Improving Maize Production and Ground-Water Quality through Nitrogen Management in Minnesota's Irrigated Coarse-Textured Soils

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Abstract

Elevated groundwater nitrate (NO_3-N) concentrations in irrigated sandy soils under corn (*Zea mays* L.) production in the Midwest is of increasing concern, and has prompted the need to identify new or enhanced nitrogen (N) management practices in these areas. