N 93˚31’20"W	Waseca	Poorly drained Nicollet clay loam (Fine-loamy, mixed, superactive, mesic Aquic Hapludolls)-Webster clay loam (Fine-loamy, mixed, superactive, mesic Typic Endoaquolls)

Table 2. Background soil characteristics for 12 field sites in Minnesota.

Location	Texture Sand, Silt, clay	Soil† pH	CEC¶	OM‡	P§	K#	Ca#	Mg#	TIN††	Tile Spacing
	%	1:1 soil:water	meq $100g^{-1}$	%		--------------mg kg^{-1}	--------------			meter
Becker1	72, 6, 22	6.1	4.3	1.6	26	95	615	113	3.0	none
Clara City1	10, 48, 42	7.7	46.7	7.2	48	531	7313	963	7.9	12
Lamberton1	29, 31, 40	5.5	14.1	4.0	27	148	2089	381	7.2	none
Theilman	1, 70, 31	6.8	13.9	3.1	53	180	1924	435	6.8	none
Waseca1	20, 34, 46	5.9	34.0	6.6	24	215	5461	727	6.8	23
Waseca2	19, 35, 46	5.6	29.6	6.7	23	161	4571	746	6.1	23
Becker2	74, 3, 23	6.2	4.4	1.5	22	94	649	100	4.6	none
Becker3	74, 3, 23	6.2	4.4	1.5	22	94	649	100	4.6	none
Clara City2	10, 48, 42	7.7	46.7	7.2	48	531	7313	963	7.9	12
Lamberton2	35, 25, 40	5.1	16.3	4.7	30	112	2375	385	11.4	none
Waseca3	19, 35, 46	5.6	29.6	6.7	23	161	4571	746	6.1	23
Waseca4	23, 30, 47	6	26.0	5.6	26	212	4042	612	7.1	23

† Soil-test levels are based on samples collected in the spring from the 0 to 15 cm depth.
‡ Loss on ignition organic matter.
§ Bray-1 P (pH ≤ 7.2) or Olsen P (pH > 7.2).
# Cation exchange capacity.
¶ Ammonium acetate exchangeable K, Ca, or Mg.
†† Total inorganic N includes ammonium and nitrate in the top 60 cm.

Table 3. Average values of various dependent variables with standard errors between parentheses in response to N source at 102/135 kg N ha^{-1} rates.

Treatment¶	Grain Yield	Agronomic Efficiency†	R6 Plant N Uptake
	Mg ha^{-1}	Δkg kg^{-1}	kg ha^{-1}
		Group1	
Pre-Plant Urea	3.8 (0.5) c§	13.9 (3.7) c	79.1 (8.3) a
AAI	6.4 (0.5) a	33.2 (3.7) a	109.4 (8.3) a
AA	5.4 (0.5) ab	26.0 (3.8) ab	100.3 (8.5) a
PCU	6.2 (0.5) a	31.8 (3.7) a	93.6 (8.3) a
PCU-Urea 1:2	4.4 (0.5) bc	18.6 (3.8) bc	81.3 (8.3) a
PCU-Urea 2:1	5.1 (0.5) abc	23.6 (3.7) abc	81.0 (8.3) a
		Group2	
Pre-plant Urea	7.5 (0.6) bc	22.9 (4.1) bc	113.5 (8.7) a
AAI	7.2 (0.6) c	19.3 (4.1) c	112.0 (8.7) a
AA	6.8 (0.6) c	17.5 (4.2) c	103.3 (8.8) a
PCU	8.8 (0.6) ab	32.1 (4.1) ab	133.5 (8.7) a
PCU-Urea 1:2	8.9 (0.6) a	33.6 (4.1) ab	133.5 (8.8) a
PCU-Urea 2:1	9.3 (0.6) a	36.1 (4.1) a	130.9 (8.7) a
		Group3	
Pre-plant Urea	10.0 (1.2) a	29.4 (8.4) a	160.0 (12.5) c
AAI	11.2 (1.2) a	40.7 (8.4) a	204.7 (12.5) a
AA	10.4 (1.2) a	34.0 (8.4) a	184.6 (12.5) ab
PCU	10.5 (1.2) a	33.9 (8.4) a	169.4 (12.5) bc
PCU-Urea 1:2	10.9 (1.2) a	37.8 (8.6) a	193.3 (12.6) a
PCU-Urea 2:1	11.5 (1.2) a	43.4 (8.4) a	190.3 (12.5) a
		Group4	
Pre-plant Urea	12.4 (0.3) a	4.2 (2.6) b	226.0 (10.2) a
AAI	13.5 (0.3) a	11.9 (2.6) a	246.2 (10.2) a
AA	13.5 (0.3) a	12.2 (2.6) a	222.0 (10.2) a
PCU	12.9 (0.3) a	9.0 (2.6) ab	223.0 (10.2) a
PCU-Urea 1:2	12.8 (0.3) a	7.4 (2.6) ab	227.7 (10.2) a
PCU-Urea 2:1	13.1 (0.3) a	7.9 (2.6) ab	221.7 (10.2) a

