NITROGEN FERTILIZER RATE, SOURCE, AND APPLICATION TIMING EFFECTS ON SOIL NITROGEN AND CORN YIELD

A THESIS
SUBMITTED TO THE FACULTY OF THE
UNIVERSITY OF MINNESOTA
BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

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May 2018

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ACKNOWLEDGEMENTS

I would like to thank Dr. Fabián Fernández who has been my advisor, mentor, and friend since 2014. His mentorship and guidance has been key to helping me to develop research skills and my intellectual development. I would also like to thank Andy Scobbie and Thor Sellie for their technical and managerial help for maintaining our field sites, equipment, and in processing the thousands of plant and soils we collected. I thank Gabriel Paiao who also worked on the Spring N project for his friendship, collaboration, and help in sample processing. I thank Darby Martin, Nick Severson, and Erik Joerres and the undergraduates from the Soil, Water, and Climate field crew. The intensive soil and plant sampling associated with this project was only possible because of their efforts. I thank Dr. Daniel Kaiser for his assistance in the lab and Dr. Jeffery Coulter for his help with the statistics. I thank them both for serving as members on my committee and for providing feedback on the manuscripts. I thank my family, especially my mother, for teaching me the importance of education and for training me up in the way I should go (Proverbs 22:6). I am grateful for the righteous example of integrity and service my father, Dr. Ross Spackman, has set for me. I am proud to be able to follow in his footsteps and for the lengthy discussions we have about soil and plant science. I thank my dear wife Kathryn for her support. She has helped me collect samples, spent late nights in the lab grinding soil and plant samples, and been my greatest cheerleader. I am grateful for her faith and patience with me and for bearing the cold, Minnesota winters. I thank my Heavenly Father for the comfort, guidance, and direction He gives me. Lastly, I thank the Minnesota Corn Growers Association for funding this research and my education.

DEDICATION

This thesis is dedicated to my wife Kathryn and our son, whose support has been essential for completion of this degree.

ABSTRACT

Use of the 4R's (right rate, right source, right placement, right time) for nitrogen (N) management may improve farmer productivity and enhance environmental sustainability. However, best management practices for the 4R's are not consistent across landscapes due to variable soil and growing season conditions. Research that systematically modifies the 4R's may allow for selection of best N management practices for high yielding corn (*Zea mays* L.) and N use efficiency. Because corn yield is dependent on N uptake from the soil, frequent in-season soil sampling may be useful to assess N availability to the crop over time and may be a useful tool to forecast soil N sufficiency for agronomically optimal grain production. We examined the effect of N rate, source, and time of fertilizer application on soil N availability and corn grain yield for 12 site-years across Minnesota for the 2014 and 2015 growing seasons. Fertilizer treatments consisted of: pre-plant urea applied at 35 to 45 kg N ha^{-1} increments at seven to eight N rates; pre-plant applications at 105 or 135 kg N ha^{-1} of anhydrous ammonia with (AAI) and without (AA) nitrification inhibitor, polymer coated urea (PCU), and PCU-urea blends at ratios of 1:2 (PCU-U 1:2) and 2:1 (PCU-U 2:1); and split fertilizer applications of 35 or 45 kg N ha^{-1} urea ammonium nitrate applied as a starter fertilizer and side-dressed with 70 or 90 kg N ha^{-1} urea plus nitrification inhibitor at the V2, V4, V6, V8, or V12 vegetative development stage. Site-years were grouped based on similar soil textures and responses of grain yield to either N rate or time of fertilizer application. In-season soil and plant samples were collected five times during the growing season. The modified arcsine-log calibration curve was used to examine the potential of in-season soil nitrate-N, ammonium-N, and total inorganic N concentrations to predict corn grain yields and the in-season N fertilizer rate needed to achieve those yields.

Coarse textured soils were prone to rapid N loss for all pre-plant fertilizer treatments where yield was not maximized even when 315 kg N ha^{-1} urea was applied. AA, AAI, and PCU delayed nitrification or fertilizer N release from the prill relative to pre-plant urea for improved synchrony of N availability to corn demand with a 1.6-fold yield improvement on average. Likewise, split-applications from V4 to V12 improved yields 1.5 to 1.9-fold over pre-plant urea with 50 to 63% of the applied fertilizer N rate recovered in plant biomass.

On fine-textured soils, seasonal precipitation strongly influenced site response to N fertilizer treatments. Site-years with low N loss potential had no yield differences between N sources and were either non-responsive to N rate or optimized yield at 180 kg N ha^{-1}. Site-years with high N loss potential had reduced N availability and did not maximize yield regardless of the applied N rate. Under these conditions, yield, N use efficiency, and economic return was greatest for PCU-U blends relative to other N sources. Precipitation timeliness was important for incorporation of split-applied urea and for corn N uptake. With dry summer conditions, fertilizer N accumulated in the 0- to 30-cm soil layer primarily as ammonium-N. Under well-distributed rainfall, side-dressed N was rapidly nitrified and taken up by the crop with the V2 to V8 timings producing 11.2 Mg grain ha^{-1} on average. This highlights the importance of synchronizing in-season fertilizer applications with precipitation events and that adequate soil moisture is required for soil N to be crop available.

The modified arcsine-log calibration curve successfully correlated grain yields with soil test values for fine-textured sites but showed limited utility for coarse textured soils because of excessive N loss. For fine-textured soils, V4 soil nitrate from the 0- to 30-cm was better correlated than pre-plant or V8 timings and was similarly correlated to deeper sampling depths or N species. This is positive as it represents labor and analysis cost savings as well as greater time for side-dress fertilization when the crop is small. With this study, we demonstrated that seasonal weather patterns and soil texture are major drivers of soil N availability such that there is not a single N fertilizer rate, source, or application timing that will optimize yields in all situations. On coarse-textured soils or when early spring conditions are expected to be wetter than normal, pre-plant urea should be avoided in favor of split-applications or other N sources, but little differences are likely between sources or applications timings when N loss potential is low.

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LIST OF ABBREVIATIONS

AA, anhydrous ammonia

AAI, anhydrous ammonia with nitrapyrin

AE, agronomic efficiency

AONR, agronomic optimum nitrogen rate

CSTV, critical soil test value

EONR, economically optimum nitrogen rate

FRE, fertilizer recovery efficiency

GDD, growing degree day

GNHI, grain nitrogen harvest index

GNRE, grain nitrogen recovery efficiency

MALCC, modified arcsine-log calibration curve

NBPT, N-(n-butyl) thiophosphoric triamide

NUE, nitrogen use efficiency

PCU, polymer coated urea

PFP, partial factor productivity

SD, sidedress

STV, soil test value

CHAPTER 1: SOIL NITROGEN AVAILABILITY FOR CORN AS INFLUENCED BY NITROGEN RATE AND SOURCE IN MINNESOTA

1.1. SYNOPSIS

Application of the right rate and right source are two of 4R's recommended to improve nitrogen use efficiency (NUE) in corn (Zea mays L.) but the literature often reports contrasting recommendations. This study determined the effect of fertilizer rate and source on soil N and corn grain yield and evaluated in-season soil N testing to forecast grain yield. Experiments were conducted at five locations in Minnesota over two growing seasons with site-years grouped according to soil texture and grain yield response to N rate: Group 1 (coarse, linear), Group 2 (fine, linear), Group 3 (fine, quadratic-plateau), Group 4 (fine, non-responsive). Site-years with soil and weather conditions favoring N loss had linear responses to N rate applied as pre-plant urea and produced less yield at equivalent N rates relative to site-years where N loss potential was low. Anhydrous ammonia with (AAI) and without (AA) nitrification inhibitor, polymer coated urea (PCU) and PCU-urea blends improved yield 1.2- to 1.7-fold greater than urea in site-years with high N loss potential, but there were limited differences due to N source in low N loss potential site-years. Soil nitrate-N collected at the 0- to 30-cm layer at the four-leaf collar stage (V4) correlated well to relative yield on fine-textured soils with a critical soil test value (CSTV) of 24 to 30 mg kg-1 but showed no utility for coarse-textured soils. This study illustrates that weather and site-year conditions strongly influence yield response to fertilizer source and rate. Pre-plant urea should be avoided in

favor of controlled-release products or sources that delay nitrification on coarse-textured soils but may be acceptable on fine-textured sources.

1.2. INTRODUCTION

Minnesota is the fourth largest corn grain producing state in the United States with over 36 million Mg produced in 2015 (USDA NASS, 2016). Nitrogen is frequently limiting for corn production (Mamo et al., 2003) and is often supplied through inorganic fertilizers that represent a large cost to growers (Raun and Johnson, 1999). It can also degrade air and water quality as nitrous oxide or methane emissions (Venterea et al., 2011) or nitrate-N leaching to ground and surface waters (Randall and Vetsch, 2005; Rubin et al., 2016). Under ongoing climate change, it is predicted that the Midwest will experience warmer winter and night-time temperatures (Seeley, 2015) and more intense precipitation events during the early spring months followed by dry summer months (USEPA, 2013). Changes in temperature will likely affect corn growth and development (Muchow et al., 1990) and N cycling processes (Leirós et al., 1999; Rawluk et al., 2001; Morris et al., 2018). Large rainfall events and warmer temperatures in the early spring can be especially important in enhancing N loss potential, while reduced soil moisture during dry summers may reduce N availability to the crop. Modification of grower management practices of fertilizer rate, source, time, or placement may be required to minimize potential for N losses and optimize yield.

Application of the right rate of N has long been recognized as one of the most effective management strategies to produce corn and improve N use efficiency (Roberts, 2007; Kaiser et al., 2011; Burzaco et al., 2013). With variable yearly and seasonal weather conditions, determining the right rate for a given field each year is a significant challenge (Johnson and Raun, 2003; Mamo et al., 2003). Some farmers apply excess N as "insurance" to avoid unrealized yield potential, but this practice can incur significant N loss when rates exceed crop needs (Fernández et al., 2016) reducing NUE (Baker and Johnson, 1981; Francis et al., 1993; Van Groenigen et al., 2010; Wortman et al., 2011; Burzaco et al., 2013). Minnesota has developed N best management practices regions for corn production based on soil and climatic conditions (Lamb et al., 2008). Nitrogen rate guidelines cannot be viewed as static values because they are influenced by many evolving variables such as climate and agronomic practices. The University of Minnesota increased its N rate guidelines for corn on irrigated sands (Lamb et al., 2015) raising concerns of increased potential for nitrate-N leaching. Struffert et al. (2016) found no difference between nitrate-N leaching losses for corn receiving N at the economic optimal N rate (EONR) and reduced N rates.

Nitrogen source can have a significant impact on NUE and corn production. In the Upper Midwest, the preferred N source has changed from anhydrous ammonia to urea (Bierman et al., 2012). Use of enhanced efficiency products including slow- and controlled-release fertilizers and nitrification and urease inhibitors are becoming increasingly common (Trenkel, 2010; Halvorson and Bartolo, 2014). Enhanced efficiency fertilizers may improve NUE by delaying the rate of N release at times when the potential for N loss is high, extending the period of N availability by inhibiting microbial and enzymatic activity, or by improving the synchrony of fertilizer availability and corn N uptake (Motavalli et al., 2008; Sistani et al., 2014). Enhanced efficiency fertilizers are likely to be of greatest efficacy when potential for N loss is high such as on coarse-textured soils or poorly-drained fine-textured soils (Nelson et al., 2008). Enhanced efficiency fertilizers need further exploration because growing season conditions and soil characteristics can affect their usefulness (Motavalli et al., 2008).

Nitrogen research often focuses on the effect of a given treatment on end of season metrics, such as grain yield. Relatively less attention has been devoted to the impact of N management on N availability throughout the growing season. Many midwestern U.S. soils are high in organic matter mineralizing 80 to 240 kg N ha-1 each growing season (Cassman et al., 2002). However, soil supplying capacity is variable depending on weather, soil properties, landscape aspect, and cropping history (Cassman et al., 2002; Dyson and Conyers, 2013; Morris et al., 2018). Corn producing 10 Mg grain ha-1 requires approximately 190 kg N ha-1 with a median value of 130 kg N ha-1 coming from the soil (Cassman et al., 2002). Soil testing can provide valuable information on N availability at the time of sampling and estimates of future soil supply (Dyson and Conyers, 2013). The pre-plant soil nitrate test is recommended as a tool to credit residual soil nitrate from the previous growing season on semi-humid regions on medium and fine-textured soils (Kaiser et al., 2011). This test has limited or unreliable application for coarse-textured soils or soils that have received above normal precipitation (Bundy et al., 1999).

In more humid regions of the US Midwest and Northeast, the pre-sidedress soil nitrate test is often used during the V4 to V6 corn development stage (Abendroth et al., 2011). This test provides an estimate of the amount of N that could be available to the crop throughout the growing season from organic matter, manure, and crop residues

(Magdoff, 1991b). When pre-sidedress soil nitrate test soil test values (STV) are above the critical STV (CSTV) of 20-25 mg kg-1, it is likely that the crop will not respond to N fertilizer (Fox et al., 1989; Bundy et al., 1999). Soil test values less than the CSTV are not well correlated to yield, relegating its usefulness only as a predictive tool to identify crop responsivity to fertilizer N needs (Fox et al., 1989). Research has provided calibrated or suggested calculations for fertilizer recommendations when STVs are below the CSTV (Blackmer et al., 1997; Laboski and Peters, 2012; Ferrer et al., 2003). Research in Minnesota has not found the pre-sidedress nitrate test to be effective (Lamb et al., 2014; Yost et al., 2014; Walker 2018). The pre-sidedress soil nitrate test may not perform well following greater than normal precipitation on permeable soils or if soil conditions were cold and wet resulting in poor N mineralization rates (Magdoff, 1991a; Andraski and Bundy, 2002). Additional research is needed to determine the value of in-season soil testing as a tool to determine sufficiency levels and predict in-season N rate application to optimize yield and improve NUE.

The objectives of this study were to determine the effect of N rate and source on soil N availability throughout the growing season and its impact on corn grain yield and NUE, and to determine the potential of in-season soil N testing as a tool to predict optimum corn grain yield and N rate needed to achieve that optimum.

1.3. MATERIALS AND METHODS

1.3.1. Study Sites

Field trials were conducted in 2014 and 2015 on 12 field site-years that represent major soils and agricultural regions across the upper Midwest. Field sites were located at the University of Minnesota Sand Plain Research Farm in Becker, MN, at the University of Minnesota Research and Outreach Centers at Lamberton and Waseca, MN, and on farmers' fields near Theilman and Clara City, MN (Table 1.1). All site-years were corn following corn except for Waseca14a that was corn following soybean [Glycine max (L.) Merr.]. All site-years were dryland, except for those at Becker that were irrigated. Air temperature and precipitation data were obtained from the National Weather Service weather stations in closest proximity to each site (MNDNR, 2016).

1.3.2. Soil Sampling

Before site-year establishment, a 10-core (1.8-cm diameter) composite soil sample was collected from the 0- to 15-cm layer from each replicate and analyzed for texture by the hydrometer method (Gee and Bauder, 1986), pH (1:1 soil:water) (Peters et al., 2012), cation exchange capacity and ammonium-acetate exchangeable K, Ca, and Mg (Warncke and Brown, 2012), organic matter by loss on ignition (Combs and Nathan, 2012), and Bray-P1 for all site-years except Clara City (pH > 7.2), which was analyzed by Olson-P (Frank et al., 2012) (Table 1.2). Bulk density was measured at the center of 0- to 30- and 30- to 60-cm increments (Table 1.2) by collecting two 5 cm deep samples per replication using the intact core technique (Blake and Hartge, 1986). An additional 10-core (1.8-cm diameter) composite soil sample was collected from the 0- to 30- and 30- to 60-cm layer from each replicate, dried at 35°C in a forced-air oven until constant mass, ground to pass through a 2 mm sieve, and analyzed for nitrate-N (Gelderman and Beegle, 2012) and ammonium-N (Bremner and Mulvaney, 1982). Additional soil samples were collected for nitrate-N and ammonium-N analysis from each treatment plot at 0- to 30- and 30- to 60-cm increments concurrent with plant sampling (V4, V8, V12, R1) as four-core (1.8-cm diameter) composite soil samples using a hand probe and at post-harvest as a two-core (5-cm diameter) composite soil sample using a hydraulic probe.

1.3.3. Experimental Design

Treatments were arranged in a randomized complete block design with four replications. Treatments consisted of pre-plant urea (46-0-0, N-P-K) at each site-year at 45 kg N ha-1 rate increments from 0 to 270 kg N ha-1 except at Theilman14 and Waseca14a, where the N rates were reduced by 25% and at the Becker site-years that received an additional rate of 315 kg N ha-1. Additional pre-plant treatments consisted of 135 kg N ha-1 (102 kg N ha-1 at Theilman14 and Waseca14a) as polymer-coated urea, (PCU) (44-0-0) (ESN® Smart Nitrogen, Agrium Advanced Technologies, Loveland, CO) that releases urea in response to temperature and moisture conditions; PCU-urea (U) blends of 45/90 (PCU-U 1:2) and 90/45 (PCU-U 2:1) kg N ha-1; and anhydrous ammonia (AA) (82-0-0), applied with (AAI) and without (AA) a nitrification inhibitor [2-chloro-6-(trichloromethyl) pyridine (N-Serve®, Dow Agrosciences LLC, Indianapolis, IN)]. Urea and PCU fertilizer treatments were incorporated into the soil by shallow (5-cm) tillage or 6 mm of irrigation within two days of broadcast application. Corn was planted in rows spaced 76 cm apart at all site-years except in Clara City (56 cm). Plots were 21.3 meters long by 3.0 meters wide in Becker, Lamberton, and Theilman, 12.2 meters long by 3.4 meters wide in Clara City, and 15.2 meters long by 4.6 meters wide in Waseca. Becker15a, Waseca15a, and Clara City15 were placed on the same treatment-plots as the 2014 site-years of Becker14, Waseca14b, and Clara City14 because the 2015 pre-plant soil samples indicated that no residual N treatment effects existed from the previous year (TIN in all treatments was similar to the unfertilized check plot).

After full width tillage, site-years were planted at 84,000 to 89,000 seeds ha-1 with PIONEER P9917AMX at Theilman14, Clara City15, and all Becker and Lamberton site-years; DKC44-13 RIB AR at Clara City14; and DKC53-56 RIB at all Waseca site-years (Table 1.3). Following university guidelines (Lamb et al., 2015), the N rates were not adjusted for nitrate-N contributions from the irrigation water for the Becker site-years because concentrations were <10 mg L-1 supplying a total of 20-27 kg N ha-1. Irrigation was applied 17 times in 2014 (266 mm) and 12 times in 2015 (188 mm) based on the water-balance approach (Steele et al., 2010). Other than N treatments, experimental areas were fertilized and limed to maximize corn yield.

1.3.4. Corn Sampling

Stand counts were taken at V4 from 6.1 m of the two center rows of each plot. Nitrogen uptake was measured by collecting six representative whole plant samples cut at the soil surface at V4, V8, V12, and R1. Plant samples were chipped, dried at 60 °C in a forced-air oven until constant mass, and weighed. Dried samples were then mixed and ground to pass through a 2-mm screen. Cobs, grain, and vegetative tissues were partitioned at the R6 stage and processed similar to earlier samplings. Total N of the ground plant samples was determined by combustion analysis using a Carlo Erba 1500 elemental analyzer (Carlo Erba, La Metairie, France) (Horneck and Miller, 1998). Grain yield was measured by harvesting the center two rows by hand or using a research grade plot combine. A representative grain subsample was saved to determine grain moisture content and analyzed for total N content by combustion analysis using an Elementar Analyzer (Langenselbold, Hesse, Germany). Grain yield was adjusted to 155 g kg-1 moisture. Nitrogen uptake was calculated as the product of dry matter for the grain, cob, and stover and their respective N concentrations.

1.3.5. Nitrogen Use Efficiency Calculations

In units of kg kg-1, agronomic efficiency [(AE= YldN - Yld0)/N rateN], partial factor productivity (PFP=YldN/N rateN), grain N harvest index (GNHI=GN/TN), fertilizer recovery efficiency [FRE= (TN - T0)/N rateN * 100%], and grain N recovery efficiency [GNRE= (G N - G0)/N rateN * 100%] were calculated to describe crop-N utilization (Sawyer et al., 2017). In these equations, T, G, and Yld represent total aboveground N uptake, grain N uptake, and grain yield, respectively, and the subscript “N” represents the fertilizer N treatment of interest, while subscript “0” represents the nonfertilized control treatment. Gross revenue differences between PCU and urea were calculated as: Gross revenue={[Yld(PCU or PCU blend) – YldUrea] * corn price} – {[fertilizer cost(PCU or PCU blend) – fertilizer cost(Urea)] x fertilizer application rate} at a corn price of $198.41 Mg-1, urea fertilizer-N cost of $1.10 kg-1, and a PCU fertilizer-N cost of $2.15 kg-1 (ESN-ROI, 2018).

1.3.6. Data Analysis

Site-years were initially separated by soil texture where site-years with coarse-textured soils (loamy sands) were separated from site-years with fine-textured soils (loam or finer). Within those groups, site-years were separated into subgroups based on the response of grain yield to N rate using the two-tailed log likelihood test at $P > 0.15$. Group 1 (Becker14, Becker15a, Becker15b) had a linear response and were loamy sands, Group 2 (Clara City14, Waseca14a, Waseca14b, Waseca15a, Waseca15b) had a linear response and were silty-clay loam or finer soils, Group 3 (Clara City15, Lamberton14, Theilman14) had a quadratic-plateau response and were loam or finer soils, and Group 4 (Lamberton15) was non-responsive and was a loam soil (Table 1.4). The same groupings were maintained for analysis of other dependent variables.

Data were analyzed using the MIXED procedure of SAS (SAS Institute, 2012). Nitrogen treatments associated with N rate were analyzed separately from N treatments comparing N sources. In both analyses, N treatment was considered a fixed effect, while site-year, block (nested within site-year) and interactions of fixed effects with site-year and block were considered random effects. Model assumptions of normally distributed residuals and homogeneity of variance of treatment means were verified using the UNIVARIATE procedure of SAS (Kutner et al., 2004). When appropriate, pairwise mean comparisons were made with t-tests at $P \leq 0.05$ using the PDIFF option in the MIXED procedure of SAS (SAS Institute, 2012).

For the N rate analysis, the REG or NLIN procedures were used to relate the response variables (i.e., grain yield, corn N uptake, NUE variables, etc.) with N rate when the main effect of fertilizer N rate was significant (SAS Institute 2012). When regression models were not significant, results were averaged across N rates and reported. The agronomic optimal N rate (AONR) was the point at which the model plateaued for quadratic-plateau regressions or the highest applied N rate for linear or quadratic regression models. The EONR was determined by setting the first derivative of the regression model to the urea fertilizer cost/corn price ratio of 0.0056 (i.e., \$1.10 kg-1 N, \$198.41 Mg-1 corn grain) based on the regional N rate guideline method by Sawyer et al. (2006).

Repeated measures analysis was performed for in-season soil and plant samplings using the MIXED procedure of SAS and autoregressive covariance structure, where N treatment, time, and depth and their interactions were considered fixed effects while site-year, block (nested within site-year) and interactions of fixed effects with site-year and block were considered random effects. Significant fixed effects or interactions of fixed effects were compared using means separation at $P \leq 0.05$ with the PDIFF option of the MIXED procedure of SAS (SAS Institute, 2012).

Soil-test value and yield calibration curves were performed using the modified arcsine-log calibration curve (MALCC) to determine the confidence interval of STVs required to produce near-optimal yield (Dyson and Conyers, 2013; Correndo et al., 2017). Following Correndo et al. (2017), STVs from the various site-year groupings, and an additional grouping consisting of all fine-textured site-years (Group Fine) were natural log transformed (Y) while relative yield was transformed by taking the arcsine of the square root of relative yield (X). The transformed relative yield was then centered with respect to a given yield goal (i.e., 90%) and fitted with an ordinary least squares regression line. To estimate the bivariate equation between X and Y, the fitted least squares regression line was adjusted to a standardized major axis line by dividing the least squares regression line slope coefficient by the Pearson correlation coefficient. The estimated CSTV (y-intercept of the standardized major axis line), its associated confidence limits, and the standardized major axis line were back transformed to the original units. The MALCC was used to examine soil nitrate-N, ammonium-N, and TIN for pre-plant STVs plus the applied N rate, and the V4 and V8 STVs at the 0-30 and 0-60 cm sampling increments. Each model was visually inspected for homogeneity of variance using scatterplots of the residuals vs. predicted values, and best-fit models were selected based on greater squared Pearson correlation coefficients.

While determining yield level with a CSTV can be valuable, from an N management perspective it is more important to predict how much additional N fertilizer may be needed when STV are less than the CSTV. Others have reported no yield differences between a single and split fertilizer applications on fine-textured soils (Jokela and Randall, 1989; Jokela and Randall, 1997; Scharf et al., 2002; Venterea and Coulter, 2015; Mueller et al., 2017). Therefore, it may be realistic to use in-season STV from pre-plant fertilizer applications to determine the amount of N fertilizer needed at sidedress when split applications are used. To examine this hypothesis, STV from selected MALCC's were regressed against applied N fertilizer rates using the REG procedure of

SAS (SAS Institute, 2012). Because STV variability increased with increasing N rate, STVs were natural log transformed prior to analysis. Model assumptions of normally distributed residuals and homogeneity of variance of treatment means were verified using the UNIVARIATE procedure of SAS (Kutner et al., 2004). Seventy-percent confidence limits were calculated (approximately one standard deviation) for the regression lines to account for STV variability and the regression line and confidence intervals were back-transformed to the original units.

1.4. RESULTS AND DISCUSSION

1.4.1. Weather

Monthly precipitation was arbitrarily considered below average when it was at least 25-mm less than the 30-yr normal and considered above average when it was at least 25-mm greater than the 30-yr normal. Likewise, monthly mean air temperature was considered below average when they were at least 0.55 ˚C less than 30-yr normal and considered above average when they were at least 0.55 ˚C greater than the 30-yr normal.

In 2014, the period from April to June was wetter than normal for all site-years, with 46-60% of the total annual precipitation compared to 33-37% for the 30-yr normal (Table 1.5). July through October was normal or drier than normal at all site-years except Clara City and Theilman in August and Lamberton in September that were wetter than normal (Table 1.5). The air temperature was generally cooler than normal at all site-years in 2014 in April, May and July while June and August through October were generally near the 30-yr normal. Wetter and cooler than normal conditions in April and May delayed planting until mid- to late-May at all site-years (Table 1.3, 1.5). These conditions, especially in Becker and Waseca, may have negatively impacted seedling growth by slowing germination and nutrient uptake (Abendroth et. al, 2011). Excessive precipitation in June set many new records across Minnesota and likely reduced N availability through leaching at Becker and denitrification at Waseca and Clara City where soils were saturated for several days following four 50-mm rain events. Drier than normal conditions at all site-years in July corresponded to V8 to VT development stages that is typically a time of rapid plant growth and N uptake (Bender et al., 2013). Water stress, especially two weeks before and after silking, can negatively impact N uptake and yield (Abendroth et. al, 2011). Additionally, in Waseca, there was an early frost on 13 Sept. and the Waseca14a site-year was damaged by hail on 20 Sept. when the crop was at R5. Excessively wet soil conditions followed by freezing prevented post-harvest soil sampling at Waseca14a.

Overall, the 2014 growing season was less favorable for corn production due to excessive precipitation in the early spring months followed by dry conditions starting in July, while the 2015 growing season was overall more favorable due to evenly distributed precipitation events and a longer growing season. In 2015, May through August precipitation was normal or above normal for all site-years, except Becker and Clara City in June that were below the 30-yr normal. April, September, and October temperatures were warmer than normal that enabled planting in late April to early May (except Lamberton15 that was not planted until 21 May) and a longer growing season than normal (Table 1.3, 1.5). May through August temperatures were normal or slightly cooler than normal at all site-years.

1.4.2. End of Season Yield Metrics – Nitrogen Rate

Groups 1 (loamy sands) and 2 (silty clay loam or finer) had positive linear grain yield responses to N yielding 8.0 Mg ha-1 in Group 1 and 11.3 Mg ha-1 in Group 2 at the highest applied N rate (Table 1.4). Group 3 (loam or finer) had a quadratic-plateau response with an EONR and AONR of 163 and 182 kg N ha-1, respectively but similar yield of 11.1 Mg ha-1. Group 4 (loam) was not responsive to N with a mean yield of 12.6 Mg ha-1. These results illustrate that site-specific differences can result in variable yield responses to pre-plant urea and represents commonly observed N responses contained within the EONR database used to generate N rate guidelines. In the upper Midwest, the EONR (ratio=0.0056) for corn following corn is 215 to 252 kg N ha-1 on irrigated coarse-textured soils (Lamb et al., 2015) and 165 to 189 kg N ha-1 for fine-textured soils (CNRC, 2017).

The linear responses of grain yield for Groups 1 and 2 are indicative of substantial N fertilizer loss (Table 1.4). Pre-plant N applications are highly susceptible to leaching losses on irrigated coarse-textured soils (Group 1). Applying the full N rate at pre-plant contrasts best management practices for irrigated sands (Lamb et al., 2015), but urea was applied at pre-plant to maintain experiment uniformity across all site-years in this study. Because Group 1 precipitation was at or above normal in April and May (Table 1.5) and crop N uptake and water use were low, leaching potential of pre-plant N was likely high. Although potential for N loss on fine-textured soils is generally lower than on sands, Group 2 also had linear yield response to N likely as result of several large rain events in

June 2014 and 2015 that produced waterlogged conditions and increased potential for N losses.

Corn N uptake at the end of the growing season (R6) and grain N removal had positive linear responses to N rate for all groups except Group 3 where grain N removal showed a quadratic response (Table 1.4). Others have observed similar values and responses for N uptake and removal (Halvorson et al., 2006; Van Groenigen et al., 2010; Holou et al., 2011; Sindelar et al., 2015). Similar to grain yield response to N, corn N uptake and grain N removal at the 0 N rate increased sequentially from Group 1 to Group 4. Also, the slopes of the regression models increased from Groups 1 to 3 indicating that for the years of the study, these soils had different yield potentials (Table 1.4). Group 4 had the smallest slope but largest intercepts for N uptake (204 kg N ha-1) and grain N (139 kg N ha-1) indicating that indigenous soil N supply was adequate for the crop (Table 1.4).

There was generally no response of NUE indices to increasing N rate for all groups (Table 1.6) except for PFP (Table 1.4). There was a quadratic decrease with increasing N rate for PFP, which was minimized at 23, 38, 42, and 45 kg kg-1 for Groups 1, 2, 3, and 4, respectively when the N fertilizer rate was 224 to 238 kg N ha-1. Partial factor productivity values declined most rapidly in groups with high soil N availability (i.e., Group 4) whereas in Group 1, where N was limiting, the decline was more gradual (Table 1.4). Averaged across N rates, AE and GNRE increased from Group 4 < Group 1 < Group 2 <Group 3 (Table 1.7). The low NUE’s in Groups 1 and 2 are likely due to N losses (Cassman et al., 2002). Low NUE at rates greater than the AONR in Groups 3 and 4 are due to N supplied in excess of crop needs (Baker and Johnson, 1981; Francis et al.,

1993; Van Groenigen et al., 2010; Burzaco et al., 2013). Even at the AONR in Group 3, FRE was only 48% indicating that the right N rate alone might not be sufficient to substantially increase NUE. Simultaneous manipulation of N fertilizer rate, source, application timing, and placement may be needed to significantly improve NUE. Using three of the four management strategies, Venterea et al. (2016) reduced the N rate by 15% and increase FRE by 16% using a split application of urea with urease and nitrification inhibitors relative to pre-plant urea. An additional potential challenge with improving NUE was demonstrated by Francis et al. (1993) who reported that approximately 15-20% of 15N fertilizer incorporated into aboveground biomass was lost between R2 and R6, potentially as ammonia volatilization from the leaves. Improving NUE may require further adaptation of crop genetics in addition to reducing N loss from the soil or improving N uptake.

1.4.3. In-Season Corn Nitrogen Uptake - Nitrogen Rate

In-season corn N uptake had a significant N rate by time interaction for all groups (Table 1.7). Corn N uptake increased over time, but the increase was most pronounced with greater N fertilizer rates (Table 1.7). Differences in N uptake due to N rate within groups were not statistically evident until V8. In a related study, Paiao (2017) also observed that different canopy sensors at V4 were unable to detect crop differences due to N rate. These findings indicate that little, if any, N needs to be applied before V4 because crops have limited N requirements and the native soil supply is sufficient to satisfy the crop demand. Irrigated, coarse-textured soils or cold, fine-textured soils may still require a small (< 45 kg N ha-1) starter fertilizer N application if the soil N supply is low. This finding supports guidelines for sandy soils, where pre-plant N applications are not recommended because the potential for N loss is too great and N application is not warranted by crop demands (Laboski and Peters, 2012; Lamb et al., 2015).

Starting at V8 and persisting throughout the growing season, corn N uptake was greater with increasing N rate in all groups but the magnitude of uptake at equivalent N rates followed the order Group 1 < Group 2 < Group 3 < Group 4 (Table 1.7). In Illinois under optimal growing conditions, Bender et al. (2013) reported maximal corn N uptake rates from V10 to V14. Nitrogen uptake was most rapid between V8 and V12 for all N rate treatments (Table 1.7). At the highest applied N rate, plant uptake rates were generally smaller (0.30, 0.39, 0.39, and 0.72 kg N ha-1 GDDC-1 for Groups 1 through 4, respectively) than 0.66 kg N ha-1 reported by Bender et al. (2013) (Table 1.7). Rates of N uptake declined in all groups from V12 to R1 relative to the V8 to V12 period (Table 1.7) and by R1 Group 1, 2, and 3 accumulated 60, 67, and 70%, respectively of the total R6 N uptake, similar to 66% reported by Bender et al. (2013) but Group 4 was greater at 83%. This illustrates the importance of supplying adequate soil N during the vegetative and reproductive stages to maximize yield potential.

1.4.4. In-Season Soil Nitrogen - Nitrogen Rate

In-season soil TIN values may help explain yield and corn N uptake differences due to N rate. There was a significant N rate by soil depth by sampling time interaction for TIN in Group 1 (Table 1.8). Soil TIN increased with increasing N rate for both surface (0- to 30-cm) and subsurface (30- to 60-cm) layers, with increasingly greater N in the top layer than the subsurface with application > 90 kg N ha-1 at V4, but after V4 differences in TIN due to soil layer became negligible (Table 1.7). Differences due to N rate persisted only through V8 for rates ≥135 kg N ha-1 (lower rates being similar to the check) where increasing N rates increased TIN, though 0- to 60-cm layer TIN values for those N rates were reduced by an average of 45% relative to the V4 sampling time (Table 1.7). After V8, no differences in TIN were observed due to soil depth or N rate. The large decline in TIN (59 kg N ha-1 on average) from V4 to V8 for rates ≥135 kg N ha-1 (Table 1.8) was substantially greater than what can be attributed to corn N uptake (21 kg N ha-1 on average) during this period (Table 1.7), and reflects N loss by leaching or denitrification. Across rates the ratio of TIN for the surface vs. subsurface was 1.7 at V4 and 0.9 at V8, illustrating downward movement of N. Because TIN at V8 was similar to the unfertilized check for rates ≤135 kg N ha-1 and for all rates at V12 or later help explain the low grain yield and linear response to N observed (Table 1.4).

Similar to Group 1, Group 2 had a significant N rate by soil depth by sampling time interaction for TIN (Table 1.9). Soil TIN increased with increasing N rate at both increments at V4 and V8; at V12 and R1 the effect of N rate was only detected at the highest N rate. Greater TIN in the surface than the subsurface due to N fertilizer was consistently observed only at V4 and the difference between increments increased with increasing rate (4 to 17 mg kg-1 for the 45 to 270 kg N ha-1, respectively) (Table 1.9). Accounting for corn N uptake (Table 1.7) and the change in soil TIN in the top 60 cm (Table 1.9) from V4 to V8, it was clear that as N rate increased the amount of unaccounted N also increased. This disparity may be indicative of greater N loss potential with greater fertilizer rates under waterlogged conditions following several large rain events. Although Groups 1 and 2 had similar responses of yield and corn N uptake to fertilizer rate (Table 1.4, 1.6), Group 2 had 0.9 to 4.2 times greater TIN concentration in the top 60 cm of soil than Group 1 across timings at equivalent N rates (Table 1.9), likely resulting from greater mineralization of organic N and improved corn grain yield in Group 2.

The N rate by depth interaction for Group 3 and Group 4 was explained by no TIN differences between soil layers for rates <180 kg N ha-1 and topsoil TIN being greater than the subsoil when rates were ≥180 kg N ha-1 with the difference becoming larger as N rates increased ($P = 0.1$ and 0.05 for Group 3 and 4, respectively) (Table 1.10, 11). Greater N in the surface than the subsurface is a result of N being applied directly on the surface layer. For the highest N rate, relative to the subsoil, the topsoil was 1.6 times greater for Group 3 and 1.9 times greater for Group 4. The N rate by time interaction for Group 3 and Group 4 can be explained by a decline in TIN as the season progressed regardless of N rate, though the decline was greater with increasing N rates that had greater starting TIN concentrations. Averaged across all N rates, from V4 to V8, V8 to V12, V12 to R1, and R1 to post-harvest TIN declined by 33, 23, 36, and 4%, respectively in Group 3 and by 15, 34, 14, and 44%, respectively in Group 4. Additionally, TIN for N rates ≥135 and <270 kg N ha-1 were greater than the check until V12 or later in Group 3, while rates ≥180 kg N ha-1 were greater than the check until post-harvest in Group 4. Slightly greater concentrations of TIN from V4 to V8 may have improved N uptake in Group 4 (63-95 kg N ha-1 across all N rates) relative to Group 3 (30 to 60 kg N ha-1 across N rates) and improved yield, but it is uncertain why Group 4 was non-responsive to N at all rates when both groups had similar soil types, cropping history, agronomic practices, hybrids, weather, and soil fertility levels (N,P,K, pH) (Table 1.4, 1.7, 1.8) and indicates that there were other, unaccounted factors that likely influenced yield. The depth by time interaction for both Group 3 and Group 4 was explained by a decline in TIN over time for both topsoil and subsoil where topsoil was greater than subsoil TIN until V12 when differences between layers disappeared (P = 0.1 and 0.05 for Group 3 and 4, respectively) (Table 1.10, 1.11). The largest difference between soil layers was at V4 with 1.6 times and 2.0 times greater TIN in the topsoil than the subsoil for Group 3 and Group 4, respectively and reflects the influence of fertilizer applied on the soil surface.

1.4.5. Nitrogen Source

Because of its growing use in the Midwest, urea was the standard by which to compare all other N sources. In Group 1, 135 kg N ha-1 as PCU, AA, and AAI produced an average grain yield that was 1.6-fold greater than urea (Table 1.12). Based on the grain yield response to urea N rate (Table 1.4), this average yield increase would correspond to a urea fertilizer rate of 216 kg N ha-1. Similarly, AE was 1.2-fold greater than urea averaged across PCU, AA, and AAI (Table 1.12). The N source by time interaction for corn N uptake was explained by uptake increasing over time with generally no differences between N sources at V4 and V8 but from V12 through R6 PCU, AA, and AAI were 1.6, 1.9, 1.3 times greater than urea at each timing (Table 1.13). This indicates that N loss potential was greater for urea with less N available to the crop later in the season. Relative to urea, AAI increased grain N removal by 21.9 kg ha-1 and FRE by

22% (Table 1.12). At V4 and V8, 58 and 63% of soil TIN was ammonium-N averaged across AA and AAI while it was only 28 and 44% at each timing for urea. Delayed nitrification of ammonium-N for the AA products may have improved soil N availability and uptake for the greater yield and efficiencies. Grain yield, grain N removal, AE, and GNHI was greater with increasing concentrations of PCU with urea < PCU-U 1:2 < PCU-U 2:1 < PCU (Table 1.12). This indicates that PCU improved N availability compared to urea especially after V12 (Table 1.13). While the soil data did not show improved retention of TIN with PCU (only the depth by time interaction for soil TIN was significant indicating no differences between layers except at V4 when topsoil was greater than the subsoil by 4.6 mg kg-1), it is possible that PCU retained N in urea form until the crop was quickly utilizing N. On average TIN values in the 0- to 60-cm increment declined to 2.6 mg kg-1 by V12 with no differences at later timings (Table 1.14). The data illustrate that urea is a poor choice for pre-plant applications on irrigated corn in sandy soils and agrees with current guidelines for these soils (Laboski and Peters, 2012; Lamb et al., 2015). These results indicate that on coarse-textured soils, pre-plant urea should be avoided in favor of other N sources that will not readily nitrify, providing increased soil time presence. Applying N only at pre-plant regardless of the source can be problematic for these soils. This was pointed out by another Minnesota study in irrigated corn in sandy soils where a split urea application (half of the N applied pre-plant and half at V4) was superior to a single pre-plant PCU application (Rubin et al., 2016).

Treatment differences were less pronounced for the fine-textured groups relative to Group 1, although the magnitude of yield, and plant and grain N uptake increased from Group 2 < Group 3 < Group 4 (Table 1.12). In Group 2, PCU, PCU-U 2:1, and PCU-U

1:2 performed similarly, with no differences for grain yield, grain N removal, and AE. Relative to urea, AA, and AAI on average: PCU-U 2:1 and PCU-U 1:2 improved grain yield by 1.3 Mg ha-1; PCU and PCU-U 2:1 improved grain N removal by 23 kg N ha-1; and PCU-U 2:1 improved AE by 1.8-fold but there were no differences for GNHI or FRE. Yield and NUE differences were supported by corn N uptake that had a significant source by time interaction. Plant uptake increased over time with no differences between treatments from planting through V8, but from V12 through R1 PCU, PCU-U 2:1, and PCU-U 1:2 improved uptake 1.2- to 1.4-fold on average relative to urea, AA, and AAI (Table 1.13). The soil TIN source by time interaction also validated these results as at each sampling time, soil TIN was lowest for AA and AAI, similar to urea, while soil TIN concentration increased with increasing amounts of PCU, although it was only at trend starting at V12. Further, soil TIN concentrations were greatest at V4 and declined over time for all treatments until V12 when differences between sampling times disappeared (Table 1.14). Downward movement of soil TIN may be indicated in the depth by time interaction as there was a 56% decline of topsoil TIN from V4 to V12 while subsoil TIN was constant from V4 to V8 and declined thereafter (Table 1.14) that corresponded to several large (28- to 53-mm) rain events. These results indicate that PCU products may increase soil TIN, yield, and NUE on fine-textured, poorly-drained soils in wet years. Similar results were reported by Noellsch et al. (2009), who found PCU improved yield 1.2-fold over urea in two growing seasons but yield for PCU-U at a 50/50% blend improved only in one year. In other studies, PCU reduced the amount of nitrate-N early in the season relative to urea, which may have reduced nitrate leaching and improved plant N availability (Motavalli et al., 2005; Nelson et al., 2009; Venterea et al., 2011).

