Influence of Nitrogen Rate on Corn Grain Yield, Nitrogen Use Efficiency, and Nitrate Leaching on Coarse-Textured Minnesota Soils

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Abstract

Nitrogen (N) is often the limiting nutrient in irrigated sandy soils. Nitrogen poses a threat to water quality in its nitrate form because it is easily leached through the root zone of the corn (*Zea Mays* L.) crop following rain and irrigation events. Leaching is enhanced in sandy soil conditions because sandy soils are particularly well drained. In this study, N was broadcast applied as urea on fields planted with corn at eight rates from 0 kg ha^{-1} to 314 kg ha^{-1} in 45 kg ha^{-1} increments. Urea was applied as a split application with half at planting and half at the V4 growth stage. The study was conducted at four locations, each containing four replications in a randomized complete block. In addition to urea treatments, two coated urea products, Environmentally Smart Nitrogen and SuperUrea, were applied as a single at planting application. Nitrogen uptake, leaf chlorophyll, normalized difference vegetation index (NDVI), grain yield, grain N, nitrogen use efficiency (NUE), basal stalk nitrate (BSN), and residual soil nitrate-N (RSN) were evaluated with respect to N rate. Nitrate-N leaching was monitored with suction tube lysimeters at three of four locations. Results showed an increase in leaf chlorophyll, N uptake, grain yield, grain N, and basal stalk nitrate-N with increased N rate. Normalized difference vegetation index was not affected by N rate for most locations and sampling times. Residual soil nitrate-N and nitrate-N in the leachate tended to be least for the control, but their relationship with applied N rate was not significant because of variability in the data. Nitrate concentration in the leachate was affected by the day of the year at all three locations in which it was evaluated. Coated urea products generally did not increase NDVI, N uptake, NUE, grain yield, or grain N in comparison with split-applied urea at identical N rates. Results for coated urea products were similar to those of untreated urea, despite being applied only at preplant and not as a split application.

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1.0 Introduction

1.1 Justification

Minnesota has approximately 202,500 hectares of irrigated sandy soils. These soils were formed from glacial outwash, and are characterized by their coarse texture and high infiltration capacity. At least half of these hectares are in corn production each year. Nitrogen is of great importance for corn grown on these soils because it is often the most limiting nutrient, and because N management has an impact on water quality. Nitrate contamination of groundwater is widespread, and a substantial portion of the population in the Corn Belt depends on ground water for its drinking water supply (Gehl et al., 2005). Nitrate in drinking water is a health concern because the compound's potential harmful effects on humans. The drinking water standard for water nitrate concentration is 10 parts per million (US EPA, 2012). Infants who ingest water containing nitrate levels above the drinking water standard may suffer shortness of breath and methemoglobinemia, which can be fatal (US EPA, 2012). To ensure a safe drinking water supply, best management practices including applying N fertilizer at responsible rates should be identified and followed (Klocke et al., 1999).

Because sandy soils have high infiltration rates and low water holding capacities, corn grown on this soil type is commonly irrigated. Supplemental irrigation has potential to greatly increase corn grain yield (Wienhold et al., 1995), but also has the potential to move nitrate-N though the soil profile and below the rooting zone (Smika et al., 1977). Once nitrate-N is moved below the rooting zone, it cannot be taken up by the crop before it enters the groundwater. In Minnesota, sandy soils can be highly productive, but large N inputs are necessary to maximize grain yield. The combination of irrigation, N inputs, and high leaching potential makes productive sandy soils a concern for water quality.

In addition to concerns over water quality, N is of notable interest in corn production systems because of the relatively high cost of fertilizer and of the nutrient's potential for yield increases. The goal of N applications should be to achieve high N use efficiency (NUE), avoid over-application of N, and attain high grain yield. Determining fate of applied N, NUE, and grain yield at various N rates in irrigated sandy soils planted with corn is a direct means of assessing those N rates for their impacts on agricultural output and on water quality.

1.2 Literature Review

1.2.1 Nitrate Leaching in Sandy Soils

Nitrogen has been well researched because of its importance in the life cycle of all plants and because it is commonly the most limiting nutrient in corn production systems. On well-drained sandy soils, soil nitrate-N derived from inorganic fertilizer-N is more easily leached through the soil profile in comparison with heavier-textured soils (Derby et al., 2009). A rainfall event of 25 mm can move nitrate 64 mm down the soil profile in sandy soils (Nelson and Huber, 2001). Nitrate-N concentrations in water leached below the roots of a corn crop have been well above the drinking water standard of 10 mg kg^{-1} when recommended N rates are applied (Klocke et al., 1999; Andraski et al., 2000; Zue and Fox, 2003; Gehl et al., 2005; Derby et al., 2009). Irrigation also increases the risk for nitrate leaching, especially if irrigation water is applied in excess of evapotranspiration, or if irrigation water is applied prior to a significant rainfall event. Water added to the soil by irrigation contributes to leaching because the increase in soil moisture raises hydraulic conductivity, thereby increasing drainage through the soil profile (Gehl et al., 2005).

The quantity of nitrate-N that moves below the root zone is proportional to the nitrate-N concentration in the soil solution and the quantity of water moving through the soil (Smika et al., 1977). Quantifying the amount of nitrate-N lost in the leachate presents challenges. Water nitrate concentrations in suction tube lysimeters often have high variability. The heterogeneity of soil properties even within the same area of a field results in varying solute concentrations (Weihermuller et al., 2007). In addition, lysimeters used in quantifying water infiltration rates may not accurately represent how much water is truly moving through the soil profile because of limitations involved with disturbing the soil during their installation (Weihermuller et al., 2007). Nevertheless, suction tube lysimeters have been used with much success in determining nitrate-N concentrations in leachate. In sandy loam and loamy sand, the concentration of nitrate-N in leachate collected by suction cups was similar for leachate collected from monolith lysimeters, and measurements of the amount of nitrate-N leached were the same with both sampling devices (Webster et al., 1993).

Because the amount of water moving through the soil profile directly influences the quantity of nitrate-N lost through leaching, a reduction in leachate volume will decrease nitrate-N leaching losses. The mean quantity of water moved past the root zone was found to range from 53 mm yr^{-1} to 42 mm yr^{-1} for corn and soybean (*Glycine* max), respectively (Zhu and Fox, 2003). In central Kansas, the quantity of nitrate-N leached was calculated using weekly leachate concentration sampling data. During the growing season, the amount of nitrate-N leached was greater with an irrigation rate of 1.25 times the optimal water rate in comparison with the optimal water rate at every sampling in which the lysimeters contained water (Gehl et al., 2005). Results showed nearly a ten-fold increase in leachate volume in sandy soil from a 25% increase in irrigation. These studies show the potential of water management to impact leaching amounts.

In a long-term study by Derby et al. (2009), nitrate-N lost through leaching was greater than 100 kg ha^{-1} in 6 of 25 site years in corn. Under soybean, losses greater than 100 kg nitrate-N ha^{-1} occurred in one of three site years. The site was located in North Dakota and featured a loamy fine sand under supplemental irrigation. Smika et al. (1977) applied 224 kg N ha^{-1} and reported a mean leaching loss from two separate irrigation treatments of 74 kg nitrate-N ha^{-1} on an irrigated sandy soil in Colorado. Generally, nitrate-N leaching losses are greater with increased N application rates. A significant increase in nitrate-N leaching was observed in August and September samplings as applied N rates increased from 250 to 300 kg ha^{-1} (Gehl et al., 2005). Comparison between a 185 kg N ha^{-1} split application and a 250 kg N ha^{-1} single application showed a significant increase in nitrate-N leaching with the 250 kg N ha^{-1} N rate during July and early August. In a continuous corn system on a silt loam, Andraski et al. (2000) found a mean nitrate-N loss of 55 kg ha^{-1} over two years when N was applied at 204 kg ha^{-1}. The results from these studies show variability in the quantity of nitrate-N leached, but also provide confirmation that a significant portion of applied N can be leached from a field in the same year it is applied.

It is commonly believed that rotating soybean with corn will enhance water quality by reducing nitrate leaching. Field studies do not find agreement on the impact of a corn-soybean rotation on nitrate-N leaching. Klocke et al. (1999) evaluated nitrate-N leaching for continuous corn and corn-soybean rotations. The continuous corn rotation was found to result in an annual average leaching loss of 52 kg nitrate-N ha^{-1} over six growing seasons. The corn-soybean rotation averaged a loss of 91 kg nitrate-N ha^{-1} over the same period. One reason for the increased loss with soybean in the rotation is that N credits for soybean were likely underestimated. This resulted in over-application of N fertilizer to corn following soybean years, which caused greater nitrate-N concentrations in the leachate.

One study found nitrate-N leaching totals to be the least for a continuous corn system in comparison to a second year of corn following three years of alfalfa, with mean leaching totals of 20 and 34 kg nitrate-N ha^{-1}, respectively (Andraski et al., 2000). Owens et al. (1995) concluded that a corn-soybean rotation would reduce nitrate-N leaching compared to a continuous corn rotation based on results from corn-influenced years and soybean-influenced years. Corn was fertilized at a rate of 224 kg N ha^{-1} and soybean received no N fertilizer. Crops planted in the spring were assumed to influence the leachate for a one year period spanning from August of the year they were planted to July of the following year. Most of the nitrate-N found in the leachate was applied in the previous growing season because of the high clay content of the soil and the timing of rainfall (Owens et al., 1995).

Another factor to consider when evaluating the impact of including soybean in a rotation is that it will often result in elevated residual soil nitrate-N and therefore elevated leaching potential for the following year compared to a continuous corn system with moderate or low N rates (Zhu and Fox, 2003). Fields planted in corn following soybean will generally have greater leaching totals than fields planted in soybean if high N rates are applied to the corn crop and N credits for soybeans as the previous crop are not used or are too small.

High N rates usually result in a greater percentage of the N lost through nitrate leaching. Zhu and Fox (2003) reported that the portion of applied N leached as nitrate increased from 22 to 55% when N rate was increased from 100 to 200 kg ha^{-1}. The study found a significant increase in the amount of nitrate-N leached per year with soybeans in comparison to corn when the corn was not fertilized with N. At either the 100 or 200 kg N ha^{-1} rates applied to corn, there was no difference in the quantity of nitrate-N leached between corn and soybean years (Zhu and Fox, 2003). In addition to adjustments in N rate, fertilizer additives may influence leaching. Owens et al. (1995) reported mean nitrate-N leachate concentrations of 22.0 and 28.6 mg L^{-1} from N-fertilized corn plots with and without a nitrification inhibitor, respectively. The effects of rotation and N fertilizer product on nitrate-N leaching are not as clear as the effect of excess N fertilization and irrigation.

1.2.2 Assessing Crop Nitrogen Status with Optical Sensors

Optical sensing devices are useful tools in determining how well a crop has been fertilized with N. Sensors used in determining crop N status include canopy sensors, which measure light reflected from the crop canopy, and chlorophyll meters, which measure transmittance of light through the leaf tissue.

Chlorophyll sensors measure light in a range between 650 and 940 nm (Blackmer et al., 1996). When a corn plant is deficient in N, leaves will contain less chlorophyll, which results in the transmission of more light through the leaves (Blackmer et al., 1996). The chlorophyll meter is able to measure the transmission of light and use it to generate a relative value. When many leaves are read with a chlorophyll meter, the mean of the readings gives a reliable relative value that corresponds to the N status of the plant.

Canopy sensors are effective for sensing entire fields because they can be used while walking through a field, or can be mounted onto a tractor. These devices are non-passive because they supply their own light source and are therefore not sensitive to sunlight variations during data capture. Reflected red radiation detected by a canopy sensor has a negative correlation with green leaf area because the red radiation is returned when it is directed at bare soil or lighter-colored leaves (Martin et al., 2007). Reflected radiation in the infrared wavelengths positively correlates with leaf area because it is returned to the optical sensor once the canopy has filled out (Martin et al., 2007). These two measurements are used in calculating the NDVI. Biomass and corn grain yield have a direct relationship with NDVI (Martin et al., 2007).

The relationship between near infrared reflectance and N status of corn was described in an early study by Walburg et al. (1982). Reflected radiation wavelengths ranging from 0.4 to 2.4 µm were evaluated and spectral differences between treatments were found in each of the wavelengths tested. In Ontario on a sandy loam, Ma et al., (1996) concluded that canopy light reflectance during the growing season correlates with grain yield in corn. Martin et al. (2007) found that measurements taken from the V8 growth stage until the V12 growth stage are the best indicators of corn grain and plant biomass yields in comparison with readings taken earlier or later in the growing season. At the V8 growth stage, the corn plant has 8 collared leaves, and at the V12 stage, the corn plant has 12 collared leaves (Abendroth, 2011). After the V12 stage, NDVI is generally lower and more variable because the tassels begin to turn yellow as the corn crop senesces. Before the V8 stage, variability in NDVI measurements is large because the canopy has not filled in and there is exposed soil between the rows (Martin et al., 2007).

Non-passive crop canopy sensors and chlorophyll sensors both have the capability to detect N stress in a corn crop, but each has distinct characteristics that make them suitable for different applications. Chlorophyll sensors require many more individual measurements to be taken, which makes for tedious, time-consuming data collection. The relationship between actual leaf chlorophyll content and chlorophyll meter values is strong for corn (Samborski et al., 2009), and there is a strong correlation between leaf N and leaf chlorophyll (Blackmer and Schepers, 1995). Ma et al. (2007) found correlation between canopy reflectance, leaf chlorophyll, and N uptake at the V6 growth stage in sweet corn. Chlorophyll meters may not represent fields as effectively as crop canopy sensors because they only sample small areas on some of the leaves (Kim et al., 2000). In addition to surveying the crop over larger areas more effectively, canopy sensors can be mounted to tractors and used for determining variable N rates in real time (Samborski et al., 2009). Canopy sensors do have some limitations not shared with chlorophyll meters. Canopy sensors do not work well in fields with minimal canopy coverage, such as early in the season, during drought, or as a result of pest damage. Unlike chlorophyll meters, canopy sensors are not practical for potted plants.

1.2.3 Nitrogen Use Efficiency Methods with Corn

For economic and environmental reasons, it is beneficial to maximize how efficiently applied N contributes to grain yield. The relationship between applied N and N use by the crop is broadly defined as nitrogen use efficiency (NUE). The two primary factors which influence NUE are recovery efficiency (RE) and internal efficiency (IE) (Moll et al., 1982). Recovery efficiency represents the portion of applied N that is recovered in the biomass at the end of the growing season. The IE is a measure of how efficient the plant is at using N contained in the biomass to contribute to grain yield (Wortmann et al., 2011). There are other factors which indicate NUE as well. These include residual soil nitrate (RSN), agronomic efficiency (AE), and grain N (Wortmann et al., 2011). Agronomic efficiency is a measure of the increase in grain yield per unit of applied N (Cassman et al., 2002). These components of NUE give information on how well N is being managed in a cropping system.

The majority of soil N is contained in the organic matter. This organic-N is released slowly to the soil by mineralization. In soils which are not undergoing changes in tillage or cropping system, the organic N pool in the soil is at or near steady-state (Cassman et al., 2002). Uniformity in N inputs from atmospheric deposition and biological N_2 fixation can also be assumed to be constant. Under these conditions, the NUE of a cropping system can be estimated by the RE (Cassman et al., 2002). Generally, NUE is greater when low N rates are used because of increased N losses and declining uptake efficiency at greater applied N rates.

The most influential factor in NUE is N rate (Wortmann et al., 2011). Nitrogen use efficiency in corn is also influenced by temperature and precipitation patterns (Raun and Johnson, 1999), overall crop health (Cassman et al., 2002), hybrid (Moll et al., 1982) and N management factors including fertilizer placement and timing (Vetsch and Randall, 2004). Recovery efficiency was reduced from 87 to 45% with fall N application in comparison to spring N application in a corn following soybean rotation in Minnesota (Vetsch and Randall, 2004). Results from Wortmann et al. (2011) showed in-season N application based on crop needs resulted in greater NUE than single preplant applications. Wienhold et al. (1995) found that in abnormally cool or hot years, crop stress caused by weather decreased NUE at higher N rates.

Recovery efficiency figures differ among studies as a result of different conditions mentioned above. Cassman et al. (2002) evaluated RE for corn from 55 on-farm trials in the primary corn-producing states and found an average RE of 37%. For cereal crops including corn, Raun and Johnson (1999) estimated a NUE of 42% for developed countries. Wienhold et al. (1995) found a five year average RE of 50% for corn in the Northern Great Plains. At the EONR, a mean RE of 64% was reported for corn grown in Nebraska (Wortmann et al, 2011). In an early NUE study conducted in North Carolina, Moll et al. (1982) reported a mean NUE for eight corn hybrids of 95.7 and 26.5% with N rates of 56 and 224 kg ha^{-1}, respectively. This study exemplifies the decrease in NUE that results from increased N rate. Nitrogen use efficiency figures alone do not give information on why the majority of applied N was not taken up by the plant for use in the grain. For this reason, measurements of RSN and nitrate leaching are helpful in understanding the fate of applied N.

Increases in applied N often result in increased residual soil nitrate-N in field trials (Wilson et al., 2010; Zhu and Fox, 2003). Large quantities of post-harvest RSN signify that the crop received more fertilizer-N than is needed to achieve the agronomic optimum grain yield (Gehl et al., 2006). Wilson et al. (2010) found mean residual soil nitrate-N to be 2.9 kg ha^{-1} in the top 60 cm of soil with a N rate of 360 kg ha^{-1} for potato grown in sandy soils. Residual soil nitrate in the control plots averaged only 1.8 kg nitrate-N ha^{-1}. Mean residual soil nitrate-N was found to be as high as 6.0 kg ha^{-1} following a corn crop applied with 200 kg N ha^{-1} on a silt loam (Zue and Fox, 2003).

Residual soil nitrate-N is at high risk for leaching to groundwater because of the mobility of nitrate in the soil and because there is often no crop in place to take up RSN post-harvest. The association between RSN quantities in the fall and nitrate-N leaching potential is difficult to determine due to soil variability and timing of nitrate-N leaching (Gehl et al., 2006). Low fall RSN may or may not indicate a low risk of nitrate-N leaching because the nitrate-N may have already move downward through the soil profile earlier in the season (Gehl et al., 2006). Residual soil nitrate-N in the fall after harvest can indicate if N was over-applied. Determining nitrate-N leaching potential with RSN may not be practical because of variables other than N rate such as soil texture variability and the timing of nitrate movement within the soil.

Similar to RSN, another method of evaluating how well the crop was fertilized with N is the basal stalk nitrate (BSN) test. When corn plants do not receive adequate N, they will remove N from the lower stalks during grain filling. This results in a low concentration of nitrate in the stalk post-harvest. Conversely, nitrate will accumulate in the lower portion of the stalk if the plant is undergoing luxury consumption of N (Blackmer and Mallarino, 1996). For this reason, analyzing the corn basal stalk for nitrate-N once the growing season is over can elucidate how well the crop was fertilized for N and if N was applied in excess of the AONR. These tools which directly or indirectly indicate NUE are useful for comparison at varying N rates.

1.2.4 Urea and Coated Urea Products as a Nitrogen Source

Urea can be coated for the purpose of slowing the release of N and lengthening the time it takes for the N in the urea to be transformed into nitrate-N. This allows N to be available later in the growing season instead of during a short span of time immediately following application. Coated urea products include those with a polymer coating and those which feature an enzyme inhibitor. A polymer coating on the urea granule has no biological function, but delays the release of N by preventing the granule from dissolving as rapidly (Agrium Advanced Technologies, 2011). Fertilizer additives which inhibit the transformation of fertilizer N have the potential to increase NUE and limit N losses from volatilization, denitrification, and leaching. There are two principal types of inhibitors used to increase NUE: nitrification inhibitors (NI) and urease inhibitors (UI).

The purpose of adding a NI is to delay the oxidation of ammonium to nitrate, which can ultimately decrease the potential for denitrification and leaching. This is done by inhibiting the growth of the soil bacteria *Nitrosomonas*, which facilitates the transformation of ammonium to nitrite (Zacherl and Amberger, 1990). Nitrification inhibitors may also be used for the prevention of denitrification losses, which are the most prominent form of fertilizer-N losses in fine-textured soils (Nelson and Huber, 2001). Denitrification occurs when microbes convert ammonium to nitrate and use the nitrate as a terminal electron acceptor under saturated soil conditions.

Laboratory evaluation of DCD found that it has the capability of decreasing N loss (Jantalia et al., 2012). In one year of the study, urea coated with DCD was found to decrease N loss by 32% in comparison with untreated urea. Nitrogen loss from DCD-coated urea was found to be very low over the two years of the study, with a 0.8% loss. In contrast, uncoated urea was found to have a mean loss of 2 % under the same laboratory conditions. The results of this study show potential for DCD as a useful tool when fertilizing in conditions favoring high N losses.

Urease inhibitors have the purpose of protecting applied urea-N from volatilization losses. N-(n-butyl) thiophosphotic triamide (NBPT), the most widely used UI, competes for the active sites on the urease enzyme, which facilitates the conversion of urea to ammonia (Mullen and Lentz, 2011). Frame et al. (2012) conducted an in-vitro study to assess volatilization losses of ammonia from urea-fertilized soil with and without NBPT. Results showed a delay in volatilization of 96 hours on average when NBPT was added to the urea. Ammonia-N losses were between 34 and 37% for untreated urea and between 18 and 25% for urea treated with NBPT. These results in the controlled setting of a gas chamber show the potential of urease inhibitors for substantially reducing volatilization losses.

Fertilized soil amended with NBPT in a lab experienced a delay in ammonia volatilization and a decrease in total gaseous N losses (Murphy and Ferguson, 1997). Ma et al. (2010) found that the rate of volatilization losses from ammonia is greatest between three and seven days after application. This amount of time can be lengthened and total losses can be decreased if a UI is added. Goos (2011) found NBPT to inhibit urease activity by more than 80% in a laboratory setting. NBPT also significantly increased the amount of urea-N remaining ten days after application in comparison to urea alone.

Urease inhibitors have been used in the field with varying levels of success depending on factors including application timing and tillage practices. A study conducted by Tiessen et al. (2006) evaluated NBPT applied at different dates in the fall. Banded urea with NBPT was compared to a banded urea alone by soil sampling plots for ammonium-N and nitrate-N. Recovered fertilizer ammonium-N was greatest under late fall application and with the addition of NBPT. The added cost of including NBPT was not justified based on the outcome of the field trials (Tiessen et al., 2006).

The North American industry standard rate for NBPT is 0.08% of the fertilizer on a weight basis (Frame et al., 2012). NBPT has been found to be effective at rates less than the industry standard. One study showed that there was no significant difference in ammonia volatilization losses between NBPT applied at rates of 0.04% w/w and 0.1 % w/w (Frame et al., 2012). Even when considerable decreases in volatilization are observed, the observed prevention of ammonia volatilization often does not result in a grain yield increase when the N application is in excess of crop need (Tiessen et al., 2006).

Inhibitor products have been shown in numerous field trials to be ineffective, and in some cases, detrimental. The nitrification inhibitor DCD and the urease inhibitor NBPT were evaluated for nitrate leaching losses and volatilization losses (Gioacchini et al., 2002). The two products were tested separately and in combination with one another. NBPT alone significantly reduced volatilization. For treatments in which DCD was combined with NBPT, volatilization losses were greater than with NBPT alone. The sum of leaching and volatilization losses was the greatest when NBPT and DCD were both applied, and was less with uncoated urea.

Polymer coated urea (PCU) has potential to slow the release of urea-N to the soil and presents another approach to limiting N losses and improving NUE. One relatively new PCU product, marketed as Environmentally Smart Nitrogen (ESN; Agrium Inc., Calgary, AB), is of relatively low cost. Field evaluations of ESN have produced mixed results as to its effectiveness in improving grain yield in comparison to other N sources at the same application rates. Under conventional tillage in Canada, there was no difference in corn grain yield between urea and PCU applied at the same rate (Drury et al., 2011). Nelson et al. (2009) also found no difference between PCU and urea applied at equal rates, and found a 51 to 63% decrease in nitrate-N concentrations in the groundwater at 59 days after application with PCU. By 153 days after application, the nitrate-N concentration in the leachate was lower in plots applied with urea. The lower concentration later in the season with urea is likely the result of high nitrate-N losses earlier in the season. Nitrogen uptake and silage yield were not affected by fertilizer source in the study, indicating that any delay in the release of fertilizer-N did not benefit the crop (Nelson et al., 2009).

Wilson et al. (2010) found the total quantity of nitrate leached per season to be lower with ESN than with soluble N applied in the irrigation water for potato (Solanum tuberosum) in Minnesota. Applying PCU in the place of another N source can be advantageous because it can be used as a single application early in the season. For potato tuber yield on sandy soils, there was no difference between fertigated soluble N and PCU; however, the PCU was applied once in the spring and the soluble N was applied at emergence and hilling and posthilling (Wilson et al., 2009). A study with wheat (Triticum) in Minnesota found that PCU increased whole plant N concentration and grain protein in comparison to urea, likely as a result of increased plant available N later in the growing season (Bhupinder and Sims, 2013). Grain yield was greater with urea, and maximum grain yield was achieved at a lower N rate with urea than with PCU (Bhupinder and Sims, 2013). Polymer coated urea shows potential for increased NUE because of its slow release characteristics, but field trials have shown mixed results for yield, and the added cost of using PCU may not be recouped.

1.3 Objectives

The purpose of this study is to evaluate corn response to multiple N rates and N products on highly productive irrigated sandy soils in Minnesota. This study also evaluated the amount of nitrate-N leaching with eight N rates in order to test for a relationship between N rate and nitrate-N leaching. The response of corn to a range of applied N rates was measured with multiple factors including N uptake, NDVI, leaf chlorophyll, NUE, residual soil N, and basal stalk nitrate concentration. These measurements evaluate the N status of corn as well as how fertilizer N from urea broadcast in the spring moves within the crop, soil, and soil water. This study examined in-season optical crop canopy measurements as predictors of N uptake and biomass in order to evaluate their effectiveness.

Additionally, the purpose of this study is to evaluate polymer coated urea and urea coated with enzyme inhibitors (ICU). Each of these products has potential to limit N losses by slowing the release of mobile forms of N to the soil. These products add cost to a fertilizer plan, and it is important to determine how feasible their use is with irrigated sandy soils in Minnesota.

2.0 Materials and Methods

2.1 Locations and Soil

Field trials were conducted in 2011 and 2012 at four locations. One location is in Dakota County, MN on a Sparta loamy fine sand (sandy, mixed, mesic, Entic Hapludolls) derived from a sandy outwash parent material. This location will be referred to as Dakota. The slope ranges from 0 to 2 % at this location. The field plots are located within the NW ¼ of the NW ¼ in Section 9, Township 114 N, Range 17 W, 5th PM. The other three locations are located in Pope County, MN on an Estherville loam (sandy, mixed, mesic, Typic Hapludoll) formed fromh a sandy/ gravelly outwash parent material. These three locations will be referred to as East, Center, and West, because of their spatial arrangement. The slope at these three sites is between 0 and 2%. The field plots are located in the SE ¼ of the SW ¼ in Section 14, Township 126 N, Range 36 W, 5th PM. All locations were sprinkler irrigated.

2.2 Layout and Treatments

The Dakota and West locations were in a continuous corn rotation with 48 plots in the 2011 and 2012 growing seasons. Individual plots received the same treatments each year. The Center and East locations were in a corn/soybean rotation. The Center location was planted to corn in 2011 while the East location was planted to corn in 2012. These locations also contained 48 plots each. The four locations represented continuous corn and corn/soybean rotations. In the corn/soybean rotations, N treatments were applied only to corn plots. Sulfur was applied in a liquid starter fertilizer to all plots at the Dakota location at a 28 kg S ha^{-1} rate. Phosphorus and potassium were added at West, Center, and East locations at non-limiting rates. A small amount of N was supplied in the irrigation water at each location.

All plots were 4.6 meters by 12.2 meters. Each plot contained six 76 cm wide rows. Each replication at both locations contained the same 12 fertilizer treatments, listed in Table 1. Treatments were arranged in a randomized, complete block with four replications. Nitrogen was applied in the form of granular urea (46-0-0) N-P-K, an enzyme inhibitor treated urea product (ICU) called SuperU (44-0-0), and a polymer coated urea (PCU), called Environmentally Smart Nitrogen (44-0-0), depending on treatment. SuperU is urea treated with a urease inhibitor (Agrotain) and a nitrification inhibitor (DCD) and marketed by Koch Fertilizer, LLC, Wichita, KS. The nitrification inhibitor in SuperU is dicyandiamide (DCD). The ESN is urea treated with a polymer coating that regulates the release of urea. ESN is marketed by Agrium Advanced Technologies, Inc., Calgary, AB. Each N source is in the granular form and the N contained is urea-N (CH_4N_2O). Nitrogen fertilizer was broadcast applied to the soil surface and was not incorporated. Nitrogen treatments were applied at planting and at the V4 growth stage.

2.3 Agronomic Practices

In 2011 and 2012, corn plots at the West, Center, and East locations were planted with Croplan ‘339VT3’. Planting took place on May 11, 2011 and on April 25, 2012. At the Dakota location, Dekalb ‘4812’ seeds were planted on May 6, 2011 and May 4, 2012.

Pests were controlled using farmer practices. Primary tillage was done with a chisel plow in the fall and with a field cultivator in the spring at all locations. Irrigation at each location was scheduled based on rainfall, plant water use, and soil conditions.

2.4 Plant Tissue Sampling

After emergence, stand counts were taken by counting the number of plants emerged in 12.2 meters of row. At the V8 and V12 growth stages (Abendroth et al., 2011) and at physiological maturity, whole above ground plant samples were collected from the locations planted in corn. Plant sampling was conducted at the V8 and V12 growth stages. At physiological maturity, N contained in the aboveground matter was used for total seasonal N uptake and NUE estimates. For plant sampling, six plants were cut at the soil surface. Three plants were taken from row two and row five of each plot. Once collected, plants were put through a chipper with a 0.5 cm screen and dried at 60 degrees Celsius. Once dried, plants were weighed. Samples were then mixed, subsampled, and ran through a Thomas Wiley mill with a 2mm-sized screen.

Basal stalks were collected for the purpose of obtaining the concentration of nitrate in the stalk. Residual nitrate in the basal stalk indicates whether the N supply was adequate during the season (Blackmer and Mallarino, 1996). Between one and three weeks following blacklayer, 12 sections of corn stalk were removed from each plot (Blackmer and Mallarino, 1996). Before the stalks were collected, the leaf sheaths were removed from the stalks. Stalks were cut at 15 cm above base of the plant and at 35 cm above the base of the plant. This yielded 12 - 30 cm stalk sections in each plot, which were dried in an oven at 60 degrees Celsius and ran through a Thomas Wiley Mill with a 2 mm screen.

All ground whole plant samples were analyzed at the University of Minnesota Research Analytical Laboratory for total N by combusting the samples in the LECO FP-528 Nitrogen Analyzer (Simone et al., 1994). Basal stalk samples were analyzed for nitrate-N concentration. The nitrate is extracted by shaking the plant material in a solution of acetic acid and charcoal (Gavlak et al., 1993). The sample is then filtered and the cadmium reduction method is used to determine the nitrate-N concentration in the solution. Protein content of the corn grain was determined with infrared reflectance spectroscopy. Nitrogen in the corn grain was estimated based on protein content.

2.5 Nitrogen Use Efficiency Calculations

Nitrogen use efficiency was evaluated with two different equations. The recovery RE and the AE were calculated in order to assess how applied N is assimilated into the plant tissue and how applied N impacts grain yield, respectively. Recovery efficiency is calculated according the following equation from Wortmann et al. (2011):

$$\text{Equation 1:} \quad RE = (UN_N - UN_0) / N\ rate$$

Where UN_N is the total N uptake in the silage at physiological maturity for plots fertilized with N, and UN_0 is the mean total N uptake in the silage at physiological maturity for the plots which received no N. All units are in kg ha^{-1}. The AE was calculated according to the following equation from Wortmann et al. (2011):

$$\text{Equation 2:} \quad AE = (Y_N - Y_0) / N\ rate$$

Where Y_N is the grain yield for plots fertilized with N, and Y_0 is the mean grain yield for plots which received no N. These two equations produce a proportion ranging from approximately zero to one, although values may be greater than one and less than zero in some cases in which N rate is not the main factor impacting N uptake or grain yield. Grain yield data was adjusted to a moisture content of 15.5% for all plots.

2.6 Optical Canopy Sensing

Corn plants were sensed with the Greenseeker (Trimble Navigation Limited, Sunnyvale, CA) and Crop Circle (Holland Scientific, Inc., Lincoln, NE) canopy sensors at the V8 and V12 growth stages. Leaves were sampled with a SPAD chlorophyll meter (Konica Minolta, Inc., Tokyo, Japan). The Greenseeker and Crop circle devices were used by holding each device approximately 40 cm above the crop canopy and walking the length of rows three and four in each plot. These two rows are least susceptible to border effects and are the rows used for grain harvest, making them ideal for non-disruptive sampling. The first meter and last meter of each row in the plot were not sensed in order to avoid border effects.

The Crop Circle emits visible and near infrared light using an LED light source (Holland Scientific, Inc., 2010). Light reflected from the crop canopy is detected by the device's photosensors, and NDVI is calculated and outputted by the device (Holland Scientific, Inc. 2010). The width of the light beam emitted by the Crop Circle is a function of the distance from the sensor to the canopy. The Greenseeker also measures reflected light emitted by its own light source (Trimble Navigation Limited, 2010).

Unlike the Crop Circle, the light beam emitted by the Greenseeker is less dependent on the distance of the device from the canopy, and remains at approximately 60 cm (Trimble Navigation Limited, 2010). Like the Crop Circle, the Greenseeker also calculates NDVI values.

The SPAD chlorophyll meter was used by pressing the device lightly around the surface of the leaves until the device gave a reading. Plants chosen for sensing were selected at random within the identified rows. The most recently matured leaf was sampled. Within the leaves themselves, the reading was taken approximately halfway up the length of the leaf, and halfway between the edge of the leaf and the midrib. In each plot, thirty leaves were sampled from rows three and four. The average value of the thirty leaves sampled was recorded. For data analysis and interpretation, the chlorophyll meter values were calculated as a percentage of the mean value obtained from plots which received 314 kg N ha^{-1}, which was the highest N rate used in the study. Leaves within one meter of the border were not used in order to avoid border effects.

2.7 Leachate Collection and Analysis

Suction tube lysimeters were permanently installed at the West, Center, and East locations for the purpose of collecting leachate samples and analyzing them for nitrate-N. Plots under treatments 1, 4, 5, 6, 7, 9, 10, and 12 had suction cup lysimeters installed in them (Table 1). Each plot outfitted with lysimeters contained three lysimeters in order to improve accuracy of nitrate-N concentration data of the extracted soil water. The body of each suction tube lysimeter consisted of a polyvinylchloride (PVC) pipe 3.8 cm in diameter. The pipe was capped with a porous ceramic cup at the end beneath the soil to allow water to move into the lysimeter body. Flexible tubes were contained inside the pipe for the purpose of extracting collected water and for putting a vacuum seal inside the lysimeter. The suction cup lysimeters were buried by hand at depths between 1.2 m and 1.8 meters below the soil surface. Tubes used for water extraction and pressurizing were encased in additional PVC piping in order to protect them from damage. At the soil surface, the flexible tubes were folded shut, and were accessible by removing a sleeve of protective PVC piping.

The suction tube lysimeters were placed under vacuum pressure in order to draw water from the soil into the tube bodies (Weihermuller et al., 2007). Once water was extracted from each lysimeter, negative pressure was put back on the suction tube lysimeter. Water sampling was performed weekly for the entire growing season, and after major rainfall or irrigation events. Water samples were placed in plastic vials and were immediately refrigerated on site following collection. Water samples were analyzed for nitrate-N concentration by an ultraviolet spectrophometer (Hach Company, Boulder, CO).

In order to quantify the amount of nitrate-N leached past the root zone, a measure of the depth of water which drained through the soil profile was taken. Six passive capillary lysimeters, marketed as Drain Gauges (Decagon Devices, Inc., Pullman, WA), were used for measuring the amount of water moving through the soil. The passive capillary lysimeters were installed for the 2012 growing season at the site containing the West, Center, and East locations. The passive capillary lysimeters featured an upper tube filled with soil similar to the localized soil conditions, called the divergence control tube (Decagon Devices, Inc.). Below the divergence control tube was a PVC sheath that encapsulates a fiberglass wick and a reservoir. Water percolated through the soil contained in the divergence control tube and moved through the wick into the reservoir where it was measured. The devices were buried below the rooting zone of the crop, at approximately 1.2 meters depth. The output data from the passive capillary lysimeters provided an estimate of the depth of water moved through the soil profile (Decagon Devices, Inc.).

The mass of nitrate-N leached past the rooting zone can be calculated using the amount of water that moves past the root zone and the concentration of nitrate-N in the water (Smika et al., 1977). Data was collected from the passive capillary lysimeters at 19 dates during the 2012 growing season. On these 19 dates, the depth of water moved through the soil was measured and recorded. The readings from the six passive capillary lysimeters were averaged for each date. The mean depth of drainage was converted into a quantity of water volume over an area of one hectare. Because there was an absence of significant rainfall or irrigation events in the later portion of the 2012 growing season, there was no consistent measurable water detected by the passive capillary lysimeters after 11 July 2012. For this reason, calculations of nitrate-N loss in the leachate were based on the first ten passive capillary lysimeter readings of the season. Water sampling for nitrate-N concentration was performed more frequently than passive capillary lysimeter measurements early in the season. In this instance, nitrate-N concentrations obtained between leachate quantity measurements were averaged. The average nitrate-N concentration was applied to the subsequent leachate quantity measurement.

The mass of nitrate-N leached through the soil was calculated by multiplying the mean nitrate-N concentration value on a mass/mass basis by the mass of water leached past the root zone (Gehl et al., 2005).

$$\textit{Equation 3:} \quad N = C \times q$$

Where N is the mass of nitrate-N lost through leaching, C is the nitrate-N concentration in the leachate, and q is the quantity of water leached. This calculation was executed for each passive capillary lysimeter sampling date. The mass of nitrate-N leached per day was calculated by dividing the total nitrate-N loss in each passive capillary lysimeter sampling time period by the number of days in that period. The annual nitrate-N mass loss was calculated by summing the loss from the 10 individual passive capillary lysimeter sampling dates.

2.8 Soil Sampling

The soil was sampled at each site in the fall following harvest using a vehicle-mounted hydraulic soil probe. Soil samples were collected only from plots under treatments 1, 4, 5, 6, 7, 9, 10, and 12 (Table 1). In each plot, two soil cores were taken. At the Dakota location, the cores were taken to a depth of 120 cm. These cores were divided into depths of 0-30, 30-60, 60-90, and 90-120 cm. Because the subsoil at the West, Center, and East locations was gravelly, soil cores were only taken at depths of 0-30 and 30-60 cm. The samples from each depth were then mixed to make one composite sample.

The composite samples were dried in an oven at 35 degrees Celsius for at least 24 hours and then ground through a 2 mm screen. The samples were then analyzed for nitrate-N and results were reported in kg ha^{-1} (Gelderman and Beegle, 1998).

2.9 Statistical Analysis

Data was analyzed using SAS software (SAS Institute, 2009). Analysis of variance and mean separation were performed using PROC GLM. In comparing treated urea products with urea, mean separation was performed by combining sites and years if there was not a significant interaction between treatment and site-year. If there was an interaction between treatment and site-year, locations were compared separately and years 2011 and 2012 were combined. If there was significant interaction between treatment and year, location and year were analyzed separately.

Regression analysis was used for evaluating the relationship between dependent variables and N rate. Before regression was performed, correlation among variables was determined using the Proc Corr function in SAS. Four regression models were fitted for each dependent variable using PROC REG and PROC NLIN. The four models included linear, linear plateau, quadratic, and quadratic plateau. Models were chosen if the R^2 was the greatest of the four equations (at least 0.40), and if $P \leq 0.05$. Input data for determining regression lines was separated by location. Each location had either one or two years of data collected. If there were two years of data for a location, the data was combined by location. Locations were combined for regression analysis if the R^2 value was improved by combining all locations. This was done for leaf chlorophyll data and BSN data.

Relative values were used for the chlorophyll data in order to eliminate differences caused by location and differences in the SPAD meters used to obtain chlorophyll readings.

The nitrate-N concentration in the leachate and the quantity of nitrate-N leached were analyzed using the PROC MIXED procedure. Repeated measures analysis was done using a heterogeneous compound symmetry covariance structure. This covariance structure was selected because of unequal variances in the data and because the time interval between water sample collection was not always uniform due to weather events. The repeated measures analysis was performed separately for each site-year.

3.0 Results and Discussion

3.1 Weather and Irrigation

Rainfall and irrigation totals for the each location during the 2011 and 2012 growing seasons are given in Table 2. Precipitation was close to the 30 year normal at the Dakota location from April through July during both years of the study. In 2011 at the Dakota location, the months of September and October were abnormally dry. In 2012, precipitation was less than the 30 year normal from August through October (Table 2). The West, East, and Center locations are close in proximity to one another, and thus share identical climatic and weather conditions. These three locations had a similar precipitation pattern to the Dakota location during 2011 and 2012. Precipitation totals were greater than or near the 30 year normal until the month of July. During 2011 and 2012 for the West, Center, and East locations, precipitation was much less than the 30 year normal during September and October. The unusually dry weather did not result in drought stress or decreased grain yield because supplemental irrigation was used when necessary (Table 2).

Irrigation water at each location contained some supplemental N, which was applied to all treatments. Water collected from the irrigator at the West, Center, and East locations ranged from 7.9 to 9.1 ppm nitrate-N. This amount of N added to the crop was not considered in regression analysis in the following discussion because the purpose of the study was to evaluate the effects of urea-N split-applied as a broadcast application, not of the total N applied.

3.2 Corn Grain Response to N Application

At the Dakota location, corn grain yield was increased with increasing N application rate for the 2011 and 2012 growing seasons (Fig. 1). Grain yield data from the 2011 and 2012 growing seasons was combined, and a QP model was fitted to the data (Table 3). The agronomic optimum N rate (AONR) for Dakota County over the two years of the study was 217 kg ha^{-1}. Grain yield was not increased when applying N above this rate. The economically optimum N rate (EONR) is the rate calculated using the cost of fertilizer-N and the response of grain yield to N fertilizer. The EONR at the Dakota County location was 194 kg N ha^{-1}. This rate was calculated assuming an N price to corn price ratio of 0.10, where the N price is the cost in dollars of 1.0 Mg of fertilizer N, and the corn price is the cost in dollars of 1.0 Mg of corn grain. The EONR can be interpreted as the N rate in which the economic benefit of N fertilizer is maximized.

At the Center location, corn was grown only during the 2011 season. Nitrogen rate had a significant effect on grain yield at this location. A QP model was the best fit for the grain yield at the Center location (Table 3). At 201 kg N ha^{-1}, the AONR at the Center location was the smallest of the three locations with a significant grain response to N. Accordingly, the EONR at the Center location was the also the smallest with a value of 175 kg N ha^{-1}. The EONR was calculated assuming an N price to corn price ratio of 0.10.

Grain yield data for the West location, was combined for the 2011 and 2012 growing seasons. A QP was the best fit model for the West grain yield data (Table 3). The AONR was 260 kg N ha^{-1}, and the EONR was 238 kg N ha^{-1} (EONR 0.10). It is interesting that the West location had the highest AONR and EONR, indicating that corn grown at the West location needed more N to achieve approximately the same grain yield as the Dakota and Center locations. The steepness of the slope for the regression curve at the West location raised the EONR and AONR to N rates greater than those for the Dakota and Center locations (Table 3). Only for the East location was there no significant relationship between grain yield and N application rate. Grain yield data for the East location is given in Table 4.

3.3 Monitoring N Status in the Plant During the Growing Season

3.3.1 Optical Canopy Sensors

Three different optical sensing devices were tested in this study. The Crop Circle and GreenSeeker both measure NDVI using their own light source. Normalized difference vegetation index values from the Greenseeker did not have a strong relationship to applied N rate at any location at either the V8 or V12 growth stages. Mean NDVI values for the Greenseeker are given in tables 5 and 6.

Normalized difference vegetation index values from the Crop Circle were found to increase with increasing N rate at the West and East locations at the V8 growth stage (Figure 2). At the East location, the relationship between N rate and Crop Circle NDVI was linear, and did not reach a maximum (Table 3). At the West location, mean Crop Circle NDVI was best fitted to a QP model (Table 3). One reason for the difference in lines of best fit for the V8 crop Circle NDVI data is that the East location had corn in a rotation with soybeans, and the West location was continuous corn. Additional soil N supplied by the previous soybean crop may have been the cause of the control plots having larger NDVI values at the East location, and smaller NDVI values at the West location. Crop Circle NDVI data for the Center and Dakota locations for the V8 growth stage is given in Table 7. There was no significant relationship between Crop Circle NDVI and N rate at the V12 growth stage at any location (Table 8).

Normalized difference vegetation index values from each device followed a similar pattern in which the control plots had smaller NDVI values, but plots fertilized with low N rates achieved NDVI values near those of the high N rate plots. The relationship between applied N rate and NDVI was often not significant because aside from the control plots, there appeared to be no effect of N rate on NDVI. In other cases, even the control plots had values similar to plots applied with high N rates, showing virtually no relationship between N rate and NDVI.

Leaf chlorophyll measurements were strongly related to N rate at both the V8 and V12 growth stages at all locations. The data from the four different locations was combined because the coefficient of determination was greater when the locations were treated this way. Leaf chlorophyll measurements are presented as a ratio and are therefore unitless. This ratio may change depending on how the device is calibrated. In order to compare the results taken with different devices and over multiple locations, relative values were calculated for leaf chlorophyll data. At each location, the mean chlorophyll reading for the plots fertilized at an N rate of 313 kg ha^{-1}, the greatest N rate, was used to calculate the relative values. This was done by dividing a given chlorophyll value by the mean of the plots fertilized at the greatest N rate.

Leaf chlorophyll readings at both the V8 and V12 growth stages increased with increasing N rate (Fig. 3 and 4). The relationship between relative leaf chlorophyll values and N rate at both the V8 and V12 growth stages with the largest R^2 was a QP model (Table 3). The readings reached the maximum relative value of 100% at an N rate of 174 kg ha^{-1} and 228 kg ha^{-1} at the V8 and V12 growth stages, respectively. Of the sensing data, the leaf chlorophyll measurements had the largest R^2 (Table 3). The effectiveness of the leaf chlorophyll measurements at evaluating the N status of the corn plants is a result of the sensitivity of the instruments and also of the way in which leaves are measured. The average value of 30 leaves in each plot is a reliable number and is not subject to variation caused by bare spots in the stand or the onset of tasseling.

3.3.2 Nitrogen Uptake

Corn rapidly increases the rate of N uptake at approximately the V8 growth stage (Abendroth, 2011). The quantity of N uptake at V8 was substantially less than at the V12 stage; however, there was a strong relationship between applied N rate and N uptake at the V8 growth stage at three of four locations (Table 3). Mean N uptake at the V8 growth stage was always the least for the control at each location.

At the East location, a LP was the best fit for N uptake at the V8 stage (Figure 5). Total V8 N uptake for the control was greater than that of the control for all other locations. Additionally, the critical level for N rate was the least for the East site (Table 3). As previously noted, the East location was planted with soybean in 2011 and with corn in 2012. The cause of the high V8 N uptake in the control plots for the East site may be that the previous soybean crop provided additional N to the following corn crop. The

University of Minnesota Extension guidelines for corn grown on highly productive soils allow for a reduction in N rate for corn following soybeans of between 33.6 and 39.2 kg ha^{-1} depending on the N Price to Crop Value Ratio (Kaiser et al., 2011). However, the previous soybean crop does not explain why the maximum uptake for the East location was substantially greater than the other locations because at each location, N uptake plateaued at or before an N rate of 272 kg ha^{-1} (Table 3).