¶ AAI, anhydrous ammonia with nitrification inhibitor, AA, anhydrous ammonia, PCU, polymer coated urea, PCU-urea 1:2, PCU-urea blends at ratio of 1:2, PCU-urea 2:1, PCU-urea blends at a ratio of 1:2.

† Agronomic efficiency is calculated as the yield difference between the unfertilized check plot and an N treated plot divided by the applied N rate.

§ Within group and agronomic variable, means followed by the same lower case letter are not different (P>0.05).

Table 4. Average values of various dependent variables with standard errors between parentheses in response to time of N application at 102/135 kg N ha^{-1} rates.

Treatment	Grain Yield	Agronomic Efficiency†	R6 Plant N Uptake
	Mg ha^{-1}	Δkg kg^{-1}	kg ha^{-1}
		Group1	
Pre-Plant Urea	3.8 (0.4) c§	13.9 (3.1) c	79.1 (7.8) c
V2	6.1 (0.7) b	31.3 (5.2) b	94.1 (13.0) bc
V4	7.4 (0.4) ab	40.9 (3.1) ab	117.7 (7.8) ab
V6	8.0 (0.4) a	45.2 (3.1) a	111.9 (7.8) ab
V8	8.1 (0.4) a	45.6 (3.1) a	113.6 (7.8) ab
V12	7.9 (0.4) ab	44.2 (3.1) ab	127.3 (7.8) a
		Group2	
Pre-Plant Urea	7.5 (1.0) a	22.9 (5.0) a	113.5 (11.3) a
V2	8.6 (1.0) a	31.5 (5.0) a	125.4 (11.3) a
V4	8.7 (1.0) a	31.9 (5.0) a	132.5 (11.3) a
V6	8.5 (1.0) a	29.8 (5.0) a	131.0 (11.3) a
V8	8.7 (1.0) a	30.9 (5.0) a	137.6 (11.3) a
V12	8.4 (1.0) a	29.4 (5.0) a	137.8 (11.4) a
		Group3	
Pre-Plant Urea	10.0 (1.2) a	29.4 (6.3) a	160.0 (14.8) a
V2	10.5 (1.2) a	34.7 (6.3) a	177.9 (14.8) a
V4	10.4 (1.2) a	32.8 (6.3) a	165.2 (14.8) a
V6	10.5 (1.2) a	34.4 (6.3) a	183.0 (14.8) a
V8	10.4 (1.2) a	32.8 (6.3) a	177.0 (14.8) a
V12	9.2 (1.2) a	22.9 (6.3) a	191.9 (14.8) a
		Group4	
Pre-Plant Urea	12.4 (0.2) bc	4.2 (1.8) bc	226.0 (11.3) a
V2	12.9 (0.2) ab	7.8 (1.8) ab	224.4 (11.3) a
V4	12.0 (0.2) c	1.0 (1.8) c	217.7 (11.3) a
V6	13.2 (0.2) a	10.1 (1.8) a	228.9 (11.3) a
V8	12.8 (0.2) ab	6.8 (1.8) ab	208.3 (11.3) a
V12	12.5 (0.2) bc	4.7 (1.8) bc	233.8 (11.3) a

† Agronomic efficiency is calculated as the yield difference between the check plot and an N treated plot divided by the applied N rate.