Across all N sources in Group 2, nitrate-N was 63-73% and 52-59% of TIN at V4 and V8 respectively (P = 0.0004) indicating rapid nitrification and potential for leaching or denitrification processes given observed wet conditions. The required yield increase needed to break-even for PCU, PCU-U 2:1 and PCU-U 1:2 was 1.2, 0.8, and 0.4 Mg grain ha-1, respectively at the 135 kg N ha-1 rate. Although yield was similar for all PCU treatments, PCU-U 1:2 or PCU-U 2:1 provided the greatest revenue over urea at $246.44 ha-1 on average while PCU was only $115.89 ha-1. Likewise, Halvorson and Bartolo (2014) reported a yield increase with PCU in two of three years with 4 to 14% profit over urea. These results indicate that on wet, poorly-drained fine-textured soils, PCU-U blends may provide both economic and environmental advantages over other N sources.

In Group 3 and 4 there were no differences in grain yield or grain N content due to N source (Table 1.12). This was also reflected in efficiency measurements where there were no differences or inconsistent differences due to N source except for FRE in Group 3 where the AA, AAI and PCU-U blends increased efficiency relative to urea, and for AE in Group 4 where AA and AAI increased efficiency relative to urea. Others have observed that AA is generally superior to urea but using an inhibitor is not as important for application in spring relative to fall (Randall et al., 2003; Vetsch and Randall, 2004; Randall and Vetsch, 2005). Polymer coated urea-urea blends likely synchronized N supply with crop demand and reduced potential for N loss for improved FRE over PCU or PPU. There was an economic advantage for PCU-U blends in Group 3 with a 7-11% increase in gross profit over urea, but only a 1-2% increase in gross profits for Group 4, while PCU resulted in a 2% gross loss for both groups. The significant N source by time interaction for plant N in Group 3 and 4 was explained by N uptake increasing over time with no differences due to N source until V12 (Table 1.13). In Group 3 AAI increased N uptake relative to urea starting at V12. Like FRE, N uptake at R6 was improved by PCU-U blends relative to PCU or urea alone. In Group 4, AAI increased N uptake relative to AA and PCU starting at V12, but differences between other N sources were inconsistent and reflect that corn was not responsive to N rate (Table 1.4). There were no differences in TIN due to N source (Table 1.16, 1.17). Differences in TIN due to depth and time were similar to those explained earlier in Table 1.10 and 1.11. These results demonstrate that N source for spring applications are not as important when the potential for N loss is low, and contrasts the results for Group 1 and 2 where N loss potential was greater and N source was an important variable.

1.4.6. Modified Arcsine-Log Calibration Curve

Soil N may be useful for predicting yield response and supplemental N needed to achieve optimal yield. The MALCC produced significantly correlated models for relative yield and soil nitrate-N, ammonium-N, or TIN for the pre-plant STV+N rate, and V4 and V8 STV in the 0- to 30- and 0- to 60-cm increments for all groups, except Group 4 (Table 1.18). While nitrate-N, ammonium-N, and TIN produced significantly correlated models, I decided to focus only on nitrate-N and TIN as ammonium-N had smaller correlations (data not shown). Blackmer et al. (1989) and Binford et al. (1992) similarly found stronger relationships with soil nitrate-N and TIN than ammonium-N. Because Group 4 yield was non-responsive to N rate, relative yield was not significantly correlated to STV and was not used for this analysis except when combined with all fine-textured soils (all site-years in Groups 2 and 3) in the Group Fine analysis (Table 1.18). The MALCC method estimates a CSTV assuming relative yield is calculated from a non-deficient maximum yield (Correndo et al., 2017) which did not occur in Group 1, the MALCC method produced erroneously high CSTVs for all soil sampling times and layers. This indicates that the MALCC method may have limited utility for site-years with high potential for N loss (such as coarse-textured soils when all N is applied at pre-plant) and follows what others observed for predictive models on coarse-textured soils including the pre-plant soil nitrate test (Kaiser et al., 2011) and pre-sidedress soil nitrate test (Magdoff, 1991a; Laboski and Peters, 2012). Group 2, Group 3, and Group Fine had similar squared Pearson correlation coefficients within layer for nitrate-N and TIN. Across N species, deeper increments (0- to 60-cm) had slightly greater squared Pearson correlation coefficients at pre-plant and V8 (Table 1.18). The greater sampling depth (0- to 60-cm) more completely accounts for residual N at pre-plant and total N availability within the rooting zone at V8 than the 0- to 30-cm increment. This sampling strategy may be of greater importance in years following seasons with wet conditions where soil nitrate may leach below the topsoil but remain within the rooting zone. The improvement of the 0- to 60-cm increment relative to the 0- to 30-cm increment was small (< 0.1) and may not justify the additional sampling cost (Binford et al., 1992). In Groups 2 and Fine, the V4 timing provided better correlations than the pre-plant or V8 timings with no difference in correlation coefficients across N species and between layers (Table 1.18). These are positive outcomes because of cost and time savings associated with shallow sampling depth (0- to 30-cm) and analysis of only nitrate-N (instead of nitrate-N and ammonium-N). Logistically, compared to V8 the V4 sampling timing is advantageous as it provides greater time to apply N when the crop is small and does not require high-clearance equipment.

The pre-plant MALCC model accurately reflected individual group yield responses to N fertilizer by predicting a greater CSTV for Group 2 than Group 3 (Table 1.18). This reflects the greater N needs associated with Group 2 due to N loss from excessive spring rain and reduced grain yield, as previously mentioned. Group Fine's V4 nitrate-N 0- to 30-cm CSTV was 94 kg N ha^{-1} (25 mg kg^{-1}), similar to commonly reported pre-sidedress soil nitrate-N test critical values of 20-26 mg kg^{-1} (Blackmer et al., 1989; Fox et al., 1989; Binford et al., 1992; Bundy et al., 1999). The pre-sidedress soil nitrate test is recommended for site-years where little (starter) to no N has been applied before soil sample collection, following manure application the previous year, or when high carryover of residual N is expected (Magdoff, 1991b). Variability in STVs (and related CSTVs and 95% confidence limits) increased the closer the sampling time was to the time of fertilizer application and with increasing N rate (Table 1.18). This study found a similar critical concentration following fertilizer application as the pre-sidedress soil nitrate test that may indicate the MALCC model may help manage in-season N applications even in fields where N was previously applied.

While a CSTV provides a threshold at which to estimate a response of yield to N fertilizer additions, the value itself does not indicate how much additional N fertilizer is required should a STV be suboptimal. Ferrer et al. (2003) suggested for the pre-sidedress soil nitrate test that the difference between the CSTV and a sample STV could be used as a sidedress N fertilizer recommendation. This assumes that one unit of fertilizer N is equivalent to one unit of soil N and may underestimate the actual amount needed as fertilizer use efficiency is less than 100% (Motavalli et al., 2008; Engel et al., 2011). For the pre-plant soil nitrate test in Minnesota, the University fertilizer guideline is the difference between the maximum return to N (MRTN) (kg N ha^{-1}) and a soil credit calculated as 0.6 times the STV (kg N ha^{-1}) for the top 60 cm of soil (Kaiser et al., 2011), but there is not an equivalent calculation for in-season soil samples. In this study, natural log STVs were regressed against the pre-plant urea N rate to directly correlate one-unit increase of N fertilizer to one-unit increase of natural log STV (Table 1.19). This method directly accounted for plant available N from soil mineralization and fertilizer and allowed for prediction of the amount of additional N fertilizer needed to raise the STV to the CSTV. As an example, for the V4 nitrate-N 0- to 30-cm Group Fine model, the MALCC CSTV is 94 kg N ha^{-1} (25 mg kg^{-1}) and is equivalent to a N fertilizer rate of 234 (212-259) kg N ha^{-1} (Fig. 1.1, Table 1.19). A field sample with a STV of 40 kg N ha^{-1} (11 mg kg^{-1}) is equivalent to the N fertilizer rate of 104 (90-121) kg N ha^{-1}. The fertilizer N recommendation is calculated by difference and suggests applying 130 kg N ha^{-1} to raise the sample STV to the CSTV. Using the same example, but for Groups 2 and 3, the fertilizer recommendation would be 107 and 148 kg N ha^{-1}, respectively. The ability to relate STVs directly to fertilizer N rates may help improve N management. However, because STV variability increases with increasing N rate, the 70% confidence limits around the regression line increases with greater N rates. Inclusion of additional site-years may improve the accuracy and precision of these models. This study represents a small step in that direction.

1.5. CONCLUSIONS

Nitrogen rate and source can have a significant impact on in-season soil N measurements, corn grain yield, and NUE, especially when potential for N loss is high. Both coarse- and fine-textured soils can have high soil N losses following excessive precipitation. However, even when N loss potential was low, fine-textured soils either responded similar to University of Minnesota guidelines or were non-responsive to N fertilizer illustrating the difficulty of predicting the optimal N rate. Pre-plant urea is a poor fertilizer choice for coarse-textured soils and should be avoided in favor of other sources that delay nitrification such as AA, AAI, or PCU. PCU-U blends provide both immediate and delayed N availability to corn and are likely to improve grain yield, AE, and revenue on fine-textured soils with high potential for N loss. When potential for N loss is low, N source is not an important consideration. Since response to N source effectiveness is dependent on weather, these findings underscore the challenge of selecting the correct fertilizer N source. Producers should combine knowledge of their fields' characteristics with previous years' experience of weather patterns to determine which field areas may be prone to N loss and select an appropriate rate and source that matches their growing conditions. The MALCC models predict CSTV for V4 soil nitrate-N in the top 30 cm that were similar to estimates for the pre-sidedress soil nitrate test at 25 mg kg-1 in Group Fine illustrating that this CSTV may be appropriate, even when fertilizer had been applied earlier that season. These preliminary results show that this could be especially useful in wet springs when significant N loss occurred and it might be important to determine the need for additional fertilizer. Future studies should be designed to further evaluate this model.

Table 1.1 Site location and soil classification for 12 field sites for the 2014 and 2015 growing seasons in Minnesota. Sites were separated into groups based on soil texture and response of yield to N rate.

Site	Year	Coordinates	County	Soil Series Classification
Becker 14†	2014	45˚23’32"N, 93˚52’57"W	Sherburne	Hubbard loamy sand (Sandy, mixed, frigid Entic Hapludolls)
Becker15a†	2015	45˚23’32"N, 93˚52’57"W	Sherburne	Hubbard loamy sand (Sandy, mixed, frigid Entic Hapludolls)
Becker15b†	2015	45˚23’31"N, 93˚52’57"W	Sherburne	Hubbard loamy sand (Sandy, mixed, frigid Entic Hapludolls)
Clara City14‡	2014	44˚58’14"N, 95˚22’25"W	Chippewa	Bearden-Quam silty clay loam (Fine-silty, mixed, superactive, frigid Aeric Calciaquolls)
Waseca14a‡	2014	44˚03’40"N, 93˚31’26"W	Waseca	Predominantly Webster clay loam (Fine-loamy, mixed, superactive, mesic Typic Endoaquolls) with Canisteo silty clay loam (Fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls)
Waseca14b‡	2014	44˚04’15"N, 93˚31’16"W	Waseca	Nicollet clay loam (Fine-loamy, mixed, superactive, mesic Aquic Hapludolls)-Webster clay loam (Fine-loamy, mixed, superactive, mesic Typic Endoaquolls)
Waseca15a‡	2015	44˚04’15"N, 93˚31’16"W	Waseca	Nicollet clay loam (Fine-loamy, mixed, superactive, mesic Aquic Hapludolls)-Webster clay loam (Fine-loamy, mixed, superactive, mesic Typic Endoaquolls)
Waseca15b‡	2015	44˚03’35"N, 93˚31’20"W	Waseca	Nicollet clay loam (Fine-loamy, mixed, superactive, mesic Aquic Hapludolls)-Webster clay loam (Fine-loamy, mixed, superactive, mesic Typic Endoaquolls)
Lamberton14§	2014	44˚14’50"N, 95˚18’37"W	Redwood	Amiret loam (Fine-loamy, mixed, superactive, mesic Calcic Hapludolls)
Theilman14§	2014	44˚16’46"N, 92˚12’2"W	Wabasha	Fayette silt loam (Fine-silty, mixed, superactive, mesic Typic Hapludalfs)
Clara City15§	2015	44˚58’14"N, 95˚22’25"W	Chippewa	Bearden-Quam silty clay loam (Fine-silty, mixed, superactive, frigid Aeric Calciaquolls)
Lamberton15¶	2015	44˚14’41"N, 95˚18’1"W	Redwood	Normania loam (Fine-loamy, mixed, superactive, mesic Aquic Hapludolls)

† Denotes sites included in Group 1.
‡ Denotes sites included in Group 2.
§ Denotes sites included in Group 3.
¶ Denotes the site included in Group 4.

Table 1.2 Initial site-year soil physical and chemical properties in the top 15 cm except total inorganic N (TIN) that was measured in the top 60 cm and bulk density (BD) reported for 0- to 30-cm and 0- to 60-cm increments for 12 Minnesotan field site-years. Site-years were separated into Groups based on soil texture and response of yield to N rate..

Group	Site-year	Sand, Silt, Clay	pH	CEC	SOM	P†	K†	Ca†	Mg†	TIN‡	BD	
		%	Water	cmol$_c$ kg^{-1}	g kg^{-1}	mg kg^{-1}					0-30 cm	0-60 cm
Group 1												
	Becker14, 15a§	72, 6, 22	6.1	4.3	15.9	26	95	615	113	3.0	1.58	1.61
	Becker15b	74, 3, 23	6.2	4.4	15.0	22	94	649	100	4.6	1.58	1.61
	Weighted Mean										1.58	1.61
Group 2												
	Clara City14§	10, 48, 42	7.7	46.7	71.5	48	531	7313	963	7.9	1.07	1.19
	Waseca14a	20, 34, 46	5.9	34.0	66.0	24	215	5461	727	6.8	1.19	1.27
	Waseca14b, 15a§	19, 35, 46	5.6	29.6	66.8	23	161	4571	746	6.1	1.19	1.27
	Waseca15b	23, 30, 47	6	26.0	56.0	26	212	4042	612	7.1	1.25	1.30
	Weighted Mean										1.18	1.26
Group 3												
	Clara City15§	10, 48, 42	7.7	46.7	71.5	48	531	7313	963	7.9	1.07	1.21
	Lamberton14	29, 31, 40	5.5	14.1	40.0	27	148	2089	381	7.2	1.31	1.43
	Theilman14	1, 69, 30	6.8	13.9	31.0	53	180	1924	435	6.8	1.49	1.55
	Weighted Mean										1.29	1.39
Group 4												
	Lamberton15	35, 25, 40	5.1	16.3	47.0	30	112	2375	385	11.4	1.31	1.43
Group Fine												
	Weighted Mean										1.23	1.32

† Bray-1 P (pH ≤ 7.2) or Olsen P (pH > 7.2). Potassium, calcium, and magnesium extracted with ammonia acetate.

‡ Total inorganic nitrogen includes ammonium-N and nitrate-N.

§ Becker15a, Clara City15, and Waseca15a were conducted on the same plots as Becker14, Clara City14, and Waseca14b with soil properties only measured in the first year.

¶ Group Fine consists of all site-years from Groups 2, 3, and 4.

Table 1.3 Corn hybrid, planting population, and planting and harvest dates for 12 site-years in Minnesota.

Site-year	Hybrid	Plant Population†	Planting	Harvest
		plants ha^{-1}		
Becker14†	PIONEER P9917AMX	78,400	14/05/2014	13/10/2014
Clara City14‡	DKC44-13 RIB AR	80,700	30/05/2014	15/10/2014
Lamberton14§	PIONEER P9917AMX	82,000	29/05/2014	18/10/2014
Theilman14§	PIONEER P9917AMX	81,900	22/05/2014	16/10/2014
Waseca14a‡	DKC53-56 RIB	77,400	11/05/2014	21/10/2014
Waseca14b‡	DKC53-56 RIB	81,100	23/05/2014	21/10/2014
Becker15a†	PIONEER P9917AMX	87,300	27/04/2015	13/10/2015
Becker15b†	PIONEER P9917AMX	86,000	27/04/2015	13/10/2015
Clara City15§	PIONEER P9917AMX	78,500	30/04/2015	06/10/2015
Lamberton15¶	PIONEER P9917AMX	80,800	21/05/2015	14/10/2015
Waseca15a‡	DKC53-56 RIB	85,400	30/04/2015	12/10/2015
Waseca15b‡	DKC53-56 RIB	77,600	05/05/2015	09/10/2015

†Plant population determined at the V4 development stage.

Table 1.4 Parameter estimates for response models of grain yield (Mg ha^{-1}), R6 corn N uptake (kg ha^{-1}), grain N (kg ha^{-1}), and partial factor productivity (treatment yield/applied N rate) with increasing N (kg N ha^{-1}) with associated economic and agronomic optimum nitrogen rate (EONR N/corn price ratio = 0.0056 and AONR) and yield at EONR and AONR for corn for each Group.

Group	Parameter estimates†									
	A	*B*	*C*	*X₀*	*P>F*	Adj. r²	EONR	Yield at EONR	AONR	Yield at AONR
							kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}	Mg ha^{-1}
						Grain Yield				
Group 1	1.53	0.0207	-	-	<0.0001	0.60	-	-	315	8.0
Group 2	4.72	0.0243	-	-	<0.0001	0.61	-	-	270	11.3
Group 3	6.19	0.0545	-0.00015	182	<0.0001	0.47‡	163	11.1	182	11.1
Group 4	12.6	-	-	-	-	-	-	-	0	12.6
						R6 Corn N Uptake				
Group 1	43.64	0.2890	-	-	<0.0001	0.62				
Group 2	76.78	0.3667	-	-	<0.0001	0.66				
Group 3	119.14	0.4260	-	-	<0.0001	0.54				
Group 4	203.97	0.2089	-	-	<0.0001	0.53				
						Grain N				
Group 1	15.14	0.1757	-	-	<0.0001	0.60				
Group 2	40.67	0.2861	-	-	<0.0001	0.63				
Group 3	59.29	0.5705	-0.0011	-	<0.0001	0.54				
Group 4	138.57	0.0537	-	-	0.0307	0.14				
						Partial Factor Productivity				
Group 1	68.41	-0.3800	0.0008	-	<0.0001	0.39				
Group 2	175.13	-1.2151	0.0027	-	<0.0001	0.75				
Group 3	246.73	-1.7062	0.0036	-	<0.0001	0.85				
Group 4	393.41	-3.1369	0.0070	-	<0.0001	0.95				

† A, B, and C represent the intercept, linear term, and quadratic term in the appropriate model. X_0 is the asymptotic maximum in the quadratic model.

‡ Psuedo r^2 where model sum of squares is divided by corrected total sum of squares.

Table 1.5 Monthly precipitation and mean air temperatures during the 2014 and 2015 growing seasons and for the year for 5 locations in Minnesota, with departures from the 30-yr mean (1981-2010) in parentheses†.

Site-year	Year	Apr.	May	June	July	Aug.	Sept.	Oct.	Year avg.
					Precipitation (mm)				
Becker‡	2014	140 (68)	220 (143)	216 (100)	53 (-46)	106 (-2)	98 (13)	17 (-50)	991 (227)
	2015	47 (-24)	145 (67)	87 (-29)	186 (87)	148 (40)	41 (-43)	100 (34)	877 (113)
Clara City	2014	72 (12)	40 (-37)	239 (129)	26 (-67)	169 (84)	48 (-35)	26 (-32)	747 (42)
	2015	21 (-39)	200 (123)	57 (-53)	152 (59)	101 (16)	17 (-65)	49 (-10)	714 (9)
Lamberton	2014	87 (11)	46 (-37)	188 (84)	30 (-66)	94 (1)	154 (70)	12 (-39)	705 (-1)
	2015	31 (-44)	139 (57)	128 (24)	96 (0)	113 (20)	87 (3)	41 (-11)	780 (74)
Waseca	2014	141 (60)	73 (-27)	328 (209)	30 (-83)	81 (-40)	59 (-34)	35 (-33)	903 (0)
	2015	70 (-12)	121 (21)	194 (75)	188 (75)	152 (32)	149 (56)	31 (-37)	1160 (257)
Theilman	2014	148 (71)	75 (-19)	200 (91)	25 (-84)	169 (49)	62 (-41)	59 (4)	863 (120)
					Temperature avg. (˚C)				
Becker	2014	4.5 (-3.2)	13.6 (-0.7)	19.0 (0.1)	19.9 (-1.6)	20.3 (0.2)	15.4 (0.1)	8.4 (0.1)	4.8 (-1.8)
	2015	8.5 (0.8)	13.5 (-0.8)	18.9 (0.0)	21.0 (-0.5)	19.5 (-0.6)	18.2 (2.9)	9.6 (1.3)	7.7 (1.1)
Clara City	2014	4.4 (-3.2)	13.5 (-1.0)	19.8 (0.1)	20.4 (-1.7)	20.6 (-0.3)	15.9 (0.0)	9.2 (0.5)	5.1 (-2.0)
	2015	7.9 (0.3)	13.4 (-1.1)	19.8 (0.1)	21.7 (-0.4)	19.5 (-1.3)	19.0 (3.0)	10.2 (1.5)	7.7 (0.6)
Lamberton	2014	5.6 (-1.8)	13.8 (-0.8)	20.1 (-0.1)	20.5 (-1.7)	21.0 (0.4)	16.3 (0.4)	9.6 (0.9)	5.8 (-1.3)
	2015	8.6 (1.2)	13.9 (-0.7)	20.3 (0.2)	21.7 (-0.4)	19.7 (-1.0)	19.5 (3.6)	10.3 (1.6)	8.2 (1.1)
Waseca	2014	5.9 (-1.9)	13.7 (-1.0)	20.2 (0.2)	20.1 (-1.9)	21.5 (0.8)	16.0 (-0.1)	8.8 (-0.1)	5.3 (-1.9)
	2015	8.7 (0.9)	14.4 (-0.2)	20.2 (0.1)	21.4 (-0.6)	19.8 (-0.9)	20.0 (3.9)	10.8 (1.9)	8.3 (1.1)
Theilman	2014	5.1 (-2.9)	13.4 (-0.9)	20.4 (1.0)	20.2 (-1.7)	21.4 (0.8)	15.9 (-0.1)	7.8 (-1.1)	5.2 (-1.7)

† Monthly total precipitation and average air temperature data were obtained from the Minnesota Department of Natural Resources.