At the Dakota and Center locations, a QP model was the best fit for the V8 stage total N uptake data (Table 3). Each of these locations featured a line of best fit that increased from the control mean and plateaued at an N rate within the range used in this study (Figure 5). These two locations did not have a legume planted in them for at least one year prior to being planted in corn. This allowed the higher N rate plots to have a greater total N uptake than the control plots and low N rate plots. The relationship between applied N rate and total N uptake at the V8 growth stage at the East, Center, and Dakota locations demonstrates that N applied in the form of urea in the spring is available to the plant by the V8 stage. At the West location, the relationship between N rate and V8 plant N uptake was not as strong, and there was no significant relationship. The V8 stage N uptake data for the West location is given in Table 9.

Total N uptake at the V12 growth stage was affected by N rate at all locations. At the Dakota and West locations, a QP model provided the best fit (Table 3). At the Center location, a LP model was the best fit (Table 3). Total N uptake at V12 for the East site was much greater than at the other three sites, as it was for the V8 stage N uptake. At V12, N uptake increased with N rate up to the largest applied N rate of 313 kg ha^{-1} for the

East location (Figure 6). This relationship was linear, and there was no plateau because of increased N uptake even at the highest applied N rates.

At the Center location, N uptake at the V12 growth stage was increased with N rate (Figure 6). The model of best fit for the Center location plateaued at an N rate of 277 kg ha^{-1} (Table 3). It is interesting to note that the critical N rate for N uptake was greater for each location at the V12 growth stage than at the V8 growth stage. This indicated that at the earlier growth stage, the plants were less able to assimilate N. It also suggests that N is not as limiting in plots applied with smaller N rates at the V8 stage compared with the V12 stage. This can be expected because the size of the plants at the V8 stage is substantially smaller.

By physiological maturity, the corn plant no longer requires N from the soil. Total N contained in the plant biomass can be used for NUE calculations. Total N uptake in the biomass was increased with N rate at every location (Figure 7). Total N in the corn silage was not maximized at any of the N rates used in the study for any of the four locations. Total N uptake in the silage was increased to the highest applied N rate at the Center, Dakota, and West locations, and each line of best fit was a quadratic (Table 3). At the East location, there was not a strong relationship between N rate and silage N uptake. Results for N uptake at physiological maturity for the East location are given in Table 10. The N rate at which the maximum N uptake is achieved increased slightly from the V8 to the V12 growth stage. By physiological maturity, the N rate at which N uptake was maximized was greater than the rates tested in this study. This follows the same trend seen in the leaf chlorophyll data in which the critical N rate for N uptake is larger later in the growing season. It also implies that the corn plant is capable of taking up additional N from the soil after the V12 stage, and that the plant will continue to uptake N as luxury consumption if N is available in the soil.

Grain yield was maximized at N rates lower than those which maximized N uptake at V8, V12, and at physiological maturity at all locations (Table 3). This shows that the uptake of N by the plant at high N rates did increase N in the biomass, but did not necessarily increase grain yield. This example of luxury N consumption by the plant indicates the applied N rate was too great for economic benefit, and that the plant was unable to convert N assimilated in the tissue to increased grain yield at the largest applied N rates.

3.4 Assessing Plant Nitrogen Status at Harvest

3.4.1 Grain N

Grain N was increased with increasing N application at the Dakota, East, and West locations (Figure 8). The best fit model for N in the grain at harvest was the LP (Table 3). The AONR for grain N ranged from 171 kg ha^{-1} to 272 kg ha^{-1} at the three locations for which a significant model was fitted (Table 3). The East Location plateaued near the 314 kg N ha^{-1} rate, which was expected based on V12 stage N uptake data from that location which followed a similar pattern (Figure 6). At the Center location, there was not a significant line of best fit between N rate and grain N. Grain N values for the Center location are given in Table 11.

3.4.2 Basal Stalk Nitrate

Basal stalk nitrate (BSN) concentration data was analyzed across locations because the coefficient of determination was greater when the locations were combined. Regression curves for basal stalk nitrate-N concentrations are generally steep because nitrate-N concentration values can range from 0 mg kg^{-1} to well over 1000 mg kg^{-1}. In this study, a quadratic model was fitted to the relationship between N rate and basal stalk nitrate-N concentration was found to be the best fit (Figure 9). Mean nitrate-N concentration increased with each incremental increase in applied N, and the model did not plateau. For the control, basal stalk nitrate-N averaged across all years and sites was 35 mg kg^{-1}. This is considered to be in the low range, which includes nitrate-N concentrations from 0 to 250 mg kg^{-1} (Blackmer and Mallarino, 1996). Nitrogen supply to the corn crop is optimal when basal stalk nitrate concentration is between 700 and 2000 mg kg^{-1} (Blackmer and Mallarino, 1996). The agronomic optimum N rate ranged between 201 and 261 kg ha^{-1}, and BSN concentration for these rates was close to these values according to the regression equation (Table 3). At the highest N rate of 313 kg ha^{-1}, mean BSN concentration averaged across all years and sites was at 3989 mg kg^{-1}, a level which indicates that N was applied in excess of crop needs. These results indicate that the BSN test does show whether or not the applied N rate was in the optimal range.

3.5 Correlation Analysis

Correlation analysis was performed in order to test for a relationship between certain dependent variables. Correlation between two variables was considered strong when |r| was greater than 0.33. Correlation between leaf chlorophyll, NDVI, biomass, N uptake, grain N, and grain yield was calculated. Correlation among biomass, uptake, NDVI, and leaf chlorophyll were determined for the V8 and V12 growth stages separately. This allowed for investigation of how well the NDVI sensors estimated plant mass and leaf greenness.

At the V8 growth stage, there was a very strong correlation between dry mass and N uptake (Table 12). At the V8 growth stage, NDVI as measured with the Greenseeker and Crop Circle devices was strongly correlated to V8 N uptake, and NDVI as determined by the two devices was also strongly correlated (Table 12). Leaf chlorophyll as measured by the SPAD meters was correlated with NDVI from the Greenseeker, NDVI from the Crop Circle, and total N uptake. Leaf chlorophyll was more strongly correlated to biomass at the V8 stage than were the NDVI measurements, which is interesting because NDVI is meant to be an indirect measure of plant biomass, whereas the SPAD meter is purposed to measure leaf greenness. The Crop Circle and Greenseeker NDVI data were more strongly correlated to each other at the V8 growth stage than they were to mass, or to N uptake (Table 12).

At the V12 growth stage, the relationship among crop canopy optical sensing data was weaker than at the V8 growth stage, including the relationship between the Crop Circle and Greenseeker NDVI measurements. Biomass and N uptake were still strongly related at the V12 growth stage (Table 13). Normalized difference vegetation index from the Greenseeker was strongly correlated with N uptake, but not with plant biomass at the V12 stage. The Crop Circle was not well correlated with either biomass or N uptake at the V12 growth stage (Table 13). As with the V8 stage, chlorophyll measurements at V12 were more strongly correlated with N uptake and biomass than were the NDVI measurements (Table 13).

In-season measurements were compared with grain yield, grain N, and total N uptake at physiological maturity. Grain yield was strongly correlated to both grain N and N uptake at physiological maturity (Table 14). These results were expected because if the corn plant contains greater amounts of N, it is likely that the plant was able to translocate N into the grain, and that the plant would be capable of producing a greater quantity of grain. Nitrogen uptake and grain N at physiological maturity were strongly correlated with N uptake at the V8 and V12 growth stages (Table 14). This relationship shows that plants which received more applied N were able to uptake more N by the V8 stage, and that they continued to undergo increased N uptake later in the season.

Leaf chlorophyll at the V8 and V12 growth stages was not strongly correlated with uptake or grain N at maturity (Table 14). Crop Circle NDVI at both growth stages and Greenseeker NDVI at the V12 stage were strongly correlated to both N uptake and Grain N at physiological maturity. Unlike N uptake and grain N, the relationship between grain yield and in-season sensing measurements was somewhat weak. Leaf chlorophyll and NDVI at the V8 and V12 growth stages was not strongly correlated with grain yield (Table 14). There was a strong relationship between grain yield and N uptake at V8, V12, and physiological maturity (Table 14). For predicting N status of the corn crop, in-season sensing was useful; however, N uptake was the only in-season measurement with a meaningful relationship to grain yield.

3.6 Nitrate Leaching

Nitrate-N concentration of soil pore water was measured during 2011 and 2012 at the Center, East, and West locations. The concentration of nitrate-N was not affected by the rate of N fertilizer application at any of the three locations in which water nitrate-N concentrations were measured. The nitrate-N concentration data for the 2011 and 2012 growing season for the West, Center, and East locations is given in Figures 10 and 11. Variability in nitrate-N concentration data was great, and many plots fertilized with smaller amounts of applied N had relatively large nitrate-N concentrations in the leachate. The lysimeters used the study were installed prior to the 2011 growing season. One possible reason for the lack of a significant relationship between N rate and nitrate-N concentration in the leachate is that the lysimeters may have not been functioning at their full potential because of disturbances in the soil during the installation process (Weihermuller et al., 2007). As more time passes, disturbances to the soil surrounding the lysimeter bodies may become less influential on nitrate-N concentrations.

The effect of day of the year on water nitrate-N concentration was highly significant for each year at the West, East, and Center locations for the 2011 and 2012 growing seasons (Table 15). The relationship between day of the year and nitrate-N concentration can be visualized in Figures 10 and 11. Generally, nitrate-N concentration was the least during the start of the growing season. At the Center and West locations for 2011 and 2012, and at the East location in 2012, nitrate-N concentration in the leachate was greatest between day 180 and day 200 of the year (Figures 10 and 11). After the peak at 180 to 200 days of the year, nitrate-N concentrations slowly began to decrease until the end of the growing season (Figures 10 and 11).

The concentration of nitrate-N in the soil water does not denote the quantity of nitrate-N which is leached. Using the nitrate-N concentration of the leachate and the amount of leachate which passes through the root zone, the mass of nitrate-N which is lost through leaching can be calculated (Equation 3). Nitrate leaching amounts were calculated on a mass basis for each day of the year in which the quantity of water moving through the soil profile was measured. There were ten such dates during the 2012 growing season at the West, Center, and East locations. Repeated measures analysis showed a lack of a significant relationship between applied N rate and the mass of nitrate-N leached at the ten sampling dates during the growing season. Mean leaching nitrate-N loss data for the West, Center, and East locations for the 2012 growing season is given in Table 16.

As with nitrate-N concentration, the effect of day of the year on quantity of nitrate-N leached was also highly significant for the West, Center, and East locations (Table 15). It is expected that the results for nitrate-N concentration and quantity of nitrate-N leached are similar because the nitrate-N concentrations were used in calculating the quantity of nitrate-N leached. The amount of N applied to the corn crop did not affect the nitrate-N concentration in the leachate or the quantity of nitrate-N moved below the root zone in the leachate. This can be partially attributed to the large amount of variability in the leaching data collected.

For the 2012 growing season, the total quantity of nitrate-N leached during that entire growing season was calculated for the West, Center, and East locations. This quantity was calculated by adding the cumulative nitrate-N losses which occurred during the entire growing season of 2012. Results showed no significant relationship between N rate and quantity of nitrate-N leached per year. Results for the total quantity of nitrate-N leached over the growing season are given in Table 17. The lack of relationship between nitrate-N lost through leaching and N rate is not explained by N uptake by the plant. Nitrogen uptake at the V8, V12, and at physiological maturity was greater for treatments with greater applied N rates. However, during the earlier portion of the growing season, N uptake by the corn crop was not substantial, and was too small to cause any notable decrease in nitrate-N leaching.

3.7 Nitrogen Use Efficiency

The quantity of N taken up by the corn plant at physiological maturity over a given area was used for the calculation of RE and of AE, the two measures of NUE investigated in this study. In the equations for RE and AE, the quantity of either N uptake or grain yield from the control plots is subtracted from the quantity recorded from plots applied with N (Equations 1 and 2). If the control plots have a relatively large mean N uptake or grain yield, NUE values will not decrease as drastically with increased N rate at greater N application rates, as is generally expected.

For NUE data, locations were analyzed separately and years were combined at locations which had more than one year of data. The relationship between N rate and RE as was not significant at any location. Treatment means for RE for each location are given in Table 18. As with RE, the AE of the corn crop was not affected by N rate for any location (Table 19). One reason for the insignificant relationship between N rate and RE or AE is that extreme N rates were not tested. If N rate is increased to a level at which plant N uptake is no longer increased, then RE and AE will sharply decrease. The N uptake results from physiological maturity showed that the N rates tested were not high enough for N uptake to reach a plateau (Figure 7). If substantially larger rates were added to the study, a decrease in both RE and AE would be expected.

Common values for RE have been reported from 0.42 to 0.67, and for corn, the average in the United Sates is generally reported near a value of 0.50 (Raun and Johnson, 1999; Wienhold et al., 1995; Wortmann et al., 2011). In this study, the mean RE was 0.41 across all locations and treatments. This was close to the 0.37 value Cassman et al. (2002) found from 55 on-farm trials in the primary corn-producing states. Nitrogen use efficiency as measured by RE is generally decreased with increasing N rate (Wortmann et al., 2011). Results from this experiment did not show this relationship. The lack of relationship between N rate and NUE may indicate that the N rates used in the study were not excessive. At the highest N rate tested of 313 kg N ha^{-1}, the mean RE for all locations was 0.46 (Table 18). Nitrogen rates ranging from zero to 313 kg ha^{-1} had similar RE and AE numbers because within this range of N rates, the corn crop had the ability to assimilate the additional applied N. At larger applied N rates, increased fertilizer N inputs would be more likely to result in a decline of RE and AE.

3.8 Residual Soil Nitrate

After harvest, RSN remains in the soil either because the crop did not demand it, or because the crop was unable to assimilate it. Greater applied N rates in the spring will often result in increased RSN in the fall after harvest (Wortmann et al., 2011). Applied N rates of 0, 134, 179, 224, and 314 kg ha^{-1} were sampled for RSN. Treatment means for RSN at all locations are given in Table 20. If locations had data from more than one growing season, data from multiple years was combined by location. The concentration of RSN was greater at larger applied N rates. Because of the variation in the data and a relatively weak statistical relationship between N application rate and RSN, there were no significant regression models that could be fit to the data for any of the study locations. One reason for the lack of a significant relationship between N rate and RSN is much of the soil nitrate-N is susceptible to loss through leaching during the growing season on sandy soils. This will result in lower RSN values in the fall (Gehl et al., 2006). Additionally, NUE was maintained across the range of N rates evaluated in the study. This indicates that even when larger N rates were used, the corn crop was able to assimilate the N instead of leaving it to remain in the soil where it is prone to leaching.

3.9 Coated Urea Product Comparisons

The performance of PCU and ICU was compared against that of untreated urea at equal rates. Normalized difference vegetation index was generally not increased with coated urea in comparison to urea. All locations and years were combined for Greenseeker NDVI results because there was not a significant interaction between site and year. At the V8 growth stage, Greenseeker NDVI was the least for the control and greatest for the urea and PCU at the 240 kg N ha^{-1} rate. Normalized difference vegetative index did not differ among urea, PCU, and ICU applied at identical rates (Table 21). At the V12 growth stage, NDVI as measured by the Greenseeker was lowest for the control, and there was not a difference between urea and either the PCU or the ICU (Table 21).

Normalized difference vegetative index as measured by the Crop Circle was similar to NDVI values found with the Greenseeker. Crop Circle NDVI values at the V8 stage were combined for all locations and years because there was no interaction between site and year. Plots fertilized with urea, PCU, or ICU each had a greater mean NDVI value than the control. There was no significant difference in Crop Circle NDVI among the three different urea products at the 179 and 224 kg ha^{-1} N rates (Table 21). At the V12 stage, Crop Circle NDVI at the Dakota and West locations for both years was not affected by the type of urea product, but was significantly greater for the plots applied with urea or urea products than for the control (Tables 22 and 23). Interestingly, Crop Circle NDVI was not impacted by treatment at the Center and East locations for the V12 growth stage (Table 22). Normalized difference vegetative index was not significantly greater in the plots which received N than the control plots. It was not unexpected to find a lack of differences among the three urea products; however, the control plots were expected to have smaller NDVI values that the treated plots. One reason for the lack of significant differences between the treated plots and the control is that the East location had a previous crop of soybeans. This provided additional N to the following corn crop and may have made differences in NDVI measurements less pronounced. In general, the relationship between N rate and NDVI was weak as evidenced by R^2 values below the 0.40 level for the V8 Greenseeker NDVI measurements for both years at each location and the Greenseeker and Crop Circle V12 NDVI measurements at all locations and years (Tables 5, 6, 7 and 8).