§ Within group and agronomic variable, means followed by the same lower case letter are not different (P>0.05).

Table 5. Regression models for grain yield (Mg ha^{-1}) against in-season soil N values (kg N ha^{-1}).

	Group1				Group2			
	Best Fit Equation	SNP	YP	r^2§	Best Fit Equation	SNP	YP	r^2§
V4 NO3 0-30 cm	$y=2.3442+0.0732x-0.00029x^2$	126	7.0	0.31	$y=3.5278+0.1287x-0.00048x^2$	139	12.1	0.69
V4 NO3 0-60 cm	$y=1.9967+0.0436x-0.00009x^2$	301	7.0	0.38	$y=2.9163+0.0848x-0.00021x^2$	214	11.4	0.69
V4 TIN 0-30 cm	$y=2.1274+0.0455x-0.00009x^2$	253	7.9	0.40	$y=2.3847+0.1109x-0.00032x^2$	173	12.0	0.63
V4 TIN 0-60 cm	$y=2.74504+0.01479x$	-	-	0.44	$y=3.76+0.037x$	-	-	0.61
V8 NO3 0-30 cm	$y=2.3941+0.1784x-0.00138x^2$	65	8.2	0.32	$y=5.3308+0.1683x-0.00139x^2$	61	10.4	0.25
V8 NO3 0-60 cm	$y=2.746+0.04061x$	-	-	0.42	$y=3.7807+0.121x-0.00054x^2$	112	9.8	0.40
V8 TIN 0-60 cm	$y=1.6859+0.1061x-0.0004x^2$	133	8.7	0.3	$y=4.5823+0.0991x-0.00043x^2$	155	9.6	0.17
V8 TIN 0-60 cm	$y=1.4916+0.04632x-0.00006119x^2$	-	-	0.4	$y=3.0811+0.0775x-0.0002x^2$	194	10.6	0.27
	Group3				Group4			
V4 NO3 0-30 cm	$y=5.3963+0.092x-0.00037x^2$	122	11.1	0.27	$y=10.44+0.059x-0.00037x^2$	83	12.8	0.06*
V4 NO3 0-60 cm	$y=0.8306+0.1487x-0.00055x^2$	135	10.9	0.33	$y=9.8358+0.0454x-0.00017x^2$	134	12.9	0.11*
V4 TIN 0-30 cm	$y=4.5891+0.081x-0.00025x^2$	162	11.2	0.20	$y=9.8554+0.061x-0.00032x^2$	95	12.8	0.12*
V4 TIN 0-60 cm	$y=-1.07+0.128x-0.00034x^2$	188	11.0	0.26	$y=9.072+0.0476x-0.00015x^2$	159	12.8	0.13*
V8 NO3 0-30 cm	$y=6.8704+0.1203x-0.00087x^2$	69	11.0	0.20	$y=12.289+0.00472x$	-	-	0.12
V8 NO3 0-60 cm	$y=4.8566+0.1304x-0.00069x^2$	94	9.9486	0.25	$y=12.2061+0.00355x$	-	-	0.13
V8 TIN 0-60 cm	$y=6.4874+0.0846x-0.00041x^2$	103	10.9	0.14	$y=3.06551+0.04471x$	-	-	0.26
V8 TIN 0-60 cm	$y=3.0548+0.1157x-0.00043x2$	135	10.8	0.19	$y=2.32155+0.02885x$	-	-	0.16

† SNP, Soil N at plateau, YP, Yield at plateau

* Significant at P>0.1 level

§ R^2 values are not valid for non-linear regression models as the individual sum of squares do not add to the total sum of squares. These pseudo R^2 values should be regarded as a quick comparison tool and not as valid statistical measures.