‡ Precipitation values at Becker do not include irrigation events.

Table 1.6 Treatment means for each Group of agronomic efficiency (AE), grain N harvest index (GNHI), and fertilizer recovery efficiency (FRE) with standard errors (SE) in response to pre-plant fertilizer N rate applications. The nitrogen rates were reduced by 25% for Waseca 14a in Group 2 and Theilman in Group 3.

Treatment†	AE†	GNHI	FRE	GNRE	AE	GNHI	FRE	GNRE
	kg kg^{-1}	kg kg^{-1}	%	kg kg^{-1}	kg kg^{-1}	kg kg^{-1}	%	kg kg^{-1}
N rate		**Group 1**				**Group 2**		
0		0.37d‡				0.62		
45	11.9	0.43cd	14	0.12	20.7	0.57	45	0.16c
90	17.3	0.51abc	18	0.15	33.0	0.67	40	0.32bc
135	13.9	0.43bcd	22	0.11	22.9	0.64	31	0.21ab
180	20.4	0.54ab	24	0.17	26.2	0.69	35	0.27ab
225	14.4	0.43bcd	26	0.12	24.1	0.68	36	0.26ab
270	18.2	0.52abc	24	0.16	24.9	0.72	40	0.31a
315	22.2	0.55a	30	0.19				
SE	5.0	0.04	5	0.04	3.2	0.04	8	0.04
Pr(>F)	0.7445	0.0229	0.4855	0.7449	0.0876	0.1043	0.7716	0.0291
		Group 3				**Group 4**		
0		0.54				0.69a		
45	24.9	0.58	25	0.20	16.8	0.63bcd	42	0.01
90	47.6	0.63	61	0.51	11.6	0.68ab	28	0.16
135	29.4	0.65	37	0.32	4.2	0.61cd	20	0.01
180	28.7	0.62	48	0.35	6.0	0.64abc	29	0.13
225	25.7	0.66	49	0.38	1.9	0.60cd	20	0.04
270	20.1	0.61	47	0.31	4.5	0.58d	23	0.05
SE	7.9	0.03	14	0.12	6.5	0.02	10	0.07
Pr(>F)	0.283	0.152	0.5796	0.6126	0.6163	0.0078	0.5858	0.4798

† AE and FRE are calculated as the yield or corn N uptake difference between the 0N and treatment of interest divided by the applied N rate. GNHI is the quotient of grain N and R6 corn N uptake.

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

Table 1.7 In-season plant nitrogen uptake treatment means for urea nitrogen rate treatments of each group with time in cumulative growing degree days Celsius (GDD). The nitrogen rates were reduced by 25% for Waseca 14a in Group 2 and Theilman in Group 3 relative to rates presented in the table.

	Group 1					**Group 2**				
	V4	V8	V12	R1	R6	V4	V8	V12	R1	R6
GDD†	196	388	586	758	1180	238	410	587	728	1283
N Rate	kg N ha^{-1}					kg N ha^{-1}				
0	0.4aC‡	4.8bC	15.4dBC	21.0dB	50.2dA	1.2aC	9.7cC	29.0dB	40.1eB	76.6fA
45	1.1aC	7.4bC	21.4cdBC	27.7cdB	56.4dA	2.5aE	15.6bcD	39.2dC	53.4dB	95.2eA
90	1.3aC	12.6aC	28.7cdB	39.1cB	66.0dA	3.2aE	22.7bD	56.3cC	69.9cB	109.5dA
135	1.2aC	15.0aC	37.0cB	37.0cB	79.1cdA	3.5aE	24.6bD	64.2cC	78.1cB	112.8dA
180	1.8aD	22.6aC	56.8bB	59.7bB	92.8cA	4.0aE	35.0abD	87.9bC	109.6bB	137.0cA
225	1.3aD	21.0aC	61.4bB	71.0bB	109.5bA	4.4aE	34.0abD	87.9bC	113.2bB	151.3bA
270	1.4aD	25.3aC	79.9aB	93.0aB	114.2bA	4.9aE	42.5aD	112.0aC	134.3aB	177.2aA
315	1.4aE	26.7aD	85.1aC	103.5aB	143.5aA					
	Group 3					**Group 4**				
GDD†	231	438	585	724	1293	279	563	675	859	1158
N Rate	kg N ha^{-1}					kg N ha^{-1}				
0	2.6aD	32.3cC	51.8dBC	63.9dB	115.1dA	3.1aD	66.3bC	120.7cB	137.0dB	199.6cA
45	5.9aD	49.3bC	76.9cB	87.7cB	127.1dA	3.6aE	82.7abD	134.6bcC	167.1cB	218.1bcA
90	5.1aE	55.3abD	99.1bC	124.9bB	164.2cA	3.4aE	86.4abD	151.6bC	201.8bB	224.6bA
135	6.2aD	62.2abC	95.4bB	119.5bB	160.0cA	3.7aE	91.4aC	159.9abB	175.2cB	226.0bA
180	6.6aE	68.0aD	117.7aC	153.8aB	194.8bA	3.4aE	92.2aD	159.0abC	212.5bB	251.1bA
225	6.5aE	69.7aD	122.2aC	150.0aB	212.7aA	3.6aD	98.7aC	165.2abB	230.9abA	244.9abA
270	5.6aE	66.0abD	122.6aC	150.6aB	228.1aA	3.6aE	98.4aD	179.4aC	235.1aB	260.3aA

Test of fixed effects

Source of variation	Group 1	Group 2	Group 3	Group 4
N	<0.001	<0.001	<0.001	<0.001
Time	<0.001	<0.001	<0.001	<0.001
N*Time	<0.001	<0.001	<0.001	<0.001

† GDD calculated as daily max temperature (Tmax) plus daily min temperature (Tmin) all divided by 2 and all subtracted by 10. If Tmax >30 ˚C, then it was set to 30 ˚C and if Tmax or Tmin <10 ˚C, it was set to 10 ˚C.

‡ Within Group, same lower-case letters within column and same uppercase letters across rows are not significantly different at $P = 0.05$.

Table 1.8 Group 1 pre-plant urea nitrogen rate treatment means for in-season total inorganic nitrogen at the 0- to 30- and 30- to 60-cm increments with time in cumulative growing degree days Celsius (GDD).

	V4		V8		V12		R1		Post-harvest	
GDD†	196		388		586		758			
	mg kg^{-1}									
kg N ha^{-1}	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm
0	3.6eA‡	2.5cA	4.5cA	3.8cA	2.9aA	2.4aA	2.4aA	2.3aA	3.9aA	2.7aA
45	5.3eA	4.4cA	4.4cA	4.9cA	2.9aA	2.4aA	2.6aA	1.9aA	4.3aA	2.2aA
90	6.5eAB	7.3bcA	4.9cAB	6.2cAB	2.6aAB	1.9aB	2.2aAB	2.0aAB	4.7aAB	2.3aAB
135	14.9dA	10.2bB	4.8cBC	7.8bcBC	3.1aC	2.5aC	2.7aC	2.3aC	4.1aC	4.0aC
180	21.6cA	12.5abB	7.5bcBC	9.4bcBC	2.6aC	2.0aC	2.7aC	2.1aC	5.1aC	2.5aC
225	26.9bA	15.6aB	8.8bcC	11.0bcBC	2.8aD	2.3aD	2.1aD	1.8aD	3.9aCD	2.2aD
270	24.3bcA	11.7abB	10.7bB	12.2bB	3.6aC	2.9aC	2.4aC	2.1aC	4.9aC	2.7aC
315	36.4aA	16.5aB	17.0aB	17.8aB	4.0aC	4.0aC	3.5aC	3.5aC	4.1aC	2.6aC

Test of fixed effects

Source of variation	
Nitrogen rate (N)	<0.0001
Depth (D)	0.0004
Time (T)	<0.0001
N*D	0.0651
N*T	<0.0001
D*T	<0.0001
N*D*T	<0.0001

† GDD calculated as daily max temperature (Tmax) plus daily min temperature (Tmin) all divided by 2 and all subtracted by 10. If Tmax >30˚C, then it was set to 30˚C and if Tmax or Tmin <10˚C, it was set to 10˚C.

‡ Same lowercase letters within column are not significantly different while same uppercase letters across rows and depths are not significantly different at *P* = 0.05.

Table 1.9 Group 2 pre-plant urea nitrogen rate treatment means for in-season total inorganic nitrogen at the 0- to 30- and 30- to 60-cm increments with time in cumulative growing degree days Celsius (GDD). The nitrogen rates were reduced by 25% for Waseca 14a relative to rates presented in the table.

	V4		V8		V12		R1		Post-harvest	
GDD†	238		410		587		728			
	mg kg^{-1}									
kg N ha^{-1}	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm
0	7.8eA‡	5.7dAB	7.8dA	5.7dAB	5.6bAB	3.9cB	5.4bAB	2.8bB	5.4aAB	2.8aB
45	11.3dA	6.9dB	8.7cdA	6.6cdBC	6.4bBC	4.2cBC	6.7bB	3.6bC	6.1aBC	2.6aC
90	13.6dA	8.7cdBC	10.3cdB	8.6cBC	6.9bC	5.4bcC	6.1bC	4.4bC	6.6aC	3.4aC
135	16.7cA	10.2cB	10.5cB	7.8cdBC	6.5bC	5.1bcCD	6.2bC	3.7bCD	6.1aC	2.3aD
180	22.9bA	12.5bcB	13.1bcB	11.9bB	7.9bC	6.3bcCD	7.5bC	5.3abCD	6.7aC	3.0aD
225	24.5bA	13.7bB	15.4bB	13.1bB	9.0abC	6.9bCD	8.0bC	5.0bD	5.9aCD	3.2aD
270	34.8aA	17.6aBC	20.4aB	16.1aC	11.3aD	11.2aD	11.0aD	7.7aE	7.4aE	3.2aF

Test of fixed effects

Source of variation	
Nitrogen rate (N)	<0.001
Depth (D)	0.001
Time (T)	<0.001
N*D	<0.001
N*T	<0.001
D*T	<0.001
N*D*T	<0.001

† GDD calculated as daily max temperature (Tmax) plus daily min temperature (Tmin) all divided by 2 and all subtracted by 10. If Tmax >30˚C, then it was set to 30˚C and if Tmax or Tmin <10˚C, it was set to 10˚C.

‡ Same lowercase letters within column are not significantly different while same uppercase letters across rows and depths are not significantly different at *P* = 0.05.

Table 1.10 Group 3 pre-plant urea nitrogen rate treatment means for in-season total inorganic nitrogen at the 0- to 30- and 30- to 60-cm increments with time in cumulative growing degree days Celsius (GDD). The nitrogen rates were reduced by 25% for Theilman relative to rates presented in the table.

	V4		V8		V12		R1		Post-harvest	
GDD†	231		438		585		724			
	mg kg^{-1}									
kg N ha^{-1}	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm
0	11.7dA‡	8.3dAB	6.9eAB	5.2dAB	6.7dAB	5.2bcAB	4.0bB	3.1bB	5.8aAB	3.3aB
45	16.0cdA	11.0cdAB	8.7deBC	6.8cdBC	7.0dBC	4.6cBC	4.3bBC	3.5bC	5.7aBC	3.5aC
90	21.8cA	12.8cdB	10.9deBC	10.5bcdBC	9.9bcdBC	6.3bcBC	5.9bBC	4.4abC	6.5aBC	3.8aC
135	20.3cA	13.9cdB	13.9cdAB	11.0bcdBC	8.7cdBCD	7.6bcBCD	6.1bCD	4.2abD	7.6aBCD	3.8aD
180	29.8bA	17.8bcB	18.0cB	12.3abcBC	14.1bcBC	8.3bcCD	9.2abCD	6.7abCD	8.0aCD	5.5aD
225	34.7bA	21.4abC	26.1bB	14.8abDE	16.2bCD	12.0abDEF	10.0abDEF	8.4abEF	9.7aEF	6.6aF
270	49.0aA	26.1aB	32.6aB	19.0aC	27.9aB	17.0aCD	15.6aCDE	11.0aDE	12.3aCDE	10.2aE

Tests of fixed effects§	
Source of variation	
Nitrogen rate (N)	<0.001
Depth (D)	0.005
Time (T)	<0.001
N*D	0.001
N*T	<0.001
D*T	<0.001
N*D*T	0.088

† GDD calculated as daily max temperature (Tmax) plus daily min temperature (Tmin) all divided by 2 and all subtracted by 10. If Tmax >30˚C, then it was set to 30˚C and if Tmax or Tmin <10˚C, it was set to 10˚C.

‡ Same lowercase letters within column are not significantly different while same uppercase letters across rows and depths are not significantly different at $P = 0.05$.

§ Group 3 has a significance level of $P = 0.1$.

Table 1.11 Group 4 pre-plant urea nitrogen rate treatment means for in-season total inorganic nitrogen at the 0- to 30- and 30- to 60-cm increments with time in cumulative growing degree days Celsius (GDD).

	V4		V8		V12		R1		Post-harvest	
GDD†	279		563		675		859			
	mg kg^{-1}									
kg N ha^{-1}	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm
0	10.8cA‡	8.9cA	7.3dA	6.5cA	7.3dA	5.1bA	4.8cA	2.5bA	6.6aA	2.9aA
45	18.5cA	10.1bcAB	10.0dAB	8.5cAB	7.6dB	4.8bB	4.8cB	2.5bB	5.6aB	2.9aB
90	20.3bcAB	10.0bcBC	21.5bcA	13.1bcABC	12.6cdABC	10.3abBC	8.5cC	5.6bC	7.1aC	3.4aC
135	31.1bA	14.0bcBC	20.0cB	13.4abcBC	9.1cdC	7.9abC	8.4cC	7.6bC	7.9aC	6.3aC
180	31.9bA	13.6bcCD	29.4bcAB	17.1abcC	20.4bcBC	15.8abCD	20.1bBC	22.3aABC	13.1aCD	5.8aD
225	45.1aA	20.6abBC	30.0bB	20.1abBCD	30.1bB	16.6aCD	20.3bBCD	12.8abCD	10.9aCD	10.4aD
270	54.3aA	27.8aDE	50.6aAB	21.5aE	43.8aBC	18.6aEF	36.4aCD	23.5aE	9.5aF	9.3aF

Test of fixed effects

Source of variation	
Nitrogen rate (N)	<0.0001
Depth (D)	<0.0001
Time (T)	<0.0001
N*D	0.0217
N*T	0.0007
D*T	0.0002
N*D*T	0.3619

† GDD calculated as daily max temperature (Tmax) plus daily min temperature (Tmin) all divided by 2 and all subtracted by 10. If Tmax >30˚C, then it was set to 30˚C and if Tmax or Tmin <10˚C, it was set to 10˚C.

‡ Same lowercase letters within column are not significantly different while same uppercase letters across rows and depths are not significantly different at *P* = 0.05.

Table 1.12. Treatment means for each Group of grain yield, grain nitrogen (N), agronomic efficiency (AE), grain N harvest index (GNHI), and fertilizer recovery efficiency (FRE) with standard errors (SE) in response to source of N application at 135 kg N ha^{-1}rates. The nitrogen rates were 102 kg N ha^{-1} Waseca 14a in Group 2 and Theilman in Group 3.

Treatment†	Grain Yield	Grain N	AE‡	GNHI	FRE	Grain Yield	Grain N	AE‡	GNHI	FRE
	Mg ha^{-1}	kg N ha^{-1}	kg kg^{-1}	kg kg^{-1}	%	Mg ha^{-1}	kg N ha^{-1}	kg kg^{-1}	kg kg^{-1}	%
			Group 1					**Group 2**		
AA	5.4 AB§	46.9 AB	26.0 AB	0.47 BC	37 A	6.8 C	65.2 C	17.5 C	0.69 A	22 A
AAI	6.4 A	55.1 A	33.2 A	0.51 ABC	44 A	7.2 C	70.5 BC	19.3 C	0.69 A	27 A
PCU	6.2 A	54.8 A	31.8 A	0.61 A	32 A	8.8 AB	89.9 A	32.1 B	0.65 A	46 A
PCU-U 2:1	5.1 ABC	44.1 AB	23.6 ABC	0.55 AB	23 A	9.3 A	92.6 A	36.1 A	0.63 A	43 A
PCU-U 1:2	4.4 BC	36.5 B	18.6 BC	0.46 BC	23 A	8.9 A	86.2 AB	33.6 B	0.64 A	46 A
Urea	3.8 C	33.2 B	13.9 C	0.43 C	22 A	7.5 BC	68.8 BC	22.9 C	0.72 A	31 A
SE	0.5	4.6	3.7	0.04	6	0.6	6.7	4.1	0.03	7
Pr(>F)	0.022	0.031	0.023	0.041	0.094	0.011	0.015	0.008	0.165	0.096
			Group 3					**Group 4**		
AA	10.4 A	112.2 A	34.0 A	0.61 A	57 AB	13.5 A	160.2 A	12.2 A	0.73 A	17 A
AAI	11.2 A	128.3 A	40.7 A	0.63 A	74 A	13.5 A	153.8 A	11.9 A	0.63 BC	35 A
PCU	10.5 A	107.3 A	33.9 A	0.63 A	43 BC	12.9 A	152.0 A	9.0 AB	0.68 ABC	18 A
PCU-U 2:1	11.5 A	125.3 A	43.4 A	0.67 A	62 A	13.1 A	153.6 A	7.9 AB	0.69 AB	17 A
PCU-U 1:2	10.9 A	122.7 A	37.8 A	0.65 A	63 A	12.8 A	138.3 A	7.4 AB	0.61 BC	21 A
Urea	10.0 A	103.9 A	29.4 A	0.65 A	37 C	12.4 A	137.3 A	4.2 B	0.61 C	20 A
SE	1.2	10.6	8.4	0.04	7	0.3	6.7	2.6	0.03	8
Pr(>F)	0.357	0.079	0.359	0.902	0.01	0.133	0.071	0.04	0.037	0.448

† Anhydrous ammonia (AA), anhydrous ammonia with nitrification inhibitor (AAI), polymer coated urea (PCU), PCU-urea blends at a ratio of 2:1 (PCU-U 2:1), PCU-urea blends at ratio of 1:2 (PCU-U 1:2).

‡ AE and FRE are calculated as the yield or corn N uptake difference between the 0N and treatment of interest divided by the applied N rate. GNHI is the quotient of grain N and R6 corn N uptake.

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

Table 1.13 In-season plant nitrogen uptake treatment means for nitrogen source treatments applied at 135 kg N ha^{-1} of each Group with time in cumulative growing degree days Celsius (GDD).

	Group 1					**Group 2†**				
	V4	V8	V12	R1	R6	V4	V8	V12	R1	R6
GDD	196	388	586	758	1180	238	410	587	728	1283
	kg N ha^{-1}					kg N ha^{-1}				
AA	1.3aE‡	22.3aD	58.2abC	76.9aB	100.7abA	2.8aE	22.9abD	50.9bC	76.1bB	103.4bA
AAI	1.7aD	26.0aC	63.3aB	73.0abB	109.4aA	2.5aE	17.9bD	55.1bC	70.1bB	111.5bA
PCU	1.6aD	21.5aC	55.4abB	62.3bB	93.6bA	4.5aD	32.4aC	80.4aB	92.4aB	133.8aA
PCU-U 2:1	1.5aD	21.8aC	46.7bB	46.5cB	81.0bcA	4.2aE	31.9aD	81.7aC	98.7aB	131.2aA
PCU-U 1:2	1.6aD	19.1aC	46.5bB	46.2cB	81.3bcA	4.2aD	30.3abC	75.0abB	87.1abB	133.1aA
Urea	1.2aD	15.0aC	37.0bB	37.0cB	79.1cA	3.5aE	24.6abD	64.2bC	78.1bB	112.7bA
	Group 3					**Group 4**				
GDD	231	438	585	724	1293	279	563	675	859	1158
	kg N ha^{-1}					kg N ha^{-1}				
AA	4.6aD	56.0aC	103.0abB	126.0bB	184.6bA	3.4aE	83.2aD	130.2bC	199.5bB	222.0bA
AAI	4.8aD	61.6aC	113.5aB	143.9aB	204.7aA	3.9aD	94.8aC	167.2aB	231.5aA	246.2aA
PCU	6.4aD	66.3aC	113.1aB	125.0bB	169.4cA	3.2aE	92.9aD	136.6bC	203.9bB	223.0bA
PCU-U 2:1	5.4aE	61.5aD	106.7abC	144.2aB	190.3abA	3.8aE	87.8aD	165.3aC	192.7bcB	221.7bA
PCU-U 1:2	6.3aD	63.4aC	113.1aB	135.4abB	191.4abA	3.6aE	95.8aD	153.4abC	202.7bB	227.7abA
Urea	6.2aD	62.2aC	95.4bB	119.5bB	160.0cA	3.7aD	91.4aC	159.9aB	175.2cB	226.0abA

	Tests of fixed effects			
Source of variation	Group 1	Group 2	Group 3	Group 4
Nitrogen source (N)	0.0002	0.0001	0.0088	0.0155
Time	<0.0001	<0.0001	<0.0001	<0.0001
N*Time	0.0028	0.0093	0.0031	0.0188

† The nitrogen rates were 102 kg N ha^{-1} for Waseca 14a in Group 2 and Theilman in Group 3.

‡ Within Group, same lowercase letters within column are not significantly different while same uppercase letters across rows are not significantly different at $P = 0.05$.

Table 1.14 Group 1 nitrogen source treatment means for in-season total inorganic nitrogen applied at 135 kg N ha^{-1} at the 0- to 30- and 30- to 60-cm increments with time in cumulative growing degree days Celsius (GDD).