Chlorophyll measurements by the SPAD meter were calculated as a percentage of the mean reading of the 314 kg ha^{-1} N rate at each site. Differences in leaf chlorophyll between urea and coated urea at the V8 growth stage were not significant except for the East location in Pope County. At the East location, the relative chlorophyll from plots applied with urea at the 224 kg ha^{-1} N rate was greater than those treated with PCU at the 179 kg N ha^{-1} rate (Table 22). Relative chlorophyll readings taken at the V12 stage were similar to those at the V8 stage. Only at the East location was there a significant difference in the means for relative chlorophyll values. Plots applied with PCU at the 224 kg N ha^{-1} rate had greater relative chlorophyll than plots treated with the same product at the 179 kg N ha^{-1} rate (Table 22). These results do not show any instances in which plants treated with PCU or ICU had greater chlorophyll content than the plants treated with urea. During the mid-growing season when the corn is at the V8 or V12 stage, any differences in N release between untreated urea and urea coated with either polymer or enzyme inhibiters did not impact the chlorophyll status of the leaves.

Urea and coated urea products often will release N to the soil at different times because of differences in how easily the fertilizer granules are dissolved. These differences in N release from the fertilizer granule did not impact the in-season corn plant measurements. Leaf chlorophyll and NDVI are two measurements used to indirectly determine the N status of the corn crop. For most locations and years, these measurements showed that corn plants receiving no N fertilizer were deficient in N in comparison with the plants fertilized with N at the 179 and 224 kg ha^{-1} N rates (Tables 21, 22, 23, and 24). From that data, it is clear that at the V8 and V12 stages, the N applied in the spring does impact plant N status and also that the NDVI and leaf chlorophyll measurement tools are capable of identifying when the corn plants are stressed from inadequate N, as in the control plots.

Aboveground biomass N uptake was measured at V8, V12, and at physiological maturity. At the V8 sampling, all locations and years were combined because there was not a significant interaction between location and year. There was an increase in N uptake with the addition of each of the N fertilizer products, but there were no significant differences in N uptake for the different N sources (Table 21). The control had an N uptake at V8 of 38 kg N ha^{-1} and the fertilized corn averaged 64 kg N ha^{-1}. Both plant mass and N concentration in the plant tissue impacted the N uptake. At the V8 stage, the concentration of N in the plant tissue contributed more to overall differences in N uptake. The mean concentration of total N in the plant issue was 22.8 g kg^{-1} and 32.9 g kg^{-1} for the control plots and treated plots, respectively. Plant mass was also smallest for the control, and was larger for plots treated with urea or urea products.

All locations and years were combined for N uptake values at the V12 growth stage. Similar to the V8 growth stage, N uptake was lowest for the control, and there were no significant differences among different urea products at equal rates (Table 21). The control plots had an average N uptake of 79.1 kg ha^{-1}, and the plots treated with N had mean N uptake of 140.7 kg ha^{-1} for the V12 stage. The mean concentration of total N in the plant biomass was 1.4% and 2.0% for the control plots and the plots treated with N, respectively. Nitrogen uptake was not increased by PCU or ICU in comparison to untreated urea at the V8 or V12 growth stages. In evaluating different urea-based N fertilizers at identical N rates, there was little impact on the N status of the mid-season corn crop across each location and year.

As with the results from the in-season N status of the corn crop, the effects of using the different urea products were not pronounced at the end of the growing season when considering N uptake. Data was combined for each year and location for whole plant N uptake at physiological maturity. As expected, the control had the lowest N uptake at the end of the season, with a mean of 152.7 kg N ha^{-1} (Table 21). There was a significant difference in mean N uptake at physiological maturity between the PCU and urea mixture compared to the remaining urea and coated urea treatments. The mixture of PCU and urea and the remaining coated urea and urea treatments had mean N uptake quantities of 215.7 and 245.0 kg ha^{-1}, respectively (Table 21). This difference was not present in the mid-season N uptake data, and may indicate that when not split applied, uncoated urea is more susceptible to N loss than PCU. The PCU in the mixture with urea would have undergone N release at the same rate as the PCU in the other treatments, but the urea in the mixture was not split applied, and therefore may have resulted in less applied N contained in the plant biomass by the end of the growing season.

The data for the quantity of N contained in the corn grain at harvest was combined for all locations and years because there was not significant interaction between the location and year terms. The type of product did not influence the amount of N contained in the corn grain. The mean quantity of N in the grain was 163.0 kg ha^{-1} and 92.7 kg ha^{-1} for the plots receiving urea or coated urea and the control, respectively (Table 21).

The concentration of nitrate-N contained in the basal stalks at R6 was used as a tool to evaluate any differences among the different urea products. The basal stalk nitrate data was combined for all locations and years of the study. Basal stalk nitrate concentration was greatest for both the urea and PCU at the 224 kg ha^{-1} rate. The nitrate-N concentration in the basal stalks among PCU, urea, ICU, and the urea and PCU mixture applied at the 179 kg N ha^{-1} rate was not affected by product, and averaged 686 mg kg^{-1}. The control was significantly lower than the fertilized plots, and averaged 35 mg kg^{-1} (Table 21).

The quantity of nitrate-N remaining in the soil after the corn crop was harvested was combined for the sites planted in corn. These included the continuous corn rotations at the Dakota and West locations for 2011 and 2012, the Center location in 2011, and the East location in 2012. The control had least amount of RSN, with a mean of 14.1 kg nitrate-N ha^{-1} in the top 60 cm of soil. The urea applied at the 224 kg N ha^{-1} rate had the greatest RSN, with a mean of 27.3 kg nitrate-N ha^{-1} (Table 21). Residual soil nitrate-N data was not collected for the PCU applied at the 224 kg N ha^{-1} rate. At an application rate of 179 kg ha^{-1}, RSN was not affected by product, and the mean RSN in the top 60 of soil for all products at that N rate was 21.7 kg nitrate-N ha^{-1}.

The two measures of NUE used in this study, the RE and the AE, were compared among the different urea-containing fertilizer products. Recovery efficiency was generally not impacted by product. Data was combined for all locations and years for RE and AE. The RE was increased for urea, PCU, and ICU at the 179 kg N ha^{-1} rate in comparison to the PCU and urea mixture at the same rate (Table 21). The AE was also lowest for the PCU/urea mixture, and highest for urea at the 179 kg N ha^{-1} rate (Table 21). These results show that the coatings applied to the urea granule did not increase the NUE of the corn crop in comparison to urea. Additionally, the results for RE and AE indicate that the mixture of urea and PCU did not perform as well as the other treatments at the same rate. This was expected because of the somewhat lower values for N uptake in the silage for the mixture of urea and PCU (Table 21).

There was significant interaction between treatment and location for the grain yield data. For this reason, analysis was performed separately for each location. If a location had corn grown on it for more than one year, the years were combined. Grain yield was not affected by product at the Dakota, East, or Center locations. At the Dakota and Center locations, the control had a significantly smaller grain yield than the treated plots (Table 22). The East location had unusually large grain yields in the control plots, and subsequently did not have any significant differences in means between any on the treatments, including the control. At the West location, grain yield was significantly larger with the 224 kg ha^{-1} urea than with the 179 kg ha^{-1} PCU and urea mixture. The mean grain yield for the control plots was less than any of the means for plots treated with urea or coated urea (Table 22).

The total amount of nitrate-N leached beyond the root zone of the corn crop per year was calculated for the 2012 growing season at the East and West locations. The two locations were not combined for analysis because of a significant interaction between treatment and location. At the East location, there was no significant difference in the means between the different products or the control. The control had a mean nitrate-N leaching loss of 39.16 kg ha^{-1} $year^{-1}$, which was greater than the nitrate-N leaching loss for any of the treatments at the West location (Table 25). It is not clear why the nitrate-N leaching totals were larger at the East location than at the West location. The East location was applied with the same N rates as the West location despite being planted with soybean the previous year. This may have contributed to the potential for nitrate-N leaching losses, but it does not explain why such a large increase in nitrate-N leaching was observed. One possibility is that the crop history for the East location is one that favors greater amounts of nitrate-N leaching. At the West location, the annual leaching loss for the control was the smallest of any of the treatments, at 12.36 kg nitrate-N ha^{-1} $year^{-1}$ (Table 25). The urea applied at the 179 kg N ha^{-1} and 224 kg N ha^{-1}rates, and the PCU at the 179 kg N ha^{-1} rate resulted in nitrate-N leaching losses greater than the control, with a mean loss of 25.6 kg nitrate-N ha^{-1} $year^{-1}$ (Table 25). The 224 kg N ha^{-1} PCU treatment was not evaluated for nitrate leaching.

The results from the West location show that increasing the N rate from zero to 179 kg ha^{-1} can increase the quantity of nitrate-N leached over the entire growing season. This is in contrast to the results from repeated measures analysis of the quantity of nitrate-N leached on an event basis. In that case, the applied N rate did not significantly impact nitrate-N leaching (Table 16). Additionally, there was no significant regression line for the relationship between N rate and quantity of nitrate-N leached per year. When comparing annual losses from plots fertilized at rates of 179 and 224 kg N ha^{-1} with different urea-containing fertilizer products, however, the West location did show an increase in nitrate-N leaching in comparison to the control. The values for the quantity of nitrate-N leached per year do not support the use of PCU or ICU to decrease nitrate-N leaching. Additionally, no improvements were realized from using PCU or ICU at equal rates as urea for grain yield or silage yield. It should be noted, however, that the coated urea products were applied only pre-plant, and the urea was applied as a split application.

4.0 Conclusions

Irrigated sandy soils in Minnesota have the potential to be highly productive. These soils have less organic matter than fine-textured soils, and they responded to increased applied N. Nitrogen uptake at the V8 stage was increased with increasing N inputs in three of four locations, while N uptake at the V12 stage was increased with increasing N inputs at all four locations. The values for N uptake at V8 and V12 plateaued at N rates between 224 and 313 kg ha^{-1} at each location. Nitrogen uptake at physiological maturity was not maximized at any of the tested N rates, showing the potential of the corn crop to assimilate large amounts of N from the soil.

Unlike N uptake in the biomass at the V8 and V12 growth stages, NDVI measurements did not strongly correlate to applied N rate. Leaf chlorophyll was increased by the application of N fertilizer at every location at both the V8 and V12 growth stages. Measuring leaf chlorophyll was a useful tool for in-season evaluation of the plant's N status, and proved to be superior in comparison to the more easily acquired NDVI values. Grain yield and grain N were increased with increasing N application rate at three of four locations.

Nitrogen use efficiency was measured as RE and AE, and less directly by RSN and BSN. Because of the variation in N uptake and grain yield at low N rates, RE and AE were not significantly affected by N rate for any of the four locations. Residual soil nitrate-N and BSN both tended to increase with increasing N rate, but only BSN had a significant relationship with N rate. One of the reasons the relationship between RSN and N rate is weak was the large amount of variation in the RSN data. Another reason may have been that buildup of excess N in the soil was avoided because of increased N uptake by the plant at larger N application rates. The quadratic relationship between BSN concentration and applied N rate was similar to those reported by Blackmer and Mallarino (1996).

Coated urea products did not improve grain yield, reduce nitrate-N leaching, or increase the N status of the corn crop. The coated urea products performed equally as well as urea at the same application rates. Because the coated urea was only applied at one time instead of as a split application as the urea was, there may be potential for coated urea products to be useful in a corn production system if the added costs of using coated urea do not become restrictive.

The results of the study elucidate the difficulty of identifying the relationship between applied N and nitrate-N in the soil water. Despite the large number of suction cup lysimeters and there being three replications for each of the two years of the study, nitrate-N concentration in the leachate was often not increased with increased applied N. Only mean separation for the total annual mass of nitrate-N lost through leaching between the control and N rates of 179 and 224 kg ha^{-1} detected an increase in nitrate-N leaching loss. Other assessments including regression analysis of total annual mass of nitrate-N leached, repeated measures analysis of nitrate-N concentration, and repeated measures analysis of nitrate-N leaching loss did not show any significant relationship between N rate and nitrate-N leaching.

The corn crop response to applied N is markedly easier to measure than the impacts of applied N on soil nitrate-N concentration and leachate nitrate-N concentration. The above-ground plant matter was found to almost always respond to applied N for a variety of measurements. The N dynamics in the soil are more complicated and more variable because of factors including soil moisture, temperature, and perhaps most importantly, differences in soil properties for areas within the same field. These factors make for more challenging interpretation of soil water nitrate-N concentration values, and they indicate that more research is needed with regards to assessing how nitrate-N moves within the soil medium in irrigated sandy soils.

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Appendix

Table 1. Nitrogen treatments. Each location and year had the same treatments as listed below.

Product	Rate	Treatment Number
	kg N ha^{-1}	
--	0	1
Urea	45	2
Urea	90	3
Urea	134	4
Urea	179	5
Urea	224	6
Urea	269	7
Urea	314	8
ICU	179	9
PCU	179	10
PCU	224	11
PCU/Urea[1]	179	12

[1] Mixture of 50% PCU and 50% urea

Table 2. Precipitation and irrigation data for each location during 2011 and 2012.

Location	Year	Month	Precipitation	Irrigation
			--------------mm--------------	
West, East, Center	2011	May	147	0
		June	61	0
		July	235	0
		August	142	41
		September	17	36
Dakota	2011	May	93	NA
		June	141	NA
		July	122	NA
		August	106	NA
		September	21	NA
West, East, Center	2012	May	163	0
		June	146	83
		July	133	100
		August	70	67
		September	3	21
Dakota	2012	May	205	NA
		June	152	NA
		July	77	NA
		August	43	NA
		September	17	NA

Table 3. Parameters of significant regression models for the variables of N uptake at V8, leaf chlorophyll at V8, NDVI II (Crop Circle) at V8, N uptake at V12, leaf chlorophyll at V12, N uptake in the silage, basal stalk nitrate-N concentration, N in the grain, and grain yield.

	Loc.	Model[1]	-----Model Parameter-----			R^2	*P*>F	Max.	CrL[2]
			a	b	c				
N Uptake V8	Center	QP	18.37	0.22	0.000	0.54	<0.0001	47.7	272.4
	Dakota	QP	29.89	0.20	0.000	0.52	<0.0001	54.2	242.5
	East	LP	76.96	0.16	--	0.62	<0.0001	108.9	202.6
Chlor. V8	All	QP	0.83	0.00	0.000	0.44	<0.0001	1.0	174.2
NDVI II V8	East	L	0.82	0.00	--	0.40	<0.0001	--	--
	West	QP	0.75	0.00	0.000	0.56	<0.0001	0.8	137.9
N Uptake V12	Center	LP	60.63	0.37	--	0.83	<0.0001	163.8	276.8
	Dakota	QP	67.70	0.53	-0.001	0.67	<0.0001	138.1	266.7
	East	L	133.91	0.21	--	0.42	<0.0001	--	--
	West	QP	68.57	0.68	-0.001	0.53	<0.0001	163.0	278.9
Chlor. V12	All	QP	0.74	0.00	0.000	0.70	<0.0001	1.0	228.2

Table 3 continued.

	Loc.	Model[1]	-------Model Parameter------			RSQ	P>F	Max	CrL[2]
			a	b	c				
Silage N Uptake	Center	Q	138.42	0.56	0.000	0.62	<0.0001	1005.8	3076.9
	Dakota	Q	120.68	0.62	-0.001	0.67	<0.0001	241.0	385.0
	West	Q	120.99	0.96	-0.001	0.66	<0.0001	342.6	464.1
Basal Nitrate	All	Q	194.92	-4.89	0.054	0.42	<0.0001	84.8	45.0
Grain N	Dakota	LP	80.06	0.47	--	0.58	<0.0001	160.2	170.7
	East	LP	136.24	0.32	--	0.40	0.0007	224.4	272.2
	West	LP	74.50	0.54	--	0.60	<0.0001	202.4	235.0
Grain Yield	Center	QP	7.35	0.04	0.000	0.41	0.0005	11.6	200.8
	Dakota	QP	7.93	0.05	0.000	0.60	<0.0001	13.5	216.8
	West	QP	5.76	0.06	0.000	0.66	<0.0001	13.5	261.3

[1] L, linear; LP, linear plateau; Q, quadratic; QP, quadratic plateau.