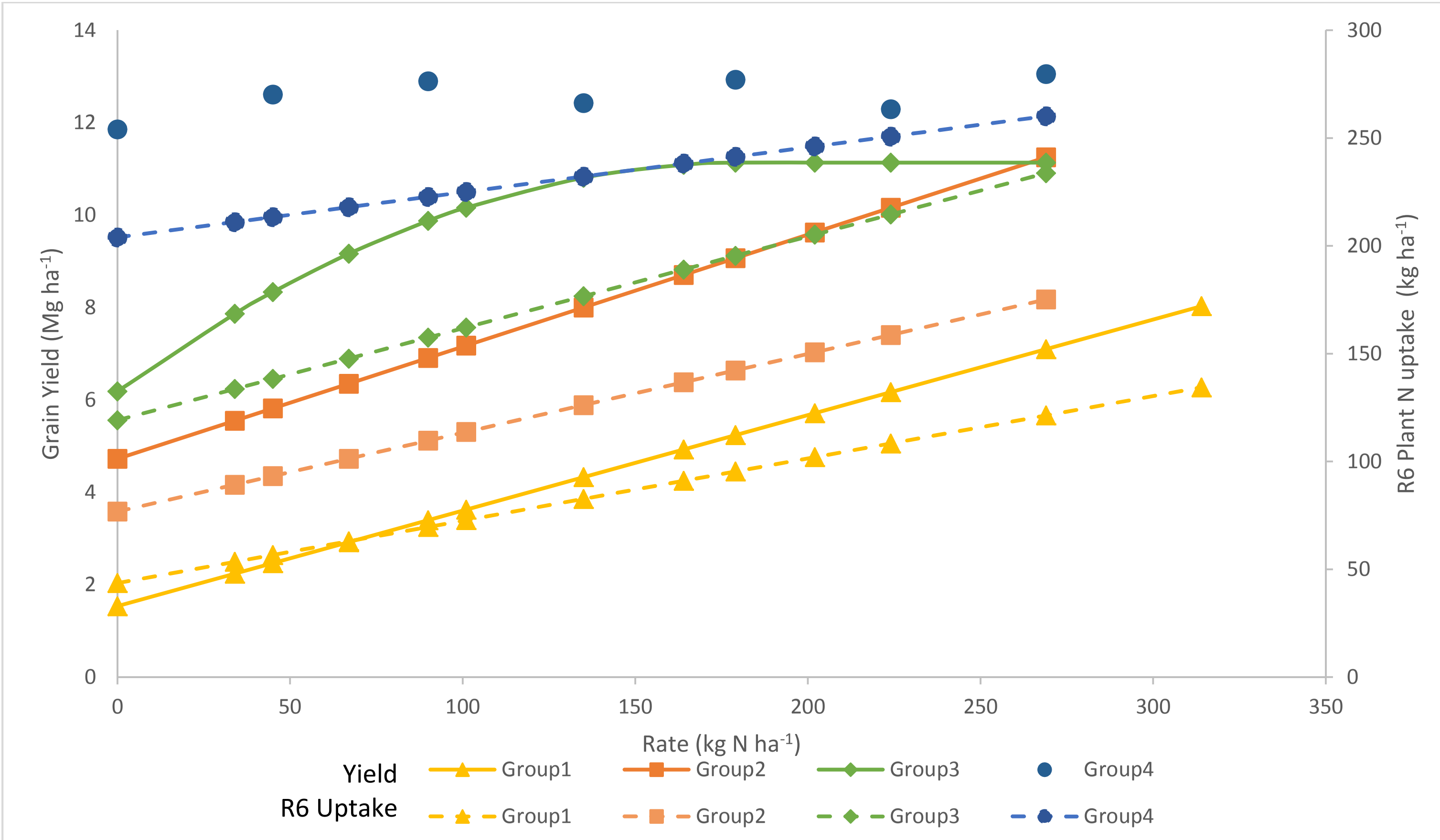

Figure 1. Relationship of grain yield and R6 plant N uptake in response to pre-plant urea with increasing N rate.

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