	V4		V8		V12		R1		Post-harvest	
GDD†	196		388		586		758			
	mg kg^{-1}									
	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm
AA‡	10.9bA§	5.2cB	5.8abB	5.5aB	3.0aB	2.9aB	2.7aB	2.4aB	4.9aB	2.1aB
AAI	10.5bA	5.5cBC	8.9aAB	5.5aBC	3.7aC	2.0aC	2.5aC	2.0aC	4.7aBC	2.8aC
PCU	13.0abA	9.0abB	7.2abBC	6.4aBC	3.0aCD	2.3aD	3.2aCD	2.1aD	4.5aCD	2.5aD
PCU-U 2:1	10.8bA	5.9bBCD	6.8abABC	7.3aAB	2.5aD	1.9aD	2.6aCD	2.3aD	4.7aBCD	3.1aBCD
PCU-U 1:2	11.9abA	8.8abB	7.1abB	7.3aB	2.6aC	2.2aC	2.8aC	2.2aC	4.6aBC	2.3aC
Urea	14.9aA	10.2aB	4.8bCD	7.8aBC	3.1aD	2.5aD	2.7aD	2.3aD	4.1aCD	4.0aCD

Tests of fixed effects

Source of variation	
Nitrogen source (N)	0.6401
Depth (D)	0.0013
N*D	0.2123
Time (T)	<0.0001
N*T	0.6777
D*T	0.0203
N*D*T	0.9006

† GDD calculated as daily max temperature (Tmax) plus daily min temperature (Tmin) all divided by 2 and all subtracted by 10. If Tmax >30˚C, then it was set to 30˚C and if Tmax or Tmin <10˚C, it was set to 10˚C.

‡ Anhydrous ammonia (AA), anhydrous ammonia with nitrification inhibitor (AAI), polymer coated urea (PCU), PCU-urea blends at a ratio of 2:1 (PCU-U 2:1), PCU-urea blends at ratio of 1:2 (PCU-U 1:2).

§ Same lowercase letters within column are not significantly different while same uppercase letters across rows and depths are not significantly different at $P = 0.05$.

Table 1.15 Group 2 nitrogen source treatment means for in-season total inorganic nitrogen applied at 135 kg N ha^{-1}, except for Waseca14a that was 102 kg N ha^{-1}, at the 0- to 30- and 30- to 60-cm increments with time in cumulative growing degree days Celsius (GDD).

	V4		V8		V12		R1		Post-harvest	
GDD†	238		410		587		728			
	mg kg^{-1}									
	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm
AA‡	12.6dA§	8.7abBC	10.4bAB	8.5bcBC	6.8aCD	5.1aDE	6.4aCDE	4.4aE	6.2aCDE	3.2aE
AAI	14.2cdA	7.8bC	10.6bB	8.0bcC	6.9aCD	4.8aDE	6.2aCD	4.2aDE	4.9aCDE	2.2aE
PCU	19.8aA	10.0aC	13.2aB	10.1abC	7.3aCDE	5.6aDEF	8.2aCD	4.8aEF	6.7aDE	3.1aF
PCU-U 2:1	19.0aA	10.1aC	13.3aB	11.7aB	8.3aCD	6.0aDE	7.2aCD	5.1aDE	7.1aCD	3.3aE
PCU-U 1:2	15.3bcA	9.8abBC	11.3abB	10.0abB	6.8aCD	5.0aDE	6.4aD	4.3aDE	6.6aCD	2.7aE
Urea	16.7bA	10.2aBC	10.5bB	7.8cCD	6.5aDE	5.1aE	6.2aDE	3.7aEF	6.1aDE	2.3aF

Tests of fixed effects	
Source of variation	
Nitrogen source (N)	0.0005
Depth (D)	0.0003
N*D	0.0598
Time (T)	<0.0001
N*T	0.0149
D*T	<0.0001
N*D*T	0.2534

† GDD calculated as daily max temperature (Tmax) plus daily min temperature (Tmin) all divided by 2 and all subtracted by 10. If Tmax >30˚C, then it was set to 30˚C and if Tmax or Tmin <10˚C, it was set to 10˚C.

‡ Anhydrous ammonia (AA), anhydrous ammonia with nitrification inhibitor (AAI), polymer coated urea (PCU), PCU-urea blends at a ratio of 2:1 (PCU-U 2:1), PCU-urea blends at ratio of 1:2 (PCU-U 1:2).

§ Same lowercase letters within column are not significantly different while same uppercase letters across rows and depths are not significantly different at $P = 0.05$.

Table 1.16 Group 3 nitrogen source treatment means for in-season total inorganic nitrogen applied at 135 kg N ha^{-1}, except for Theilman that was 102 kg N ha^{-1}, at the 0- to 30- and 30- to 60-cm increments with time in cumulative growing degree days Celsius (GDD).

	V4		V8		V12		R1		Post-harvest	
GDD†	231		438		585		724			
	mg kg^{-1}									
	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm
AA‡	19.3	12.2	14.0	9.5	12.0	8.2	6.4	4.6	6.9	5.1
AAI	21.0	11.8	18.4	11.5	13.4	7.0	10.9	6.0	8.7	5.7
PCU	27.3	14.1	20.0	14.9	17.5	8.6	7.3	6.8	7.9	4.9
PCU-U 2:1	23.1	16.5	18.0	13.9	13.5	8.5	7.6	7.9	8.5	4.7
PCU-U 1:2	28.9	17.7	22.4	15.4	11.9	11.3	8.6	7.4	9.2	4.7
Urea	20.3	13.9	13.9	11.0	8.7	7.6	6.1	4.2	7.6	3.8

Tests of fixed effects

Source of variation	
Nitrogen source (N)	0.196
Depth (D)	<0.001
N*D	0.179
Time (T)	<0.001
N*T	0.176
D*T	0.085
N*D*T	0.706

† GDD calculated as daily max temperature (Tmax) plus daily min temperature (Tmin) all divided by 2 and all subtracted by 10. If Tmax >30˚C, then it was set to 30˚C and if Tmax or Tmin <10˚C, it was set to 10˚C.

‡ Anhydrous ammonia (AA), anhydrous ammonia with nitrification inhibitor (AAI), polymer coated urea (PCU), PCU-urea blends at a ratio of 2:1 (PCU-U 2:1), PCU-urea blends at ratio of 1:2 (PCU-U 1:2).

Table 1.17 Group 4 nitrogen source treatment means for in-season total inorganic nitrogen applied at 135 kg N ha^{-1} at the 0- to 30- and 30- to 60-cm increments with time in cumulative growing degree days Celsius (GDD).

	V4		V8		V12		R1		Post-harvest	
GDD†	279		563		675		859			
	mg kg^{-1}									
	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm
AA‡	20.6A§	11.1B	9.1BC	9.9B	7.7BC	7.0BC	9.0BC	6.3BC	7.4BC	3.8C
AAI	18.0A	10.6BC	13.3AB	10.0BCD	7.4CD	6.5CD	5.6CD	4.3CD	7.4BCD	4.1D
PCU	27.3A	10.5DE	23.5AB	12.8CD	18.1BC	10.0DE	8.9DEF	6.5EF	9.3DEF	3.6F
PCU-U 2:1	26.6A	11.6BCD	17.3B	12.6BC	16.8B	9.6CDE	7.6DE	6.4	7.0CDE	4.3E
PCU-U 1:2	23.9A	11.9BCD	16.8B	12.3BCD	13.9BC	9.0CDE	7.5E	5.5	10.6CDE	5.4E
Urea	31.1A	14.0BC	20.0B	13.4CD	9.4CDE	7.9CDE	8.4CDE	7.6DE	7.9DE	6.3E

Tests of fixed effects

Source of variation	
Nitrogen source (N)	0.0918
Depth (D)	<.0001
N*D	0.1158
Time (T)	<.0001
N*T	0.133
D*T	<.0001
N*D*T	0.0918

† GDD calculated as daily max temperature (Tmax) plus daily min temperature (Tmin) all divided by 2 and all subtracted by 10. If Tmax >30˚C, then it was set to 30˚C and if Tmax or Tmin <10˚C, it was set to 10˚C.

‡ Anhydrous ammonia (AA), anhydrous ammonia with nitrification inhibitor (AAI), polymer coated urea (PCU), PCU-urea blends at a ratio of 2:1 (PCU-U 2:1), PCU-urea blends at ratio of 1:2 (PCU-U 1:2).

§ Same uppercase letters across rows and depths are not significantly different at $P = 0.05$.

Table 1.18 Modified arcsine-log calibration curve critical soil test values (CSTV), 95% upper (UCL) and lower (LCL) confidence limits, and squared Pearson correlation coefficient (r^2) of natural log transformed soil test values and arcsine of the square root for relative yield transformations for nitrate-nitrogen (NO_3) and total inorganic nitrogen (TIN) for pre-plant plus the applied N rate (PP+R) and V4 and V8 development stages.

	r^2	CSTV	95% LCL	95% UCL	r^2	CSTV	95% LCL	95% UCL
		kg N ha^{-1}				kg N ha^{-1}		
	Group 1				Group 2			
PP NO_3+R 0-30 cm	0.37	1251	748	2093	0.42	385	301	491
PP NO_3+R 0-60 cm	0.41	1009	650	1566	0.44	353	293	425
PP TIN+R 0-30 cm	0.44	796	559	1134	0.42	359	303	426
PP TIN+R 0-60 cm	0.46	687	513	921	0.37	385	331	448
V4 NO_3 0-30 cm	0.36	250	162	386	0.59	86	76	99
V4 NO_3 0-60 cm	0.40	405	276	595	0.58	146	129	165
V4 TIN 0-30 cm	0.44	337	238	475	0.58	111	100	123
V4 TIN 0-60 cm	0.48	488	362	658	0.58	177	162	194
V8 NO_3 0-30 cm	0.38	56	41	75	0.22	40	32	49
V8 NO_3 0-60 cm	0.48	172	128	232	0.31	90	76	106
V8 TIN 0-30 cm	0.37	93	74	117	0.19	67	59	76
V8 TIN 0-60 cm	0.46	207	169	253	0.24	128	114	143
	Group 3				Group Fine			
PP NO_3+R 0-30 cm	0.50	200	163	247	0.45	301	259	349
PP NO_3+R 0-60 cm	0.55	211	181	245	0.46	314	279	353
PP TIN+R 0-30 cm	0.55	213	184	247	0.44	307	275	342
PP TIN+R 0-60 cm	0.56	241	216	269	0.50	199	185	213
V4 NO_3 0-30 cm	0.42	102	87	118	0.55	94	86	103
V4 NO_3 0-60 cm	0.44	170	148	195	0.55	157	144	171
V4 TIN 0-30 cm	0.40	128	113	146	0.50	121	112	131
V4 TIN 0-60 cm	0.40	218	193	247	0.52	199	185	213
V8 NO_3 0-30 cm	0.30	61	47	79	0.25	51	43	60
V8 NO_3 0-60 cm	0.37	110	91	133	0.32	101	90	115
V8 TIN 0-30 cm	0.30	81	68	96	0.23	79	72	87
V8 TIN 0-60 cm	0.37	145	127	165	0.29	143	132	156

Table 1.19 Regression parameter estimates of soil test value (STV) by nitrogen rate (N) (kg ha^{-1}) and the associated lower (LCL) and upper (UCL) 70% confidence levels for the equation STV=e^(a+b*N).

		STV x N Rate		LCL 70%		UCL 70%					Model
		a	b	a	b	a	b	RMSE†	Adj. r^2†	CV‡	Sig.‡
Group 2	PP NO$_3$+R 0-30 cm §	3.257	0.01061	3.161	0.00999	3.353	0.01123	0.614	0.70	13.28	***
Group 2	PP NO$_3$+R 0-60 cm	3.746	0.00852	3.677	0.00807	3.815	0.00896	0.440	0.74	9.10	***
Group 2	V4 NO$_3$ 0-30 cm	2.635	0.00717	2.569	0.00675	2.701	0.00760	0.420	0.69	11.81	***
Group 2	V4 NO$_3$ 0-60 cm	3.302	0.00661	3.240	0.00621	3.364	0.00701	0.393	0.68	9.47	***
Group 2	V8 NO$_3$ 0-30 cm	1.976	0.00622	1.893	0.00568	2.059	0.00675	0.529	0.51	19.05	***
Group 2	V8 NO$_3$ 0-60 cm	2.882	0.00619	2.814	0.00576	2.949	0.00662	0.429	0.61	11.68	***
Group 3	PP NO$_3$+R 0-30 cm	3.245	0.01076	3.153	0.01015	3.337	0.01137	0.453	0.80	9.90	***
Group 3	PP NO$_3$+R 0-60 cm	3.748	0.00851	3.692	0.00813	3.804	0.00888	0.277	0.87	5.77	***
Group 3	V4 NO$_3$ 0-30 cm	3.371	0.00634	3.293	0.00581	3.449	0.00686	0.387	0.66	9.31	***
Group 3	V4 NO$_3$ 0-60 cm	3.938	0.00622	3.874	0.00579	4.001	0.00664	0.314	0.74	6.67	***
Group 3	V8 NO$_3$ 0-30 cm	2.191	0.00965	2.064	0.00881	2.317	0.01050	0.626	0.63	18.50	***
Group 3	V8 NO$_3$ 0-60 cm	3.074	0.00835	2.986	0.00777	3.161	0.00893	0.431	0.73	10.49	***
Group Fine	PP NO$_3$+R 0-30 cm	3.466	0.00989	3.390	0.00939	3.542	0.01038	0.653	0.63	13.80	***
Group Fine	PP NO$_3$+R 0-60 cm	3.948	0.00792	3.885	0.00752	4.011	0.00833	0.539	0.62	10.88	***
Group Fine	V4 NO$_3$ 0-30 cm	3.002	0.00658	2.941	0.00619	3.063	0.00698	0.525	0.54	13.66	***
Group Fine	V4 NO$_3$ 0-60 cm	3.621	0.00621	3.566	0.00586	3.676	0.00657	0.469	0.57	10.62	***
Group Fine	V8 NO$_3$ 0-30 cm	2.043	0.00793	1.963	0.00742	2.123	0.00845	0.685	0.50	22.41	***
Group Fine	V8 NO$_3$ 0-60 cm	2.981	0.00715	2.922	0.00676	3.041	0.00753	0.511	0.60	13.13	***

† RMSE: root mean square error; Adj. R2: adjusted R2; CV: coefficient of variation

‡ Model significance; *** significant at the 0.001 probability level

§ PP NO3+R: pre-plant soil values plus the applied nitrogen rate; V4: vegetative development stage 4; V8: vegetative development stage 8; NO$_3$: nitrate-N

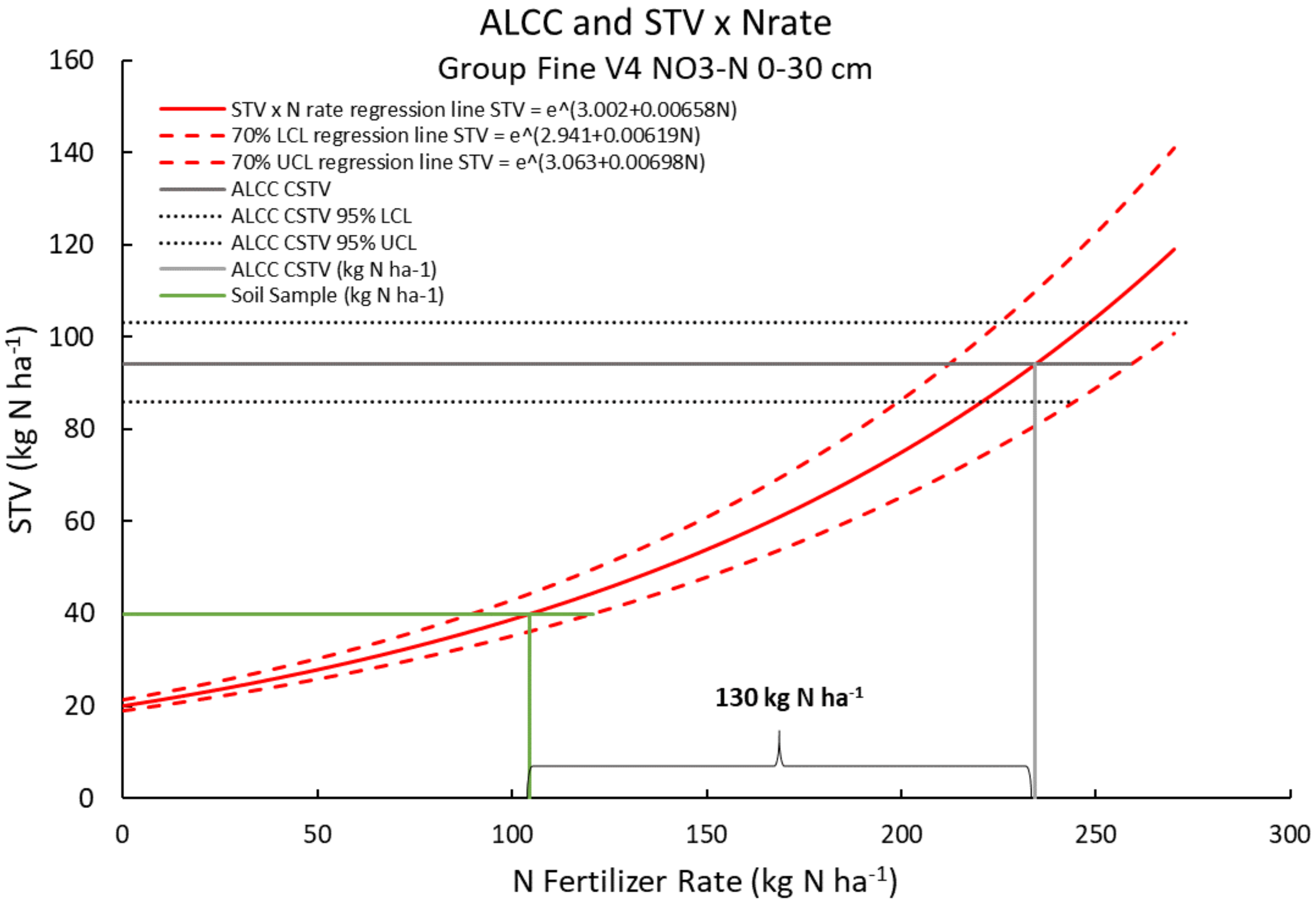


Fig. 1.1 A plot for Group Fine V4 nitrate-N 0- to 30-cm combining the arcsine-log calibration curve critical soil test value (CSTV) with the regression of soil test value (STV) against the applied N rate.

CHAPTER 2: SOIL TEXTURE AND WEATHER INFLUENCE OPTIMAL TIME OF NITROGEN FERTILIZATION FOR CORN

2.1. SYNOPSIS

In-season N fertilization is increasingly being used as a management strategy to reduce risk of N loss to the environment. This study systematically evaluated the optimal timing for a split N application in corn (*Zea mays* L.) grain production across different environments and soil textural classes in Minnesota. Fertilizer treatments consisted of urea applied at pre-plant at 45 kg N ha^{-1} increments from 0 to 270 or 315 kg N ha^{-1} and five split-applications of 45 kg N ha^{-1} urea ammonium nitrate as a starter fertilizer and 90 kg N ha^{-1} of urea with N-(n-butyl) thiophosphoric triamide applied at vegetative (V) V2, V4, V6, V8, or V12 development stage. Site-years were grouped according to soil texture and grain yield response to fertilizer timing. Irrigated coarse-textured soils produced 1.5 to 1.9 times greater grain yield when sidedress (SD) fertilizer was applied from V4 to V12 due to improved synchrony of N availability to crop demand and reduced potential for nitrate-N leaching. Rain-fed, fine-textured soils had mixed results where site-years receiving well-distributed rainfall produced greater yield when SD fertilizer was applied from V2 to V8 but site-years with dry summer months had reduced yield potential and no improvement of N use efficiencies (NUE). There is not a single N fertilizer timing that will optimize yield each year due to variable weather conditions. This study offers insights of N availability under multiple growing conditions that can be used to minimize grower risk for improved N management and corn production.