[2] CrL, critical level.

Table 4. Grain yield at 15.5% moisture for 2012 at the East location.

N Rate	Yield
Kg ha^{-1}	---Mg ha^{-1}---
0	10.92
45	11.74
90	11.37
134	12.35
179	12.37
224	12.39
269	13.90
314	13.66

Table 5. NDVI I (Greenseeker) at the V8 growth stage for all four study locations. Data was combined across years at each location. NDVI is a ratio and has no units of measurement.

	Location			
N Rate	Center	Dakota	East	West
ka ha^{-1}	--------------------NDVI---------------------			
0	0.762	0.798	0.848	0.773
45	0.693	0.819	0.856	0.811
90	0.764	0.823	0.856	0.840
134	0.819	0.836	0.861	0.839
179	0.825	0.831	0.867	0.834
224	0.729	0.839	0.863	0.849
269	0.828	0.835	0.864	0.849
314	0.832	0.825	0.862	0.843

Table 6. NDVI I (Greenseeker) at the V12 growth stage for all four study locations. Data was across years at each location. NDVI is a ratio and has no units of measurement.

	Location			
N Rate[1]	Center	Dakota	East	West
kg ha^{-1}	--------------------------NDVI----------------------------			
0	0.801	0.777	0.827	0.800
45	0.805	0.786	0.840	0.825
90	0.810	0.801	0.832	0.831
134	0.819	0.805	0.849	0.831
179	0.820	0.802	0.841	0.832
224	0.823	0.808	0.838	0.841
269	0.833	0.807	0.829	0.843
314	0.820	0.802	0.844	0.835

Table 7. NDVI II (Crop Circle) at the V8 growth stage for the Center and Dakota locations. Years were combined for the Dakota location. NDVI is a ratio and has no units of measurement.

	Location	
N Rate	Center	Dakota
Kg ha^{-1}	---------NDVI----------	
0	0.706	0.736
45	0.676	0.756
90	0.718	0.765
134	0.789	0.782
179	0.807	0.761
224	0.756	0.782
269	0.809	0.763
314	0.814	0.757

Table 8. NDVI II (Crop Circle) at the V12 growth stage for all four study locations. Years were combined for locations with multiple years. NDVI is a ratio and has no units of measurement.

	Location			
N Rate	Center	Dakota	East	West
kg ha^{-1}	----------------------NDVI----------------------			
0	0.780	0.644	0.786	0.739
45	0.787	0.683	0.796	0.790
90	0.784	0.690	0.783	0.790
134	0.790	0.711	0.792	0.795
179	0.798	0.745	0.797	0.798
224	0.785	0.728	0.768	0.806
269	0.802	0.742	0.772	0.798
314	0.805	0.745	0.793	0.797

Table 9. Mean N Uptake for 2011 and 2012 combined for the West location at the V8 growth stage.

N Rate	N Uptake
kg ha^{-1}	---kg ha^{-1}---
0	34.68
45	41.46
90	56.88
134	57.62
179	65.82
224	64.76
269	68.91
314	72.04

Table 10. N uptake at physiological maturity for the East location in 2011.

N Rate	N uptake
kg ha^{-1}	---kg ha^{-1}---
0	238.93
45	169.04
90	189.91
134	214.61
179	282.30
224	277.45
269	274.00
314	323.71

Table 11. Grain N content at the Center location in 2011.

N Rate	Grain N
kg ha^{-1}	---kg ha^{-1}---
0	81.99
45	126.66
90	111.45
134	133.59
179	145.77
224	167.62
269	154.12
314	150.50

Table 12. Correlation between NDVI I (Greenseeker), NDVI II (Crop Circle), N uptake in the biomass, and relative leaf chlorophyll measurements at the V8 stage for all locations and years. N = 24.

	Biomass V8	N Uptake V8	Chlorophyll V8	NDVI I V8
	----------------------------r-----------------------------			
N Uptake V8	0.94	--	--	--
Chlorophyll V8	0.61	0.69	--	--
NDVI I V8[1]	0.53	0.64	0.47	--
NDVI II V8[2]	0.62	0.66	0.62	0.72

[1]NDVI as measured by the Greenseeker.

[2]NDVII as measured by the Crop Circle.

Table 13. Correlation between NDVI I (Greenseeker), NDVI II (Crop Circle), N uptake in the biomass, and relative leaf chlorophyll measurements at the V12 stage for all locations and years. N = 24.

	Biomass V12	N Uptake V12	Chlorophyll V12	NDVI I V12
	-------------------------------r-------------------------------			
N Uptake V12	0.68	--	--	--
Chlorophyll V12	0.54	0.75	--	--
NDVI I V12[1]	0.31	0.61	0.48	--
NDVI II V12[2]	0.03	0.27	0.42	0.47

[1]NDVI as measured by the Greenseeker.

[2]NDVI as measured by the Crop Circle.

Table 14. Correlation between NDVI I (Greenseeker), NDVI II (Crop Circle), relative leaf chlorophyll, and N uptake at the V8 and V12 growth stages and grain yield, grain N, and N uptake in the silage, for all locations and years.

	Yield	Grain N	N Uptake Silage
	---------------------r----------------------		
N Uptake V8	0.45	0.64	0.39
Chlorophyll V8	-0.03	-0.12	0.09
NDVI I V8[1]	0.27	0.25	0.26
NDVI II V8[2]	0.32	0.42	0.47
N Uptake V12	0.62	0.76	0.69
Chlorophyll V12	-0.01	-0.11	0.11
NDVI I V12[1]	0.29	0.43	0.39
NDVI II V12[2]	0.22	0.35	0.41
Yield	--	--	--
Grain N	0.89	--	--
N Uptake Silage[1]	0.52	0.66	--

[1] NDVI as measured by the Greenseeker.

[2] NDVI as measured by the Crop Circle.

Table 15. Effects of treatment, day, and treatment x day interaction for nitrate-N concentrations and leaching at the West, Center, and East locations for 2011 and 2012.

	Center 2011	Center 2012	East 2011	East 2012	West 2011	West 2012
Nitrate-N Conc.		------------P > F------------				
Treatment[1]	0.8605	0.8994	0.2571	0.998	0.7057	0.8218
Day[2]	<0.0001	<0.0001	0.0034	<0.0001	<0.0001	<0.0001
Trt x Day	0.8845	0.8514	0.9779	0.7844	0.1931	0.5221
Nitrate-N Leached						
Treatment[1]	--	0.929	--	0.9498	--	0.6605
Day[2]	--	<0.0001	--	<0.0001	--	<0.0001
Trt x Day	--	0.4793	--	0.1845	--	0.2595

[1] Treatment includes all 12 treatments evaluated in the study.

[2] Day of the year beginning January 1.

Table 16. Mean mass of nitrate-N leached for each passive capillary lysimeter reading event at the West, Center, and East locations for the 2012 growing season.

	Location		
Day[1]	Center	East	West
	-------------kg ha^{-1} day^{-1}---------------		
118	0.237	0.387	0.215
143	0.102	0.150	0.087
151	0.734	1.117	0.621
159	0.248	0.441	0.226
165	0.054	0.087	0.053
172	0.360	0.566	0.347
173	1.392	2.187	1.340
179	0.450	0.820	0.479
185	0.154	0.275	0.168
193	0.052	0.088	0.059

[1] Day of the year.

Table 17. Cumulative quantity of nitrate-N leached per year[1] at the East and West locations for 2012.

	Location	
N Rate	East	West
kg ha^{-1}	---kg ha^{-1} yr^{-1}---	
0	39.16	12.36
44.8	--	--
89.6	--	--
134.4	49.43	20.78
179.2	49.74	22.60
224	40.27	26.51
268.8	30.61	33.18
313.6	--	--

Table 18. RE at physiological maturity for all locations. Years were combined for locations with multiple years. RE is a fraction of recovered fertilizer N and is unitless.

	Location			
N Rate	Center	Dakota	East	West
Kg ha^{-1}	-------------RE[1] -------------			
45	-0.396	0.518	-0.656	0.155
90	0.263	0.626	-0.095	0.840
134	0.726	0.490	0.120	0.901
179	0.501	0.477	0.468	0.746
224	0.413	0.395	0.353	0.728
269	0.442	0.455	0.281	0.749
314	0.532	0.360	0.400	0.583

[1] RE expressed as grams N recovered to grams N applied.

Table 19. AE for all study locations. Years were combined for locations with multiple years. AE is a fraction of recovered fertilizer N and is unitless.

	Location			
N Rate	Center	Dakota	East	West
Kg ha^{-1}	------------------AE[1]------------------			
45	1.100	0.506	0.297	0.303
90	0.453	0.590	0.081	0.856
134	0.457	0.559	0.172	0.624
179	0.463	0.478	0.131	0.573
224	0.361	0.387	0.106	0.536
269	0.270	0.294	0.178	0.442
314	0.194	0.269	0.141	0.353

[1] AE expressed as grams N recovered to grams N applied.

Table 20. Residual soil nitrate-N from 0-60 cm for all locations. Years were combined for locations with multiple years.

	Location			
N Rate	Center	Dakota[1]	East	West
Kg ha^{-1}	------------kg nitrate-N ha^{-1}--------------			
0	10.00	21.00	7.33	10.33
45	--	--	--	--
90	--	--	--	--
134	12.00	28.50	9.33	12.33
179	18.00	29.25	18.00	20.00
224	26.67	30.75	27.33	23.00
269	18.00	60.50	19.33	24.00
314	--	--	--	--

[1] Dakota location was soil sampled to a depth of 0-122 cm.

Table 21. Mean of N uptake at V8, V12, and R6, NDVI I (Greenseeker) at V8 and V12, NDVI II (Crop Circle) at V8 and V12, basal stalk nitrate-N concentration, RE, residual soil nitrate-N, AE, and grain N content for urea and coated urea product treatments at the East, West, Center, and Dakota locations in 2011 and 2012 for N rates of 0, 179, or 224 kg ha^{-1}.

Product	N Rate	N Uptake V8[1]	NDVI I V8	NDVI II V8	N Uptake V12[1]	NDVI I V12	BSN[2]	Silage N[1]	RE	RSN[3]	AE	Grain N[1]
	kg ha^{-1}	Mean										
--	0	37.7b	0.710b	0.749b	79.1c	0.800b	35c	152.7c	na	14.1c	na[4]	92.67b
Urea	179	65.0a	0.730ab	0.802a	143.1ab	0.821a	1108ab	242a	0.56a	23.1ab	0.449a	164.56a
Urea	224	65.1a	0.765a	0.802a	150.6a	0.826a	1432a	251.6a	0.51ab	27.3a	0.385abc	181.51a
ICU	179	63.6a	0.740ab	0.794a	134.5b	0.819a	673bc	236.8ab	0.55a	19.0bc	0.375abc	153.88a
PCU	179	64.5a	0.762a	0.793a	132.8b	0.822a	578bc	240a	0.56a	20.3bc	0.411ab	157.11a
PCU	224	62.0a	0.735ab	0.799a	149.8a	0.825a	1597a	254.6a	0.52ab	na	0.362bc	171.66a
PCU/U	179	61.8a	0.744ab	0.800a	133.3b	0.827a	385bc	215.7b	0.43b	24.4 ab	0.318c	149.17a

[1] Kg ha^{-1} Total plant N

[2] Mg kg^{-1} Nitrate-N

[3] Kg ha^{-1} Nitrate-N to 60 cm depth

[4] Not applicable

Table 22. Mean of SPAD reading at V8 and V12, NDVI II (Crop Circle) at V12, and corn grain yield for urea and coated urea product treatments at the West, Center, and East locations for N rates of 0, 179, or 224 kg ha^{-1}.

Location	Year	Product	N Rate	Chlorophyll V8[1]	Chlorophyll V12[1]	NDVI II V12	Grain yield[2]
			kg ha^{-1}	---Mean---			
West	2011 and 2012	--	0	74.8b	66.6b	0.739b	6.20c
		Urea	179	99.5a	97.7a	0.795a	12.58ab
		Urea	224	99.7a	99.2a	0.806a	13.67a
		ICU	179	97.4a	95.0a	0.791a	12.27ab
		PCU	179	100.2a	98.6a	0.799a	12.65ab
		PCU	224	100.6a	99.1a	0.795a	13.17a
		PCU/U	179	100.3a	99.1a	0.808a	11.69b
Center	2011	--	0	82.2b	76.6b	0.780a	6.92b
		Urea	179	98.6a	96.6a	0.798a	12.09a
		Urea	224	103.1a	100.0a	0.785a	11.95a
		ICU	179	98.2a	98.2a	0.792a	11.66a
		PCU	179	99.5a	97.8a	0.802a	11.12a
		PCU	224	98.9a	98.7a	0.801a	10.90a
		PCU/U	179	105.6a	100.2a	0.786a	10.55a
East	2012	--	0	91.4c	85.7c	0.786a	8.13a
		Urea	179	99.7ab	96.6ab	0.797a	13.46a
		Urea	224	101.8a	96.4ab	0.768a	13.53a
		ICU	179	97.6ab	96.8ab	0.798a	12.72a

Table 22 continued

Location	Year	Product	N Rate	Chlorophyll V8[1]	Chlorophyll V12[1]	NDVI II V12	Grain yield[2]
			kg ha^{-1}	--Mean---			
East	2012	PCU	179	96.9b	92.7b	0.784a	12.91a
		PCU	224	98.6ab	98.8a	0.787a	13.58a
		PCU/Urea	179	97.3ab	96.2ab	0.802a	12.99a

[1] Percent of mean chlorophyll value from plots applied with 314 kg N ha^{-1}

[2] Mg ha^{-1} at 15.5% moisture

Table 23. Mean NDVI II (Crop Circle) from the urea and coated urea product treatments at the Dakota location in 2011 and 2012 for N rates of 0, 179, or 224 kg ha^{-1} at the V12 stage.

Location	Year	Product	N Rate	NDVI II[1]
			kg ha^{-1}	
Dakota	2011	--	0	0.741b
		Urea	179	0.783a
		Urea	224	0.778a
		ICU	179	0.773a
		PCU	179	0.773a
		PCU	224	0.778a
		PCU/Urea	179	0.779a
Dakota	2012	--	0	0.547b
		Urea	179	0.708a
		Urea	224	0.678a
		ICU	179	0.700a
		PCU	179	0.653a
		PCU	224	0.679a
		PCU/Urea	179	0.630a

[1] Greenseeker NDVI

Table 24. Mean SPAD readings at V8 and V12, and grain yield from the urea and coated urea product treatments at the Dakota location in 2011 and 2012 for N rates of 0, 179, or 224 kg ha^{-1}.

Location	Year	Product	N Rate	Chlorophyll V8[1]	Chlorophyll V12[1]	Yield[2]
			kg ha^{-1}	%	%	Mg ha^{-1}
Dakota	2011- 2012	--	0	86.1b	75.5b	8.13b
		Urea	179	100.2a	99.0a	13.46a
		Urea	224	101.1a	97.6a	13.52a
		ICU	179	100.9a	95.8a	12.72a
		PCU	179	102.1a	95.2a	12.91a
		PCU	224	99.9a	96.9a	13.58a
		PCU/Urea	179	102.6a	96.1a	13.00a

[1] Percent of mean chlorophyll value from plots applied with 314 kg N ha^{-1}

Table 25. Mean nitrate-N leached from the urea and coated urea product treatments for the East and West locations in 2012 at N rates of 0, 179, or 224 kg ha^{-1}.

Location	Year	Product	N Rate	NO_3-N Leached[1]
			kg ha^{-1}	----kg ha^{-1}-----
East	2012	--	0	39.16a
		Urea	179	49.74a
		Urea	224	40.27a
		ICU	179	38.91a
		PCU	179	33.88a
		PCU	224	na[2]
		PCU/Urea	179	34.38a
West	2012	--	0	12.36b
		Urea	179	22.60a
		Urea	224	26.51a
		ICU	179	20.92ab
		PCU	179	27.55a
		PCU	224	NA
		PCU/Urea	179	18.41ab

[1] Quantity of nitrate-N leached per year in kg ha^{-1}

[2] Not applicable

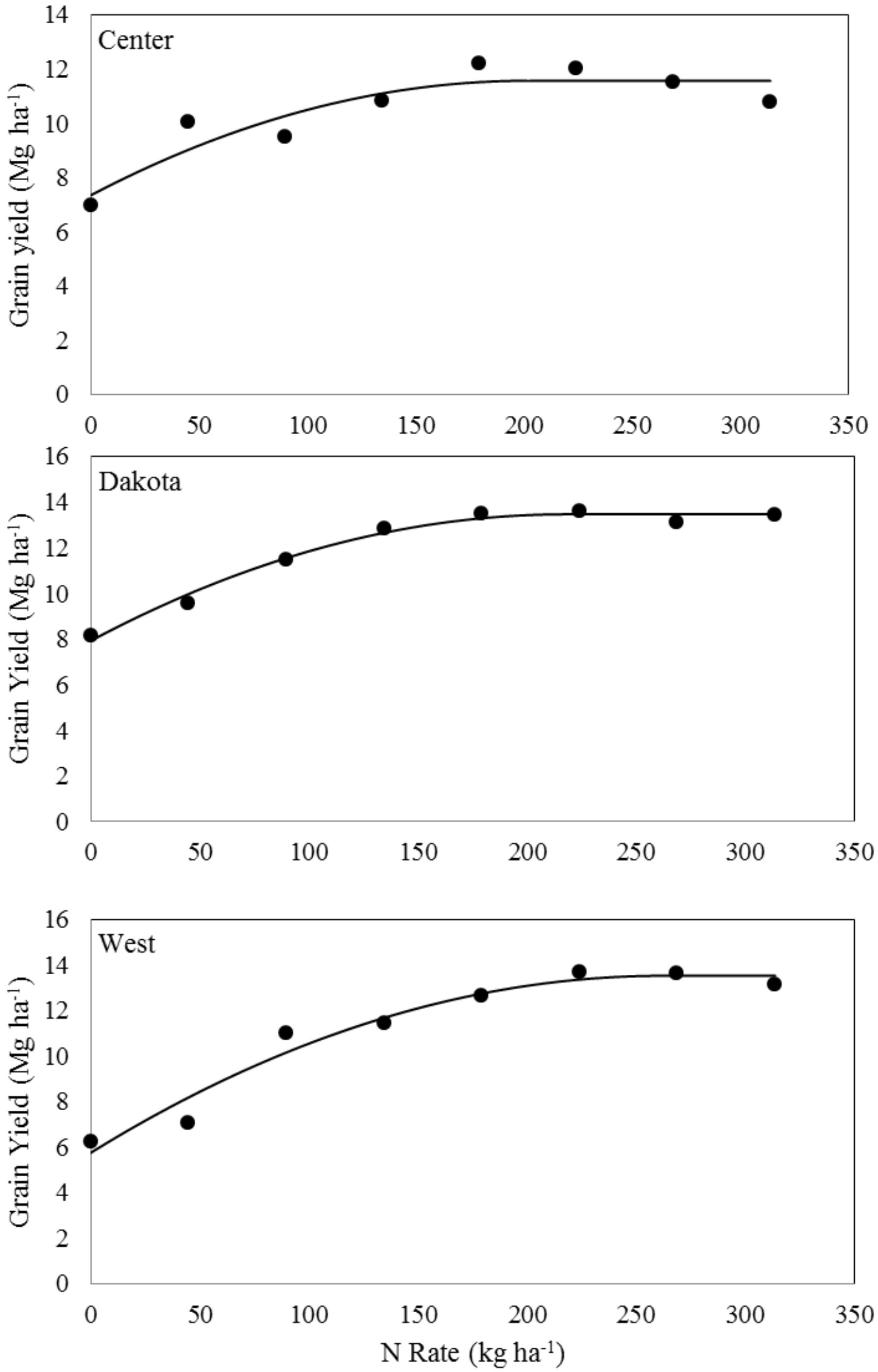

Fig. 1. Corn grain yield at 15.5% moisture as affected by N rate for the Center, Dakota, and West locations. Years were combined for locations with multiple years.

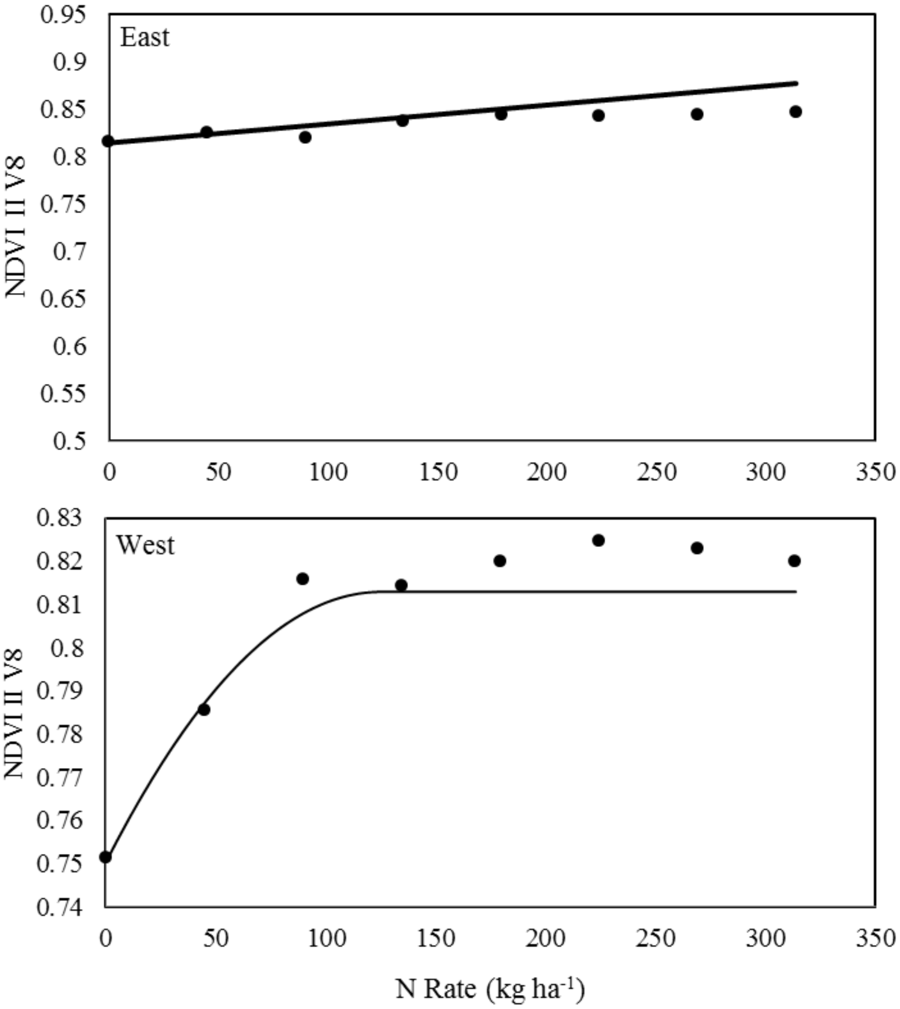

Fig. 2. NDVI II (Crop Circle) at the V8 growth stage as affected by N rate for the East location for 2012 and for the West location for 2011 and 2012 combined. NDVI is a ratio and is unitless.

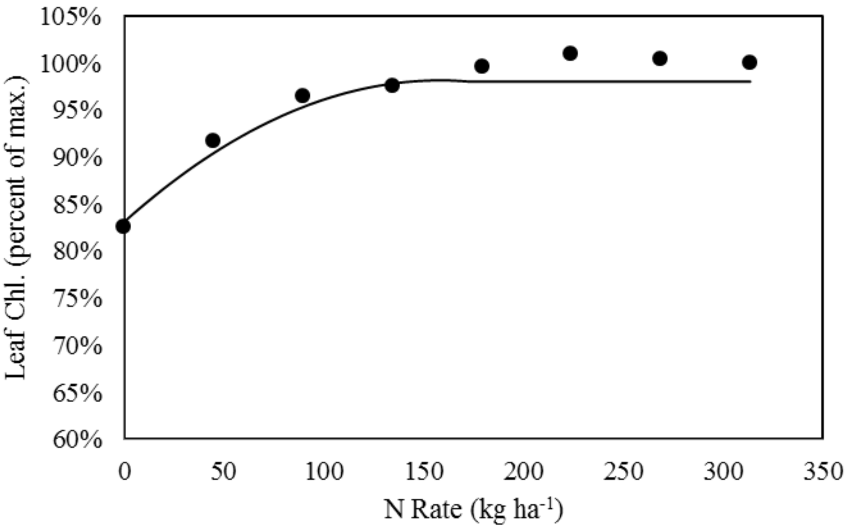

Fig. 3. Leaf chlorophyll measurements as affected by N rate at the V8 growth stage, averaged across all locations and years. Values were calculated as a proportion of the maximum mean leaf chlorophyll reading from each location and year.

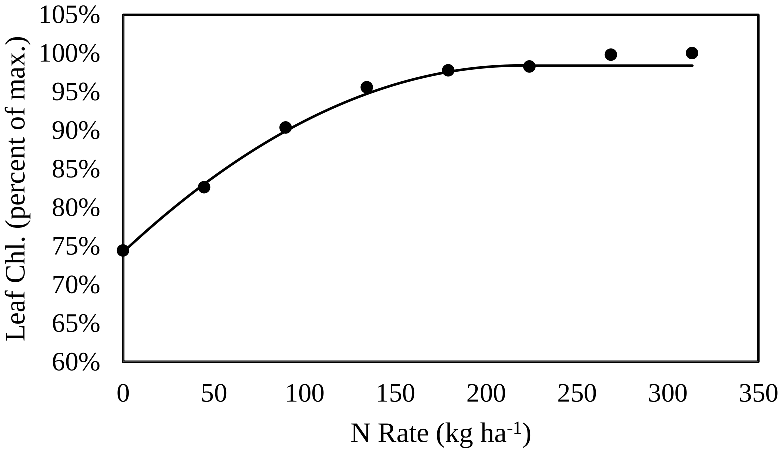

Fig. 4. Leaf chlorophyll measurements as affected by N rate at the V12 growth stage, averaged across all locations and years. Values were calculated as a proportion of the maximum mean leaf chlorophyll reading from each location and year.

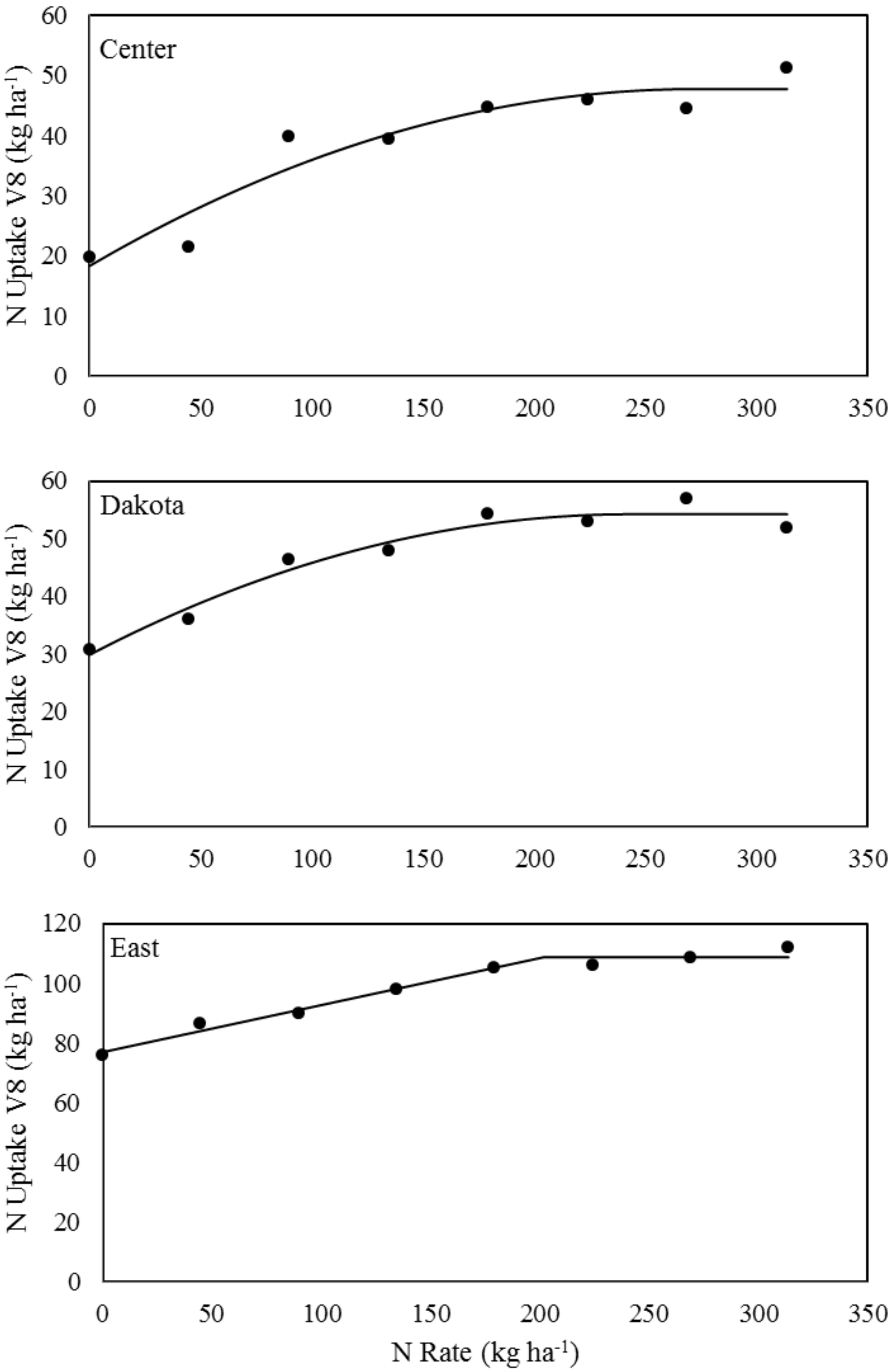

Fig. 5. N uptake in the biomass at the V8 growth stage as affected by N rate for the Center, Dakota, and East locations. Years were combined for locations with multiple years.