2.2. INTRODUCTION

Nitrogen is a major limiting nutrient for producing high yielding corn (*Zea mays* L.) that is often supplied as inorganic fertilizer. While N fertilizer can significantly improve grain yield, agricultural producers must strive to maximize NUE and produce optimal yield to stay profitable in an increasingly competitive market. One of the major difficulties to improving NUE is that once N fertilizer is applied, it is subject to loss under certain environmental conditions. This is not only detrimental to farmer's profitability, but N loss becomes a societal issue as it can also negatively impact environmental quality (Wortman et al., 2006). There is increasing scrutiny on this nutrient because of the impact of N on the environment. Many states in the US have developed nutrient reduction strategies to implement best management practices to limit the amount of N lost to the environment (MPCA, 2014; IDA, 2015; IOWA, 2017; PSE, 2018). Even when best management practices are employed, reducing N loss may still be difficult. A recent study on a coarse-textured soil in a continuous corn cropping system showed that nitrate-N leaching losses were 86 kg ha^{-1} at the economic optimal N rate (EONR) of 250 kg N ha^{-1} (Struffert et al., 2016). When the EONR was reduced by 25%, there was a 6% reduction in corn grain yield and only an 11% reduction in total nitrate-N leaching. Although application rate can have a significant role in reducing N losses, corn cropping systems are typically prone to N loss (Magdoff et al., 1991a; Lawlor et al., 2005; Struffert et al., 2016) and other practices must be evaluated. This may become especially important if climate in parts of the Midwest shifts towards cooler and wetter springs with large precipitation events, and warmer and drier summers (Seeley, 2015)

Improved synchrony of time of N application to crop uptake is one practice that has been proposed to maintain productivity and reduce N loss potential (Dinnes et al., 2002). The Minnesota Nutrient Reduction Strategy indicates that a 4 to 7% reduction in N loss to surface waters may be possible by shifting N applications from pre-plant to SD (MPCA, 2014). Predominant N loss from corn cropping systems occurs in the spring months of April to June when the Upper Midwest typically receives 35% of its annual precipitation and the corn crop is not yet actively taking up large amounts of soil water or N (Randall et al., 2003a; Randall et al., 2003b; Vetsch and Randall, 2004; Struffert et al., 2016; Chapter 1). Applying N closer to the time of crop N uptake can reduce leaching and denitrification losses (Vetsch and Randall, 2004; Fernández et al., 2016) but split-applications may also prove challenging. Surface-applied N fertilizer can result in up to 50% volatilization losses (Engel et al., 2011) or dry soil conditions following in-season application may result in inadequate uptake by corn and high residual soil N that would be susceptible to loss (Randall et al., 2003b). Split-applications can have nitrous oxide emissions equal to or greater than a single spring application (Venterea and Coulter, 2015). Grain yield response to timing of application is not conclusive. Relative to single pre-plant spring application, split-applications had no yield difference (Jokela and Randall, 1989; Jokela and Randall, 1997; Mueller et al., 2017; Randall et al., 1997; Venterea and Coulter, 2015), increased yield (Randall et al., 2003a; Tremblay et al., 2012; Jaynes, 2013), or decreased yield (Jaynes and Colvin, 2006; Tremblay et al., 2012). These differences may be related to variable growing season conditions or timings of N applications across these studies. A study that systematically evaluates when in the growing season a split N application may be most beneficial across different environments may help elucidate these seemingly contradictory reports. The objectives of the study were to determine when in-season N should be applied to optimize grain yield and NUE relative to single pre-plant N applications and to examine in-season changes in corn and soil N status due to time of application.

2.3. MATERIALS AND METHODS

2.3.1. Study Sites

Studies were conducted at twelve field sites during the 2014 and 2015 growing seasons across major soils and agricultural regions in Minnesota, US. Site-years were located at the Sand Plain Research Farm at Becker, MN, at the University of Minnesota Research and Outreach Centers at Lamberton and Waseca, MN, and on farmers' fields near Theilman and Clara City, MN. All site-years were in a continuous corn cropping system except for Waseca14a that had a soybean [*Glycine max* (L.) Merr.] corn rotation. All site-years were dryland, except for those at Becker that were irrigated. Air temperature and precipitation data were obtained from the National Weather Service weather stations in closest proximity to each site-year (MNDNR, 2016). Growing degree days was calculated as the mean of the daily maximum and minimum temperature subtracted by 10, where any temperatures less than 10 °C or greater than 30 °C were set to values of 10 or 30, respectively. Detailed site and management descriptions are provided elsewhere (Chapter 1).

2.3.2. Experimental Design

Treatments were arranged in a randomized complete block design with four replications. Treatments consisted of a single pre-plant (PP) application of urea (46-0-0, N-P-K) at 45 kg N ha^{-1} rate increments from 0 to 270 kg N ha^{-1} except at the Becker site-years that received an additional rate of 315 kg N ha^{-1}. Five additional treatments were added where 45 kg N ha^{-1} was applied in a band on the soil surface to the side of the row at planting as urea ammonium nitrate solution followed by 90 kg N ha^{-1} as urea (135 kg N ha^{-1} applied in total) with N-(n-butyl) thiophosphoric triamide (NBPT), Agrotain (Koch Fertilizer LLC, Wichita, KS) applied at the V2 (SD-V2), V4 (SD-V4), V6 (SD-V6), V8 (SD-V8) or V12 (SD-V12) corn development stages (Abendroth et al., 2011). All fertilizer rates for Theilman14 and Waseca14a were reduced by 25%. Pre-plant and starter N fertilizers were applied within one week of planting, except at Clara City15 where pre-plant fertilizer was applied 18 days before planting (Table 2.1, 2.2). All PP and SD urea N fertilizer treatments were broadcast by hand and PP was incorporated with shallow tillage (5 cm) except at Becker14 where treatments were incorporated with 6 mm of irrigation immediately after the application. The SD fertilizer applications received 6- to 20-mm of water within 2 days of fertilizer application on irrigated site-years, except for a single rain event at V4 at Becker14 where 40 mm of precipitation fell within 24 h of application. On non-irrigated site-years, incorporation occurred with at least 12 mm of precipitation within two weeks of N application at all site-years and application timings except Clara City14 at V4; Lamberton14 at V6; Lamberton15 and Waseca14b at V8; and Lamberton14, Waseca14a, and Theilman14 at V12 (Table 2.1; 2.2).

2.3.3. Corn Sampling

Corn N uptake was measured at the V4, V8, V12, R1, and R6 development stages (Abendroth et al., 2011). Six representative corn plants were collected from each plot, chipped, dried at 60 °C until constant mass, and weighed. The dried samples were then mixed and ground to pass through a 2 mm screen and analyzed for total N by combustion analysis using a Carlo Erba 1500 elemental analyzer (Carlo Erba, La Metairie, France) (Horneck and Miller, 1998). Cobs, grain, and vegetative tissues were partitioned at the R6 stage and processed similar to earlier samplings. Grain yield was measured by harvesting the center two rows of each plot by hand or using a research grade plot combine. Ears were shelled, weighed, and a representative subsample was saved to determine grain moisture content and analyzed for total N content by combustion analysis using an Elementar Analyzer (Langenselbold, Hesse, Germany). Grain yield was corrected to 155 g kg^{-1} moisture. Nitrogen uptake was calculated as the product of dry matter for the grain, cob, and stover by their respective N concentrations.

2.3.4. Soil Sampling

Concurrent with plant sampling, four-core (1.8 cm diameter) composite soil samples were collected from the 0- to 30- and 30- to 60- cm increments while at post-harvest, a two-core (5 cm diameter) composite soil sample was collected at the same increments using a hydraulic probe. However, at Waseca14a, excessively wet conditions followed by freezing prevented post-harvest soil sample collection. Soil samples were dried at 35 °C, ground to pass through a 2 mm screen, and analyzed for nitrate-N (Gelderman and Beegle, 2012) and ammonium-N (Bremner and Mulvaney, 1982). A pre-plant soil sample collected in 2015 indicated that there were no significant residual soil N treatment effects from the previous year (data not shown) so Becker15a, Waseca15a, and Clara City15 were placed on the same treatment-plots as the 2014 site-years of Becker14, Waseca14b, and Clara City14.

2.3.5. Data Analysis

Site-years were separated into three groups based on the response of grain yield to time of N application using the two-tailed log likelihood test where site-years were grouped when the chi-squared value was greater than 0.05. Group 1 had four site-years (Becker14, Becker15a, Becker15b, and Waseca15b), Group 2 had five site-years (Clara City14, Clara City15, Lamberton15, Theilman14, and Waseca15a), and Group 3 had three site-years (Lamberton14, Waseca14a, Waseca14b). These same groupings were maintained for analysis of other dependent variables.

All data were analyzed at $P \leq 0.05$ using various procedures of SAS (SAS Institute, 2012). Nitrogen treatments associated with time of N application were analyzed separately from treatments comparing N rates. Using the MIXED procedure of SAS, time of N application was considered a fixed effect, while site-year, block (nested within site-year) and interactions of fixed effects with site-year and block were considered random effects. Residual normality was verified with the UNIVARIATE procedure and scatterplots of the residuals versus predicted values verified homogeneity of variance

(Kutner et al., 2004). When appropriate, pairwise mean comparisons were made with *t* tests at $P \leq 0.05$ using the PDIFF option in the MIXED procedure of SAS.

Repeated measures were performed for the in-season soil and plant data for the time of N application (SD-V2, SD-V4, SD-V6, SD-V8, SD-V12) treatments using the MIXED procedure of SAS where time of N application, development stage, depth, and their interactions were considered fixed effects while site-year, block (nested within site-year) and interactions of fixed effects with site-year and block were considered random effects. The autoregressive covariance structure was used. The repeated subject was the N treatment by block (nested within site-year) interaction. Significant fixed effects or interactions of fixed effects were compared using means separation at $P \leq 0.05$ with the PDIFF option of the MIXED procedure of SAS.

To determine the response of grain yield to N rate, linear, quadratic, or quadratic-plateau regression models were developed using the REG or NLIN procedures of SAS. Models were selected that produced the largest correlation coefficients and had normally distributed residuals (SAS Institute, 2004, Kutner et al., 2004). The agronomic optimal N rate (AONR) was determined to be the highest applied N rate for linear and quadratic regressions or the point at which the model plateaued for quadratic-plateau regressions. The EONR was determined by setting the first derivative of the regression model to the fertilizer cost to corn price ratio of 0.0056 [\$1.10 kg^{-1} N as fertilizer), \$196.84 Mg^{-1} corn grain] based on a regional N rate guideline (Sawyer et al., 2006).

2.3.6. Nitrogen Use Efficiency Calculations

Agronomic efficiency (AE) was calculated as AE= $(Y_N\text{-}Y_0)$/N rate$_N$ while fertilizer recovery efficiency (FRE) was calculated as FRE= $(T_N\text{-}T_0)$/N rate$_N$ where Y and T represent grain yield and total aboveground N uptake, and the subscript “N” and “0” represent the fertilizer N treatment of interest and the nonfertilized control treatment (Snyder and Bruulsema, 2007).

2.4. RESULTS AND DISCUSSION

2.4.1. Weather Conditions

Monthly average precipitation, air temperatures, and departures from the 30-year average for each site year were described in Chapter 1. Briefly, 2014 was characterized by cool, excessively wet springs receiving on average across site-years 52% of the total annual precipitation from April through June. Theilman14 was the only exception for 2014 where precipitation was more evenly distributed. The wet spring conditions in 2014 likely favored N loss from the pre-plant and starter fertilizer applications. Adverse weather conditions continued in 2014 with drier than normal conditions in July that corresponded with V8 to R1 (Chapter 1; Table 2.1) that represents a critical period when moisture or nutrient deficiency can negatively impact grain yield potential (Abendroth et al., 2011). In contrast, 36% of the total annual precipitation fell in April through June in 2015 and is comparable to the 30-year normal (Chapter 1). In addition, the 2015 growing season had warm spring temperatures that facilitated earlier planting than 2014 followed by evenly distributed rain events throughout the growing season (Chapter 1; Table 2.2). Overall, the 2015 growing season was more favorable for corn production than 2014.

2.4.2. Potential for Volatilization

A 12 mm precipitation event or greater is often sufficient to incorporate surface-applied urea and reduce potential volatilization losses, but smaller precipitation events may increase the volatilization potential (Jones et al., 2013). We used NBPT (urease inhibitor) for SD applications to provide greater time for urea incorporation by rainfall and to minimize volatilization losses. The amount of time until a 12 mm rain event could impact volatilization potential because NBPT effectiveness decreases after one to two weeks (Rawluk et al., 2001; Motavalli et al., 2008; Engel et al., 2011; Silva et al., 2016). For Group 1, there was likely low potential for volatilization loss as a 12 mm precipitation or irrigation event occurred within 7 days of all SD applications (Table 2.1; 2.2). In Group 2, spring rainfall was moderate and well distributed (except Clara City14) and most SD applications were followed by a 12 mm rainfall event within 14 days of fertilizer application except for Clara City14 at V4, Lamberton15 at V8, and Theilman14 at V12 (Table 2.1; 2.2). For these reasons, Group 2 may represent site-years with low to moderate potential for volatilization. For Group 3, the V2 and V4 SD applications received 12 mm of rainfall within 7 days of application (except Lamberton14 at V4) but later applications did not receive a 12 mm rainfall event for over two weeks (except Waseca14a at V6 and Lamberton14 at V8). For these reasons, later fertilizer applications in Group 3 likely had moderate potential for N volatilization. Besides influencing potential volatilization, dry soil moisture conditions following the V6 and later SD timings for 2014 non-irrigated site-years may have limited root exploration, N uptake, and biomass production that likely reduce seed number and weight (Bennett et al., 1989). These results illustrate the challenges associated with predicting yearly weather patterns and timing in-season fertilizer applications to rainfall events of sufficient magnitude to adequately incorporate surface applied urea.

2.4.3. Group 1 – End of Season Metrics

Group 1 had a linear grain yield response to increasing rates of PP fertilizer across all site-years (Yield=0.0201*N rate+2.4945; $P<0.001$; adj. $r^2=0.43$) that is indicative of N loss, especially at the greater N application rates. Within Group 1, the coarse-textured soils at Becker (Yield=0.0207*N rate+1.5351; $P<0.001$; adj. $r^2=0.60$) produced less grain yield than the fine-textured soil at Waseca15b (Yield=0.0261*Nrate+4.7489; $P<0.001$; adj. $r^2=0.78$) at equivalent N rates. This may be due to the greater potential for nitrate-N leaching associated with coarse-textured soils than for fine-textured soils. The split-applied treatments produced 1.5- to 1.9-fold more grain yield than PP and were equivalent to applying a PP N rate of 229 to 313 kg N ha^{-1} (Table 2.3). Rubin et al. (2016) found split-applying N fertilizer was a better N management strategy than a single pre-plant application of polymer coated urea for coarse-textured soils. Split-applying N is advantageous from both a fertilizer cost savings and an environmental protection perspective when early season conditions lead to high N loss potential. This also supports University guidelines that pre-plant N fertilizer should not be applied on coarse-textured soils, except as a small amount as a starter (Lamb et al., 2015). Delaying a split-application until V6 or later increased grain yield by 23% on average compared to SD-V2 and SD-V4 that produced an intermediate response (Table 2.3). Similar responses were observed for AE where the split-applications improved AE 2.1- to 3.0-fold compared to PP and delaying SD application until V6 or later increased AE by 37% on average compared to SD-V2. The FRE and grain N content measurements highlight that the advantage of delaying SD can be significant even at SD-V12 where, compared to the SD-V8 time, SD-V12 improved FRE by 26% and grain N content by 16%. Relative to PP, N concentration in the grain was similar up to SD-V6 and increased by 10% for SD-V8 and 28% for SD-V12 (Table 2.3). The difference in grain N content was the result of both greater grain yield and N concentrations with the late SD applications. Mueller et al. (2017) also reported similar FRE values (68%) for a SD-V12 treatment, and indicated that when precipitation or irrigation is timely, delayed fertilizer applications are likely to improve uptake as the crop's root system is better developed with greater crop N demand than at earlier vegetative stages.

2.4.4. Group 1 – In-Season Corn Nitrogen Uptake and Biomass

The significant time of N application by development stage interaction for corn N uptake (Table 2.4) and biomass (Table 2.5) were explained by increasing values as the growing season progressed but the increase became larger later in the growing season for the later SD treatments (SD-V8 and SD-V12). Further evaluation showed that regardless of time of N application, corn N uptake (Table 2.4) and biomass (Table 2.5) increased as the season progressed. Others have observed similar patterns (Abendroth et al., 2011; Bender et al., 2013). Corn N uptake increased rapidly after the SD application, normally showing similar cumulative uptake to earlier SD treatments by the second sampling after N application (Table 2.4).

Corn biomass also increased rapidly after SD applications (Table 2.5). All SD treatments ultimately produced greater biomass than the PP timing but the later SD applications (SD-V8 and SD-V12) had less biomass (smaller leaves and stalks observed in the field) throughout the growing season. This follows what others have reported (Bennett et al., 1989; Walsh et al., 2012). Because vegetative biomass in general decreased while corn N uptake increased with the later SD fertilizer applications, the rapidly accumulated N was increasingly partitioned into the grain compared to earlier SD timings (Table 2.3) and is consistent with ^{15}N tracer studies (Weiland et al, 1989; Subedi and Ma, 2005). Further, Subedi and Ma, (2005) observed that N supplied right before and during critical growth periods was more likely to influence grain yield than total N availability to the crop throughout the growing season or even the total amount of N taken up by the crop.

2.4.5. Group 1 – In-Season Soil Nitrogen

A significant three-way interaction of time of N application by sampling stage by soil depth for ammonium-N, nitrate-N, and total inorganic N (TIN; ammonium-N plus nitrate-N) gave important insights on N availability throughout the growing season as affected by the different times of N application (Table 2.6, Fig. 2.1). Early in the growing season (V4 and V8) the effect of previous fertilizer timings could be observed in soil ammonium-N and nitrate-N levels at the time of sampling (Fig. 2.1A, B). Later in the season (V12 or later), only the application done two to three weeks before soil sampling (Fig. 2.1) could be detected in the soil test, likely because of rapid crop N uptake (Fig. 2.1C, D, E). As the length of time between split-application and sampling increased, earlier applications had similar TIN levels as the 0 N control at V12, R1, and post-harvest (Fig. 2.1C, D, E, F). At V8 and V12 the PP and SD treatments that had received only 45 kg N ha^{-1} starter fertilizer (SD-V8, SD-V12) had similar soil inorganic N as the 0 N control (Fig. 2.1B, C, F). The rapid decline of inorganic N from these treatments illustrates how lack of synchrony between N supply and crop N demand caused stress that reduced biomass production in all three treatments relative to earlier SD applications, and reduced N uptake and grain yield for PP. Finally, the increase in TIN (especially ammonium-N) in the 0 N control at V8 and at post-harvest are likely indicative of N mineralization (Fig. 2.1F).

At V4 and V8, a large portion of the N was nitrate except for SD-V2 at V4 and SD-V6 at V8. This indicates that fertilizer N nitrified relatively quickly at all growth stages. Nitrate is prone to loss compared to ammonium and can largely influence N availability. At the V8 sampling stage, PP and SD-V2 had greater amounts of nitrate-N in the 30- to 60-cm increment than in the surface layer (Fig. 2.1B). Reduction in N availability was also evident when available N of the 0 N control was subtracted from the 135 kg N ha^{-1} early season treatments. Assuming that N cycling was similar between the fertilized and unfertilized treatments and that N uptake early in the season is low ($\leq$2.1 kg N ha^{-1}) (Table 2.4), we observed only 79 and 72 kg fertilizer-N ha^{-1} for PP and SD-V2 present at V4 (Fig. 2.1A). The importance of retaining N in the ammonium form when nitrate leaching potential is high was illustrated by changes in soil N between V4 and V8 sampling times. For PP, where most N was nitrate at V4, TIN from the fertilizer (accounting for N in the 0 N control) changed from 79 kg N ha^{-1} at V4 to 19 kg N ha^{-1} at V8. Corn uptake during that period was only 15.7 kg N ha^{-1} (Table 2.4) and indicates that 44 kg N ha^{-1} were likely lost or unavailable for the crop. In contrast, for SD-V2, where a substantial amount of N was ammonium-N at V4, TIN from the fertilizer (accounting for N in the 0 N control) changed from 72 kg N ha^{-1} at V4 to 57 kg N ha^{-1} at V8, which is less than total corn N uptake for that period (Table 2.4). At V8, there was a substantial increase in ammonium-N levels at the 30- to 60-cm increment for the SD-V6 application (Fig. 2.1B). This increase may indicate leaching of ammonium-N or dissolved urea into the subsoil before hydrolysis (Figure 1B). Leaching of urea or ammonium-N may be plausible as three of the four site-years in Group 1 had coarse-textured soils with low organic matter (15.6 g kg^{-1}), low cation exchange capacity (4.3 cmol$_c$ kg^{-1}) (Chapter 1), and Becker15b and Waseca15b received 19- and 9-mm of water within two days of fertilization and all site-years received 28- to 79-mm of water on average from V6 to V8 (6 to 9 d) (Table 2.1, 2.2). Our data also show that there can be substantial amounts of ammonium-N in the soil from N fertilization early in the season. Soil nitrate tests, like the pre-SD nitrate test, may not fully quantify N availability. Possibly because of this reason the pre-SD nitrate test has been most successfully used in situations where little or no N has been applied before samples are taken (Bundy and Andraski, 1995).

2.4.6. Group 2 – End of Season Metrics

Group 2 had a quadratic response of grain yield to increasing rates of pre-plant fertilizer across all site-years ($\text{Yield}=-0.00005*\text{Nrate}^2+0.0339*\text{Nrate}+7.1409$; $P<0.001$; adj. $r^2=0.38$; EONR 260 kg N ha^{-1}; AONR 270 kg N ha^{-1}). Yield and AE for split-applied fertilizer treatments were not different between SD-V2, SD-V4, SD-V6, and SD-V8 (11.2 Mg ha^{-1}; 30.8 kg kg^{-1} on average) while PP and SD-V12 had smaller yield and AE at 10.1 Mg ha^{-1} and 22.3 kg kg^{-1} on average (Table 2.3). Similar patterns were observed for R6 biomass (Table 2.5) and corn N uptake (Table 2.4). Grain yield reduction for PP relative to SD-V2, SD-V4, SD-V6, and SD-V8 was likely due to lower soil N availability and corn N uptake during grain fill from R1 to R6 (Fig. 2.2D, E, Table 2.4). In contrast, yield reduction for SD-V12 relative to the earlier SD treatments (V2 to V8) was likely due to N deficiency from V8 to V12 when soil TIN (0- to 60-cm) was similar to the 0 N control (Fig. 2.2B, C, F). Inadequate N availability during the period of V8 to V12 can reduce biomass production (Table 2.5) and may have reduce the potential number of seeds set (Abendroth et al., 2011). Despite receiving SD N at V12, there was not sufficient time prior to reproduction for corn N uptake or biomass accumulation to “catch up” to the earlier SD treatments resulting in a smaller photosynthetic factory for carbohydrate production and grain fill (Table 2.4, 2.5). On fine-textured soils, others have reported no difference in grain yield when all N was delayed until V11 (Scharf et al., 2002) or observed yield losses with delayed SD applications that was attributed to early season N stress (Binder et al., 2000; Walsh et al., 2012). Similar to Group 1, FRE and grain N increased with delayed fertilization, although for FRE it was only a trend (Table 2.3). Fertilizer recovery efficiency was generally less in Group 2 than Group 1 that may indicate that site-years in Group 1 were more dependent on fertilizer N than site-years in

Group 2 where native N supply and mineralization provided a larger portion of crop N needs (Table 2.3).