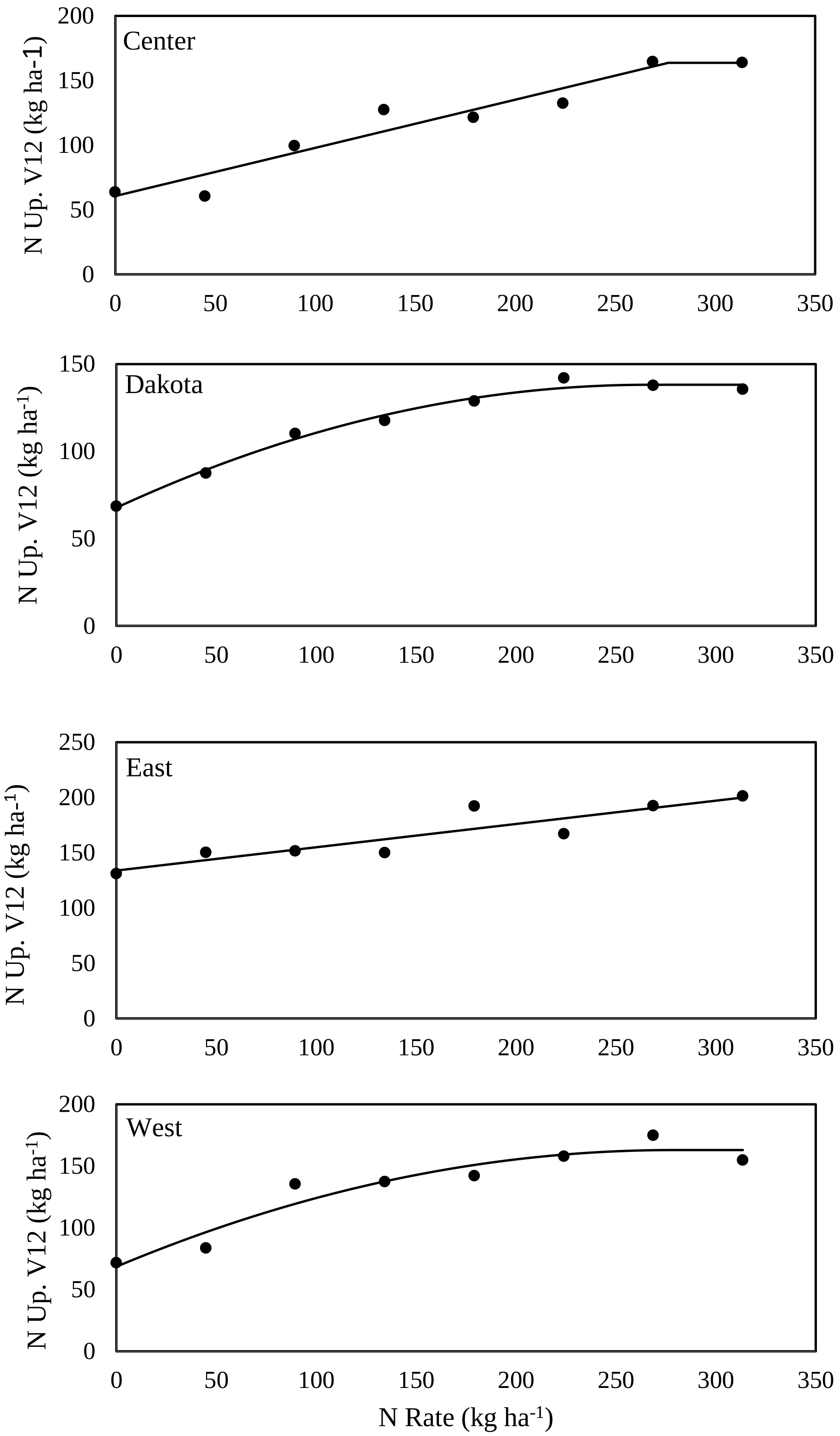

Fig. 6. N uptake at the V12 growth stage as affected by N rate for all four study locations. Years were combined for locations with multiple years.

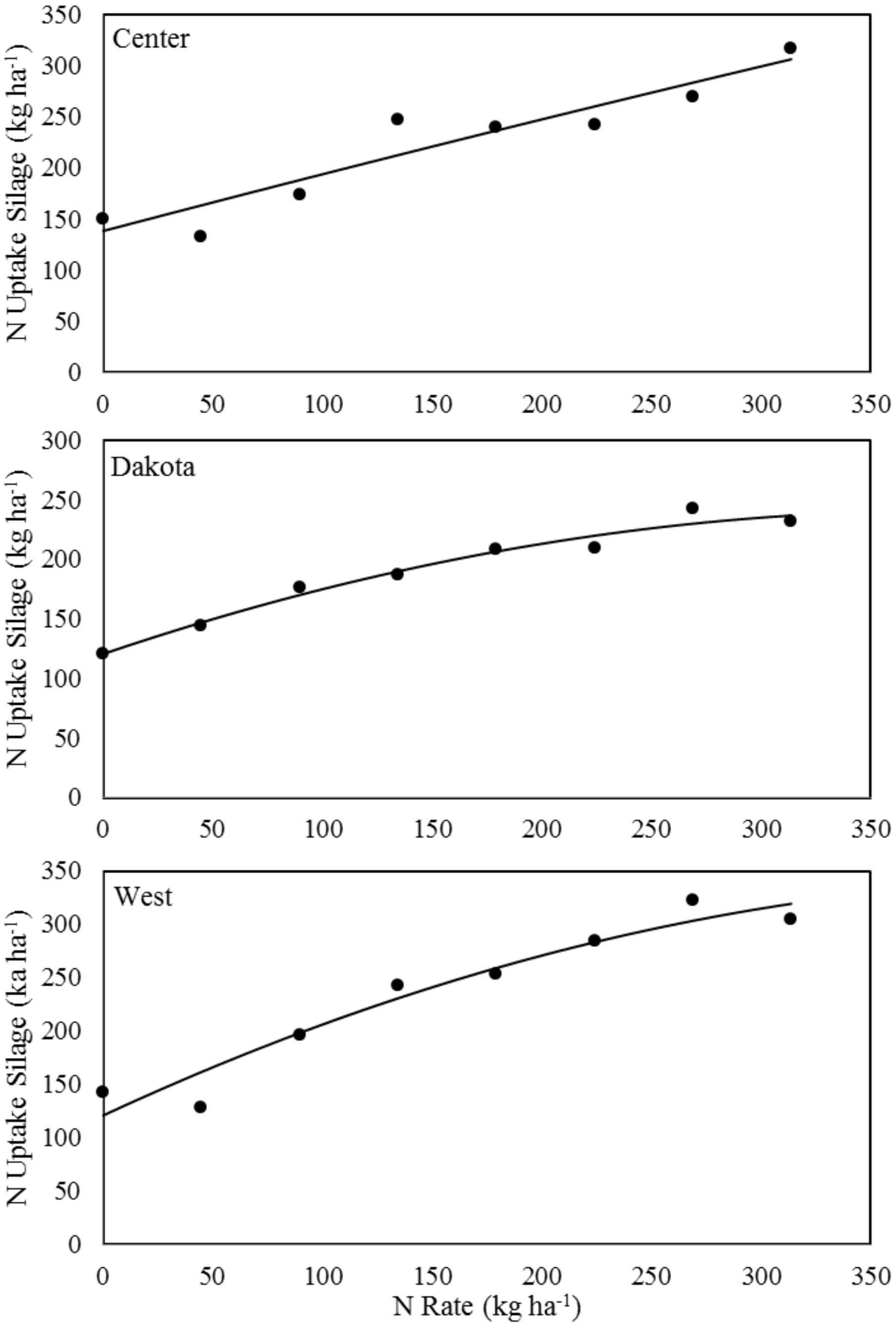

Fig. 7. N uptake in the silage as affected by N rate at the Center, Dakota, and West locations. Years were combined for locations with multiple years.

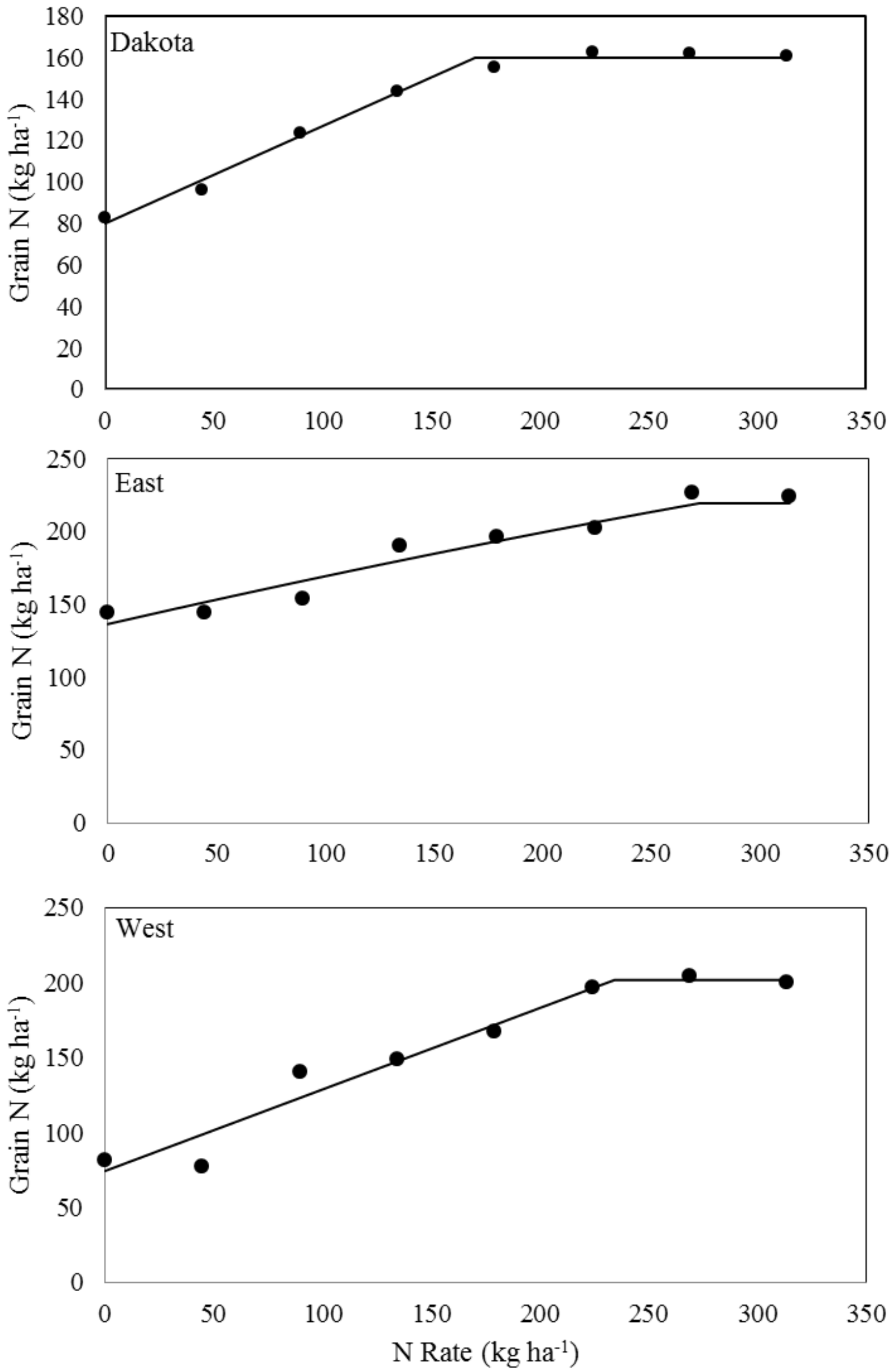

Fig. 8. Quantity of N in the corn grain as affected by N rate for the Dakota, East, and West locations. Years were combined for locations with multiple years.

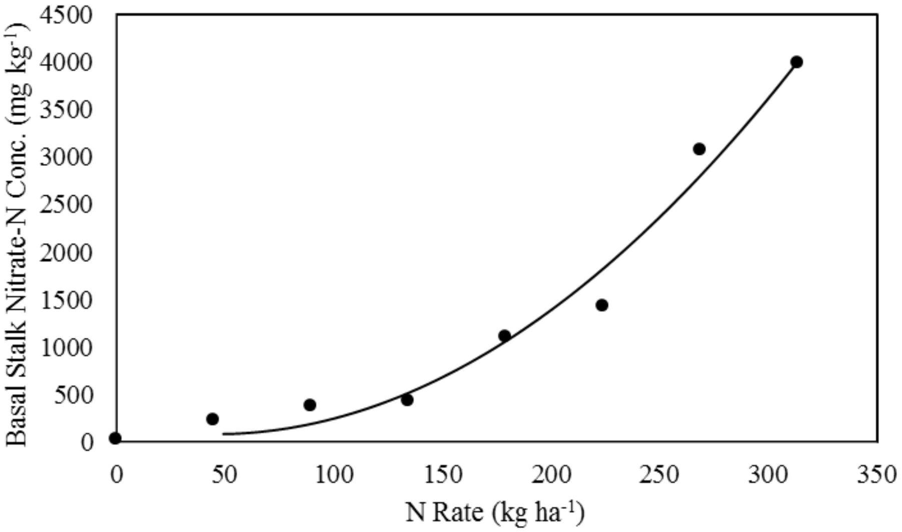

Fig. 9. Nitrate-N concentration in the basal stalk tissue as affected by N rate, averaged across all locations and years.

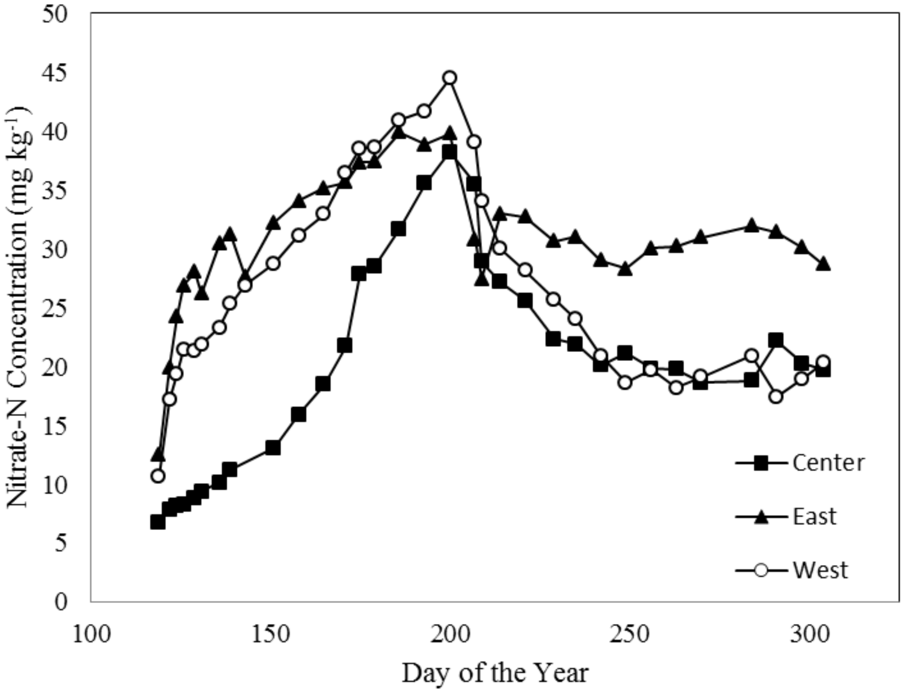

Fig. 10. Mean water nitrate-N concentration for all treatments at the West, Center, and East locations for the 2011 growing season.

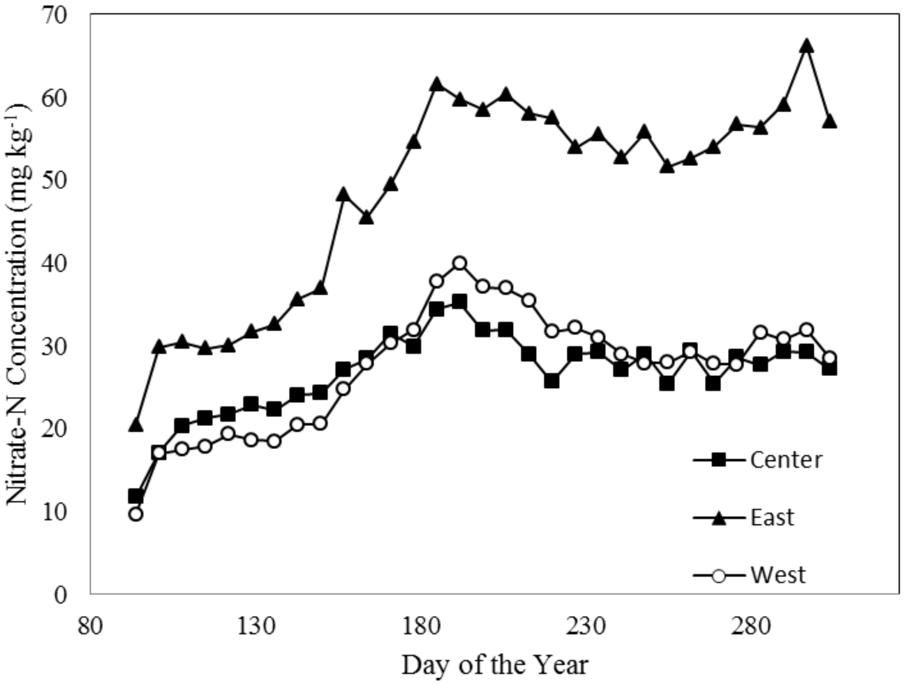

Fig. 11. Mean water nitrate-N concentration for all treatments at the West, Center, and East locations for the 2012 growing season.