2.4.7. Group 2 – In-season Corn Nitrogen Uptake, Biomass, and Soil Nitrogen

Group 2 had a significant SD time by sampling stage interaction for corn N uptake (Table 2.4) and biomass (Table 2.5). There was also a significant three-way interaction for nitrate-N and TIN, but only the SD time by sampling stage interaction and depth was significant for ammonium-N (Table 2.5). The overall response of corn N uptake and biomass was similar between Group 2 to Group 1, but the magnitude of N uptake and biomass accumulation was greater in Group 2 with smaller relative differences of uptake or biomass between PP and the SD treatments (Table 2.4, 2.5). As in Group 1, corn N uptake for later applied treatments of Group 2 “caught up” to earlier applied treatments by R6, but unlike Group 1, there was no difference between SD-V2, SD-V6, SD-V8, or SD-V12 at R6 at 164.7 kg N ha^{-1} on average (Table 2.4). Greater grain yield, N uptake, and biomass of Group 2 relative to Group 1 was likely due to greater native N fertility as indicated by 0 N control soil TIN (0- to 60-cm) levels where Group 2 was 40 kg N ha^{-1} greater than Group 1 at the V4 soil sampling and remained greater for the remainder of the growing season (Fig. 2.1F, Fig. 2.2F). Improved retention of starter fertilizer N (SD-V12) was evidenced by soil TIN-N (0- to 60-cm) being greater than the 0 N control until V12 for Group 2 compared to V8 for Group 1 (Fig. 2.1, 2.2). By the V12 sampling, SD-V12 only received 33% of the total fertilizer received in other treatments but accumulated 68 and 80% as much plant N and biomass, respectively as

PP, SD-V2, SD-V4 and SD-V6 on average (Table 2.4, 2.5). These results indicate that starter fertilizer plus soil mineralization supplied sufficient N to meet crop N demands until SD fertilizer was applied between V2 and V8.

Similar to Group 1, fertilizer applications could be observed in subsequent soil nitrate-N, ammonium-N, and TIN tests through V12, but later in the season (R1 or later) only the SD-V12 treatment could be detected at R1 (Fig. 2.2). Unlike Group 1, after receiving the full 135 kg N ha^{-1} rate, fertilized treatments had greater soil TIN values than the 0 N control for the remainder of the growing season. This supports the observation of smaller relative differences in N uptake and grain yield between PP and SD treatments. Similar to Group 1, nitrification of fertilizer was rapid with the majority of TIN as nitrate-N at V4 for all treatments and at V8 for PP, SD-V2, and SD-V4 at both increments (Fig. 2.2). From V12 forward, ammonium-N and nitrate-N each comprised about 50% of TIN.

Despite rapid nitrification, Group 2 improved retention of fertilizer N relative to the coarse-textured soils of Group 1 likely due to the greater water holding capacity associated with loam or finer textured soils. Smaller pores and greater soil surface area restricted the downward movement of nitrate-N dissolved in soil water for improved residence time of fertilizer N in the root zone. The reduction of soil TIN (0- to 60-cm) for the PP treatment was nearly identical to the amount of N taken up by the crop from V4 to V8 to V12 (Table 2.4, Fig. 2.2) contrasting Group 1 where soil N reduction was likely primarily due to leaching. Although there was a trend of increasing residual soil TIN (0- to 60-cm) with delayed N application (Fig. 2.2), cumulative corn N uptake was 4.8 to 33.8 kg N ha^{-1} greater than the applied 135 kg N ha^{-1} rate (Table 2.4).

Assuming mineralization was similar across all treatments, later SD treatments took up additional soil mineralized N while PP and early SD treatments may have had some N losses early in the season when the plants were small. Overall, these results suggest that on fine-textured soils with well-distributed rainfall, a split-application of fertilizer with a small amount applied as starter and the remainder sidedressed from V2 to V8 could potentially minimize N losses and N stress to the crop for high grain yield. These results suggest that growers have a large time-frame in which N fertilizer may be applied with minimal risk of lost grain yield potential or environmental contamination if there are early season conditions that delay fertilizer application.

2.4.8. Group 3 – End of Season Metrics

Group 3 had a quadratic-plateau response of grain yield to increasing rates of pre-plant fertilizer plateauing at 8.9 Mg ha^{-1} (Yield=-0.00008*Nrate^2+0.0381*Nrate+4.3452; $P<0.001$; EONR 203 kg N ha^{-1}, AONR of 238 kg N ha^{-1}). Similar to responses noted by Jaynes (2013) and Venterea and Coulter (2015), there were no differences in grain yield (7.0 Mg ha^{-1}), AE (22.7 kg kg^{-1}), FRE (0.41 kg kg^{-1}), or grain N (77.1 kg N ha^{-1}) regardless of time of N fertilization (Table 2.3). There was a trend of decreasing yield, AE, and FRE when SD was delayed past V4 (Table 2.3) that corresponded to dry conditions at all site-years from V8 to R1 (Table 2.1). Furthermore, the reduced yield of Group 3 treatments relative to Group 2 is similar to results reported by Venterea et al. (2016) for the 2014 growing season.

2.4.9. Group 3 – In-season Corn Nitrogen Uptake and Biomass

The significant SD time by sampling stage interaction for corn N uptake (Table 2.4) and biomass (Table 2.5) was associated with increasing uptake and biomass over time for each treatment. In addition, from V8 to R1 for N uptake and V8 to R6 for biomass, there was a pattern of decreasing values with increasing time until SD application (Table 2.4, 2.5). As previously mentioned, wet conditions with four days of ponded water at Waseca 14a and Waseca 14b in June 2014 followed by minimal rainfall in July 2014 (V8 to R1, 18- to 31-mm) caused water stress that limited soil N accessibility, corn N uptake, and biomass production (Table 2.1). The combination of delayed N application with dry conditions produced the greatest stress on SD-V8 and SD-V12 as biomass was 1.0 and 1.1 Mg ha^{-1} less than SD-PP, SD-V2 and SD-V4 on average at V12 and R1, and 2.6 Mg ha^{-1} less than SD-PP and SD-V4 on average at R6 (Table 2.5). From R1 to R6, corn N uptake increased in all treatments following several precipitation events and SD-V8 and SD-V12 had a faster rate of accumulation of plant N uptake relative to the other treatments although at the end of the season SD-V8 was still 21 kg N ha^{-1} less than PP, SD-V4, and SD-V6 on average (Table 2.4).

2.4.10. Group 3 – In-season Soil Nitrogen

There was a significant three-way interaction for nitrate-N, but only the SD time by sampling stage interaction and main effect of depth was significant for ammonium-N and TIN (Table 2.6). Similar to Groups 1 and 2, PP fertilizer N rapidly nitrified by V4 with greater nitrate-N in the topsoil than subsoil, while treatments that received only starter had similar amounts of nitrate-N and ammonium-N at both increments (Fig. 2.3 A). Dry conditions from V8 to R1 resulted in few differences of soil nitrate-N within treatments and between increments over time likely because the rate of nitrification of fertilizer and soil mineralized N was reduced resulting in ammonium-N accumulation in the topsoil from V8 to R1 (Fig. 2.3 B, C, D). During this same period, soil TIN (0- to 60-cm) reduction was similar to N uptake for all treatments, except SD-V8 from V8 to V12 and SD-V6, SD-V8, and SD-V12 from V12 to R1 where measured soil N fertility increased with later sampling time (Table 2.4, Fig. 2.3). The measured increase in N fertility over time may have been due to dry conditions slowing the rate of urea and ammonium-N dispersion from the prill into soil solution. By the post-harvest soil sampling, most of the soil ammonium-N had either nitrified or was taken up by the crop while SD-V6 and SD-V12 topsoil nitrate-N was 14.2 kg ha^{-1} greater than SD-PP and SD-V4 on average. This can represent increased potential for N loss before the next growing season for later SD applications relative to early applications (Fig. 2.3 F). These results highlight the importance of soil moisture and receiving sufficient rainfall to incorporate surface broadcast SD N. Without adequate rainfall, fertilizer N remained at the soil surface and was largely unavailable to the crop roots. Crop uptake of soil water and N in the soil solution was reduced, clearly showing that yearly precipitation patterns significantly impact the effectiveness of SD applications for rain-fed corn on fine-textured soils.

2.5. CONCLUSIONS

There is great interest in improving synchrony of inorganic N to corn demand by split-applying fertilizer N. Our research shows that the efficacy of split-fertilizer applications for improved grain yield is strongly dependent on seasonal weather patterns and soil texture. Site-years with well-distributed rainfall or irrigation following fertilizer application and throughout the growing season improve grain yield of split-applications over PP. For irrigated coarse-textured soils, split-applications from V4 to V12 are likely to improve grain yield relative to PP because of greater corn N uptake and N partitioning to the grain. Split-applications also represent a significant reduction in N rate and improved FRE over PP that may represent cost savings and environmental protection from N losses. On fine-textured soils, growing season conditions have an important role in determining success with timing of N application. When adequate precipitation is available, early split-applications (V2 to V8 SD) are likely to produce the greatest grain yield, corn N uptake, FRE, and grain N, but delaying SD beyond V8 may reduce total aboveground corn N uptake and grain yield. When precipitation is not well-distributed or timely following SD applications, there is no improvement of grain yield or efficiencies over a single PP application. With dry summer conditions, SD fertilizer N will accumulate in the surface layer as ammonium-N. Given that soil testing labs primarily test for nitrate-N, under dry conditions it would be important that farmers test their soils for ammonium-N in addition to nitrate-N to avoid underestimating soil N availability.

Table 2.1 Day of the year (DOY), cumulative growing degree days (GDD), cumulative precipitation (C-P) since pre-plant soil sampling, and days until a 12 mm precipitation event occurred following fertilization at all 2014 site-years.

	Becker14†			Clara City14‡			Lamberton14§			Theilman14‡			Waseca14a§			Waseca14b§		
	DOY	GDD¶	C-P	DOY	GDD	C-P	DOY	GDD	C-P	DOY	GDD	C-P	DOY	GDD	C-P	DOY	GDD	C-P
PP-S#	123	0	0	141	0	0	146	0	0	140	0	0	124	0	0	124	0	0
Plant	132	0	151	148	0	2	147	0	0	140	0	0	129	0	15	141	0	64
PP-N	139	32	177‡‡	146	0	4‡‡	146	0	0‡‡	140	0	0§§	125	0	4‡‡	140	0	64§§
StartN	140	38	183‡‡	152	45	50††	147	0	0††	146	36	4‡‡	133	13	54¶¶	141	0	64§§
V2	155	179	306††	159	96	96‡‡	165	163	148††	155	135	25§§	152	166	159‡‡	158	108	181‡‡
V4	161	221	335††	172	227	248¶¶	176	293	187¶¶	162	190	25††	160	234	187‡‡	175	284	383††
V6	172	326	424‡‡	179	310	248§§	181	349	188¶¶	172	301	155‡‡	172	357	383‡‡	179	336	400¶¶
V8	180	408	452††	189	416	249††	194	487	199§§	188	473	210††	179	443	400¶¶	186	403	408¶¶
V12	193	532	528††	208	612	274§§	207	629	217¶¶	196	543	225¶¶	197	611	419¶¶	200	542	419¶¶
R1	202	625	579	215	680	274	214	699	217	214	747	239	210	756	431	215	707	439
R6	259	1136	952	286	1207	501	280	1239	470	277	1273	487	271	1325	570	271	1218	570
H	284	1242	969	294	1239	509	289	1267	475	287	1299	510	292	1378	604	292	1270	604
PH-S	306	1296	973	309	1261	520	309	1323	479	298	1334	519	NA	NA	NA	459	1371	725

† Denotes site-years included in Group 1 depending on soil texture and response of grain yield to time of N application.

‡ Denotes site-years included in Group 2 depending on soil texture and response of grain yield to time of N application.

§ Denotes site-years included in Group 3 depending on soil texture and response of grain yield to time of N application.

¶ GDD calculated as daily max temperature (Tmax) plus daily min temperature (Tmin) all divided by 2 and all subtracted by 10. If Tmax >30 °C, then it was set to 30 °C and if Tmax or Tmin <10 °C, it was set to 10 °C.

PP-S, pre-plant soil sampling; PP-N, pre-plant N fertilizer application; StartN, starter fertilizer N application; V, vegetative development stage; H, Harvest; PH Soil, post-harvest soil sampling.

†† Site-year received a 12 mm precipitation or irrigation event within 3 d following fertilizer application.

‡‡ Site-year received a 12 mm precipitation or irrigation event within 7 d following fertilizer application.

§§ Site-year received a 12 mm precipitation or irrigation event within 14 d following fertilizer application.

¶¶ Site-year received a 12 mm precipitation or irrigation event greater than 14 d following fertilizer application.

Table 2.2 Day of the year (DOY), cumulative growing degree days (GDD), cumulative precipitation (C-P) since pre-plant soil sampling, and days until a 12 mm precipitation event occurred following fertilization at all 2015 field-sites.

	Becker15a†			Becker15b†			Clara City15‡			Lamberton15 ‡			Waseca15a‡			Waseca15b†		
	DOY	GDD§	C-P	DOY	GDD	C-P	DOY	GDD	C-P	DOY	GDD	C-P	DOY	GDD	C-P	DOY	GDD	C-P
PP-S¶	91	0	0	88	0	0	102	0	0	122	0	2	95	0	0	110	0	10
Plant	115	0	45	115	0	45	123	0	19	139	0	71	118	0	61	123	0	30
PP-N	109	0	37§§	109	0	37§§	105	0	0§§	139	0	71‡‡	116	0	61§§	123	0	30‡‡
StartN	119	18	46††	119	18	46††	123	0	19#	145	66	88#	118	0	61§§	123	0	30‡‡
V2	137	107	162††	137	107	162††	139	61	185‡‡	157	181	172‡‡	138	99	128††	145	108	121#
V4	150	183	207#	150	183	207#	158	209	233‡‡	164	279	185††	154	209	187#	159	233	200#
V6	162	288	243††	162	288	243††	164	269	235††	175	413	264††	167	344	294#	167	310	254#
V8	172	378	294#	172	378	294#	173	353	266‡‡	188	563	302§§	175	433	357#	174	386	318††
V12	195	614	492#	195	614	492#	194	584	336#	199	675	307††	193	621	428††	192	572	388††
R1	213	824	642	213	824	642	206	727	408	217	859	367	210	832	563	202	694	403
R6	251	1202	830	251	1202	830	272	1366	544	266	1158	564	263	1371	861	263	1336	821
H	284	1408	857	284	1408	857	277	1385	544	285	1205	565	283	1512	866	280	1457	826
PH-S	290	1428	857	291	1428	857	298	1471	586	305	1206	606	293	1552	866	292	1514	826

† Denotes site-years included in Group 1 depending on soil texture and response of grain yield to time of nitrogen application.

‡ Denotes site-years included in Group 2 depending on soil texture and response of grain yield to time of nitrogen application.

§ GDD calculated as daily max temperature (Tmax) plus daily min temperature (Tmin) all divided by 2 and all subtracted by 10. If Tmax >30 °C, then it was set to 30 °C and if Tmax or Tmin <10 °C, it was set to 10 °C.

¶ PP-S, pre-plant soil sampling; PP-N, pre-plant N fertilizer application; StartN, starter fertilizer N application; V, vegetative development stage; H, Harvest; PH Soil, post-harvest soil sampling.

Site-year received a 12 mm precipitation or irrigation event within 3 d following fertilizer application.

†† Site-year received a 12 mm precipitation or irrigation event within 7 d following fertilizer application.

‡‡ Site-year received a 12 mm precipitation or irrigation event within 14 d following fertilizer application.

§§ Site-year received a 12 mm precipitation or irrigation event greater than 14 d following fertilizer application.

Table 2.3. Average values of various dependent variables in response to time of fertilizer N application. Groups consist of the following site-years: Group 1 (Becker14, Becker15a, Becker15b, and Waseca15b); Group 2 (Clara City14, Clara City15, Lamberton15, Theilman14, and Waseca15a); and Group 3 (Lamberton14, Waseca14a, Waseca14b).

Treatment†	Grain Yield	AE‡	FRE§	Grain N
	Mg ha^{-1}	kg kg^{-1}		kg ha^{-1}
Group 1				
PP	4.7 (0.8)¶ c#	15.4 (2.5) c	0.23 (0.05) c	41.4 (9.7) d
SD-V2	7.1 (0.9) b	33.0 (3.4) b	0.37 (0.07) bc	65.0 (9.7) c
SD-V4	8.1 (0.8) ab	40.8 (2.6) ab	0.50 (0.05) b	72.7 (9.7) c
SD-V6	8.6 (0.8) a	44.2 (2.5) a	0.46 (0.05) b	75.7 (9.7) bc
SD-V8	8.8 (0.8) a	45.3 (2.5) a	0.50 (0.05) b	85.3 (9.7) b
SD-V12	8.8 (0.8) a	45.8 (2.5) a	0.63 (0.05) a	99.2 (9.7) a
P Value	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Group 2				
PP	10.0 (0.8) b	21.3 (6.6) b	0.26 (0.09) a	98.9 (11.1) b
SD-V2	11.2 (0.8) a	31.4 (6.6) a	0.43 (0.09) a	113.5 (11.1) a
SD-V4	10.8 (0.8) ab	27.9 (6.6) ab	0.33 (0.09) a	115.5 (11.1) a
SD-V6	11.2 (0.8) a	31.1 (6.6) ab	0.44 (0.09) a	116.8 (11.1) a
SD-V8	11.5 (0.8) a	32.6 (6.6) a	0.46 (0.09) a	118.9 (11.1) a
SD-V12	10.2 (0.8) b	23.2 (6.6) b	0.49 (0.09) a	122.1 (11.1) a
P Value	*0.017*	*0.019*	*0.059*	*0.030*
Group 3				
PP	7.5 (0.8) a	26.8 (3.7) a	0.49 (0.06) a	77.5 (11.2) a
SD-V2	7.4 (0.8) a	25.7 (3.7) a	0.37 (0.06) a	78.1 (11.2) a
SD-V4	7.5 (0.8) a	26.5 (3.7) a	0.48 (0.06) a	82.8 (11.2) a
SD-V6	6.9 (0.8) a	21.9 (3.7) a	0.46 (0.06) a	78.5 (11.2) a
SD-V8	6.5 (0.8) a	17.2 (3.7) a	0.29 (0.06) a	70.1 (11.2) a
SD-V12	6.5 (0.8) a	17.9 (3.7) a	0.38 (0.06) a	75.8 (11.2) a
P Value	*0.088*	*0.112*	*0.273*	*0.542*

† PP, pre-plant urea; SD, sidedress; V, vegetative stage.

‡ AE, agronomic efficiency calculated as the grain yield difference between the time of fertilization treatment and 0 N control divided by the applied nitrogen rate.

§ FRE, fertilizer recovery efficiency calculated as the corn nitrogen uptake difference between the time of fertilization treatment and 0 N control divided by the applied nitrogen rate.

¶ Standard error within parenthesis

Within Group and agronomic variable, means followed by the same letter are not significantly different at $P = 0.05$.

Table 2.4. Above ground corn N uptake as affected by time of fertilizer N application (Time) and corn development stage (Stage). Groups consist of the following site-years: Group 1 (Becker14, Becker15a, Becker15b, and Waseca15b); Group 2 (Clara City14, Clara City15, Lamberton15, Theilman14, and Waseca15a); and Group 3 (Lamberton14, Waseca14a, Waseca14b).

	V4	V8	V12	R1	R6
			Group 1		
			kg N ha^{-1}		
PP†	1.7aC‡	17.4abcC	42.9cB	45.2cB	86.7dA
SD-V2	2.1aD	28.6abC	77.6abB	88.0aAB	106.2cA
SD-V4	1.6aD	30.1aC	78.8aB	89.4aB	122.9bA
SD-V6	1.8aD	16.2bcD	72.5abC	94.4aB	118.4bcA
SD-V8	1.6aD	9.8cD	61.1bC	81.5aB	123.1bA
SD-V12	1.8aD	11.2cCD	26.2dC	65.9bB	141.6aA
			Group 2		
			kg N ha^{-1}		
PP	4.7aD	47.4abC	84.7abB	105.9aB	139.8cA
SD-V2	4.3aD	47.8aC	92.6aB	106.8aB	158.5abA
SD-V4	3.8aD	46.1abC	89.2abB	108.8aB	154.4bA
SD-V6	3.6aE	41.9abcD	86.5abC	111.1aB	164.0abA
SD-V8	3.8aE	34.9bcD	78.9bC	104.9aB	167.3aA
SD-V12	3.1aD	33.2cC	60.3cB	81.3bB	168.8aA
			Group 3		
			kg N ha^{-1}		
PP	7.4aD	40.2aC	74.5aB	89.3aB	135.7aA
SD-V2	6.5aD	33.8abC	64.6abB	81.8abB	123.9abA
SD-V4	5.6aE	31.5abD	69.0aC	92.3aB	139.1aA
SD-V6	5.9aE	29.1abD	55.7bcC	85.9aB	132.1aA
SD-V8	6.0aE	25.5bD	51.0cdC	71.0bcB	114.6bA
SD-V12	5.5aC	22.8bC	41.8dBC	58.3cB	127.7abA

	Test of fixed effects		
	Group 1	Group 2	Group 3
Source of variation		$P > F$	
Time (T)	<0.001	0.042	<0.001
Stage (S)	<0.001	<0.001	<0.001
T × S	<0.001	<0.001	0.008

† PP, pre-plant urea; SD, sidedress; V, vegetative development stage.

‡ Within Group, means within a row followed by the same upper-case letter are not different while means within a column followed by the same lower-case letter are not different at $P = 0.05$.

Table 2.5. Vegetative biomass as affected by time of fertilizer N application (Time) and corn development stages (Stage). Groups consist of the following site-years: Group 1 (Becker14, Becker15a, Becker15b, and Waseca15b); Group 2 (Clara City14, Clara City15, Lamberton15, Theilman14, and Waseca15a); and Group 3 (Lamberton14, Waseca14a, Waseca14b).

	V4	V8	V12	R1	R6
			Group 1		
			Mg ha^{-1}		
PP†	0.04aC	0.7aC	3.6bcB	5.5bcB	12.8dA
SD-V2	0.05aD	0.9aD	4.8abC	8.2aB	15.6bcA
SD-V4	0.05aD	0.9aD	5.4aC	9.2aB	17.7aA
SD-V6	0.05aD	0.6aD	4.3bcC	8.4aB	16.8abA
SD-V8	0.04aD	0.5aD	3.2cdC	6.6bB	15.7bcA
SD-V12	0.05aD	0.6aCD	2.4dC	4.5cB	14.8cA
			Group 2		
			Mg ha^{-1}		
PP	0.1aE	1.8aD	5.0abC	9.1abB	18.6cA
SD-V2	0.1aE	1.8aD	5.4aC	9.5aB	19.8abA
SD-V4	0.1aD	1.7aD	5.2aC	9.0abB	19.0abcA
SD-V6	0.1aD	1.5aD	4.8abC	8.7abB	19.8abA
SD-V8	0.1aD	1.6aD	4.4abC	8.2bB	19.9aA
SD-V12	0.1aD	1.5aD	4.1bC	7.1cB	18.8bcA
			Group 3		
			Mg ha^{-1}		
PP	0.2aD	1.6aD	4.4aC	6.9aB	17.2aA
SD-V2	0.2aD	1.5aD	4.1aC	6.8aB	15.6bA
SD-V4	0.2aD	1.3aD	4.0abC	6.9aB	17.0aA
SD-V6	0.2aD	1.3aD	3.4bcC	6.3abB	16.0bA
SD-V8	0.2aD	1.2aD	3.3cC	5.9bB	14.5cA
SD-V12	0.2aD	1.1aD	3.1cC	5.7bB	14.5cA

Test of fixed effects

	Group 1	Group 2	Group 3
Source of variation		$P > F$	
Stage (S)	<0.001	0.104	<0.001
Time (T)	<0.001	<0.001	<0.001
S × T	<0.001	0.015	<0.001

† SD, sidedress; V, vegetative stage; PP, pre-plant urea.

‡ Within Group, means within a row followed by the same upper-case letter are not different while means within a column followed by the same lower-case letter are not different at $P = 0.05$.

Table 2.6. Test of fixed effects for soil NO$_3$-N, NH4-N, and total inorganic N for Groups 1, 2, and 3. Groups consist of the following site-years: Group 1 (Becker14, Becker15a, Becker15b, and Waseca15b); Group 2 (Clara City14, Clara City15, Lamberton15, Theilman14, and Waseca15a); and Group 3 (Lamberton14, Waseca14a, Waseca14b).

	Group 1			Group 2			Group 3		
					P > *F*				
Source of variation	NO$_3$-N	NH$_4$-N	TIN	NO$_3$-N	NH$_4$-N	TIN	NO$_3$-N	NH$_4$-N	TIN
Stage (S)	0.108	0.082	0.068	0.476	0.141	0.069	0.042	0.120	0.028
Time (T)	<0.001	0.066	<0.001	<0.001	0.381	<0.001	0.013	0.006	0.011
Depth (D)	0.003	0.032	0.009	0.001	0.045	0.001	0.002	<0.001	<0.001
S × T	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.015	0.001
S × D	0.156	0.264	0.118	0.204	0.375	0.028	0.043	0.389	0.347
T × D	0.003	0.153	0.029	0.264	0.202	0.183	0.247	0.269	0.732
S × T × D	<0.001	0.001	<0.001	<0.001	0.365	<0.001	0.001	0.164	0.093

Fig. 2.1. Group 1 soil NO_3-N and NH_4-N at the 0- to 30- and 30- to 60-cm increments for time of fertilizer application treatments at each sampling stage (panels A-E). Total inorganic N values (0- to 60-cm) are also presented where treatments with the same lower-case letters within a panel are not significantly different ($P = 0.05$), while uppercase letters for the same treatment between panels are not significantly different. Treatments to the right of the dashed vertical dashed line had only received the starter fertilizer by time of sampling. Panel F presents soil NO_3-N and NH_4-N at the 0- to 30- and 0- to 60-cm increments over time for the unfertilized check plot. Values for total inorganic N (0- to 60-cm) with the same uppercase letters are not significantly different ($P = 0.05$).

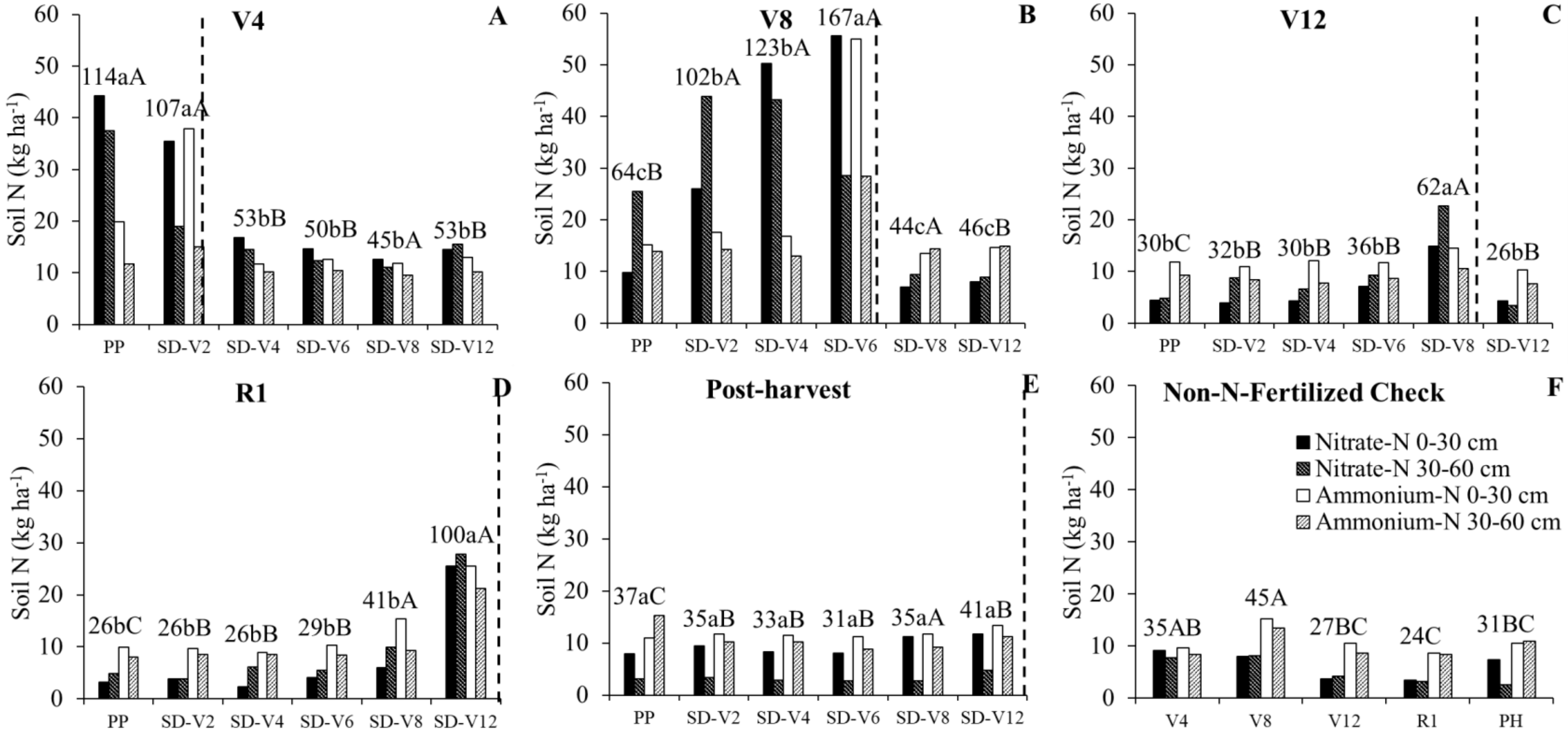


Fig. 2.2. Group 2 soil NO_3-N and NH_4-N at the 0- to 30- and 30- to 60-cm increments for time of fertilizer application treatments at each sampling stage (panels A-E). Total inorganic N values (0- to 60-cm) are also presented where treatments with the same lowercase letters within a panel are not significantly different (P = 0.05), while uppercase letters for the same treatment between panels are not significantly different. Treatments to the right of the dashed vertical dashed line had only received the starter fertilizer by time of sampling. Panel F presents soil NO_3-N and NH_4-N at the 0- to 30- and 0- to 60-cm increments over time for the unfertilized check plot. Values for total inorganic N (0- to 60-cm) with the same uppercase letters are not significantly different (P = 0.05).

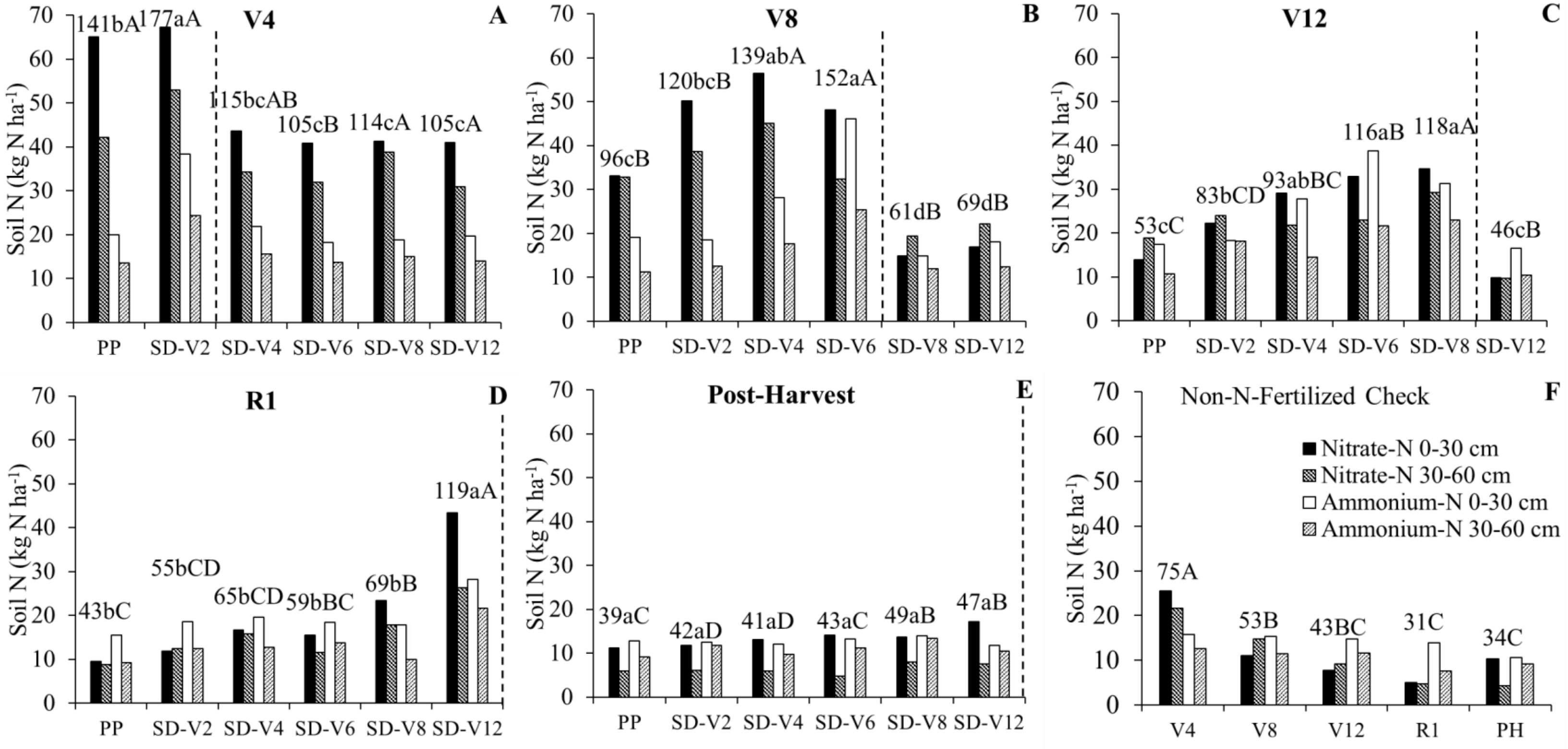
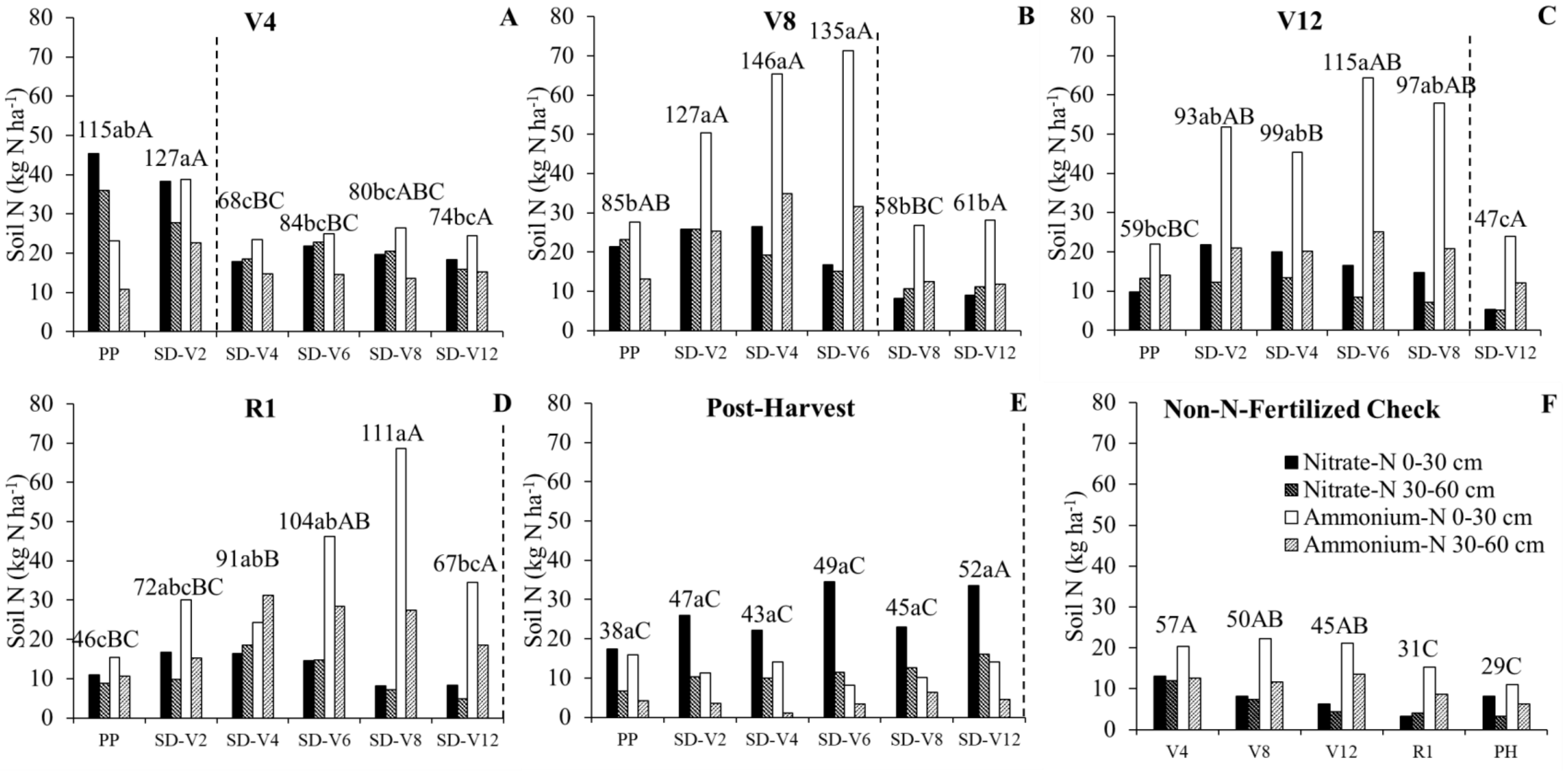


Fig. 2.3. Group 3 soil NO_3-N and NH_4-N at the 0- to 30- and 30- to 60-cm increments for time of fertilizer application treatments at each sampling stage (panels A-E). Total inorganic N values (0- to 60-cm) are also presented where treatments with the same lowercase letters within a panel are not significantly different (*P* = 0.05), while uppercase letters for the same treatment between panels are not significantly different. Treatments to the right of the dashed vertical dashed line had only received the starter fertilizer by time of sampling. Panel F presents soil NO_3-N and NH_4-N at the 0- to 30- and 0- to 60-cm increments over time for the unfertilized check plot. Values for total inorganic N (0- to 60-cm) with the same uppercase letters are not significantly different (*P* = 0.05).



CHAPTER 3: CONCLUSION

Selecting the best N fertilizer management practice is a significant challenge because soil texture and weather conditions strongly influence N availability to the crop. These studies were designed to improve our understanding of how N fertilizer rate, source, and time of application affect corn grain yield and soil N availability and how the effects change with different soil textures and weather patterns. These studies also allowed us to examine the utility of in-season soil testing for grain yield prediction and in-season fertilizer recommendations.

Regardless of soil texture, urea fertilizer was rapidly nitrified at all times throughout the growing season when soil conditions were moist. This is important because nitrate-N is susceptible to leaching and denitrification that can reduce N availability to corn. Dry soil conditions reduced nitrification and allowed for ammonium-N build up in the surface layer of the soil. Under these conditions, soil fertility analyses should test for both nitrate-N and ammonium-N to avoid underestimating N availability.

Soil texture had a significant role in determining N availability to the growing corn crop and influencing N retention in the top 60 cm of the soil profile. The coarse-textured soils we examined have low soil organic matter and low water holding capacity relative to the fine-textured soils. For pre-plant urea applications, soil N availability declined more rapidly on coarse-textured soils than for fine-textured soils limiting corn N uptake and grain yield. This illustrates the importance of not applying full N rates of pre-plant urea on coarse-textured soils. Split-applications or fertilizer sources that inhibit nitrification (AA and AAI) or slowly release urea to the soil (PCU or PCU-U blends) improve synchrony of N availability to the growing crop for greater yield and NUE.

Fine-textured soils had greater soil N levels throughout the growing season and greater yield in the non-fertilized checks than coarse-textured soils. This is likely due to greater mineralization of soil organic matter and slower downward movement of water through the soil profile. Weather patterns strongly influenced the response of N availability and yield to our N management practices on fine-textured soils. When spring conditions are wetter than normal, PCU-U blends provide a balance of immediately accessible N and later-season N that reduce potential for N losses and improved grain yield. However, under normal conditions with low N loss potential, there is not likely to be differences between pre-plant urea and other N sources. Likewise, under normal conditions, split-fertilizer applications can be done anytime from V2 to V8 with similar yield and NUE as pre-plant. However, droughty conditions, especially later in the season (V12) can reduce the efficacy of split-applications and can compound water and N stress for reduced yield.

The MALCC successfully correlated relative yield with STV to estimate a CSTV range for nitrate-N, ammonium-N, and TIN. When fertilizer is pre-plant applied, the MALCC produced similar CSTVs as commonly reported for the pre-sidedress nitrate test. Like the pre-sidedress nitrate test, the MALCC had limited utility for coarse-textured soils or sites that were not responsive to N. Twelve site-years is a limited data set to validate the MALCC model. Additional site-years should be included to strengthen our confidence in the methodology and in the MALCC's ability to estimate the CSTV and provide an in-season fertilizer recommendation. Future work should combine additional data sets from the Midwest considering crop rotation, soil texture, seasonal weather patterns, N source, and field management practices to estimate regional CSTVs. These CSTVs and in-season fertilizer recommendations should then be verified using field studies that may be concurrently used to test the ability of remote sensing algorithms to estimate in-season fertilizer recommendations.

One of the strengths of this study is that the same methodology was maintained across all 12 site-years of differing soils and weather patterns. While the literature reports improvement, no change, or reduction of yield and NUE for the same N management practice, we were able to clearly document which conditions produced these variable responses. However, because we used the same methodology for all site-years, coarse-textured soils received full rates of pre-plant urea that is not a best management practice.

One shortcoming of this study is that we did not quantify soil N additions from mineralization or losses due to immobilization, volatilization, leaching, or denitrification. We could only generalize the fate of fertilizer N. In a future study, lysimeters could be used to quantify nitrate-N leaching losses below the root zone. In-situ ammonia volatilization acid traps deployed during the two weeks following fertilizer application can quantify volatilization losses. Volatilization traps would be especially effective for side-dressed applications on rain-fed systems. Further, partitioning the 0- to 30-cm layer into two layers (0- to 15-cm and 15- to 30-cm) may provide greater resolution of N transformations and dispersion, especially as the majority of the applications were applied to the soil surface or incorporated within the top 5-cm of the soil.

Although we did not quantify N lost from the soil system, this study housed a smaller ^{15}N tracer microplot study that is not part of this thesis. The ^{15}N tracer study will be used to track enriched fertilizer N as it transforms from ammonium-N to nitrate-N, moves through the soil profile, and is taken up by the crop over two growing seasons. This study will improve our understanding of the fate of fertilizer N and help us quantify how much of the N taken up by corn is derived from the fertilizer or soil N pool.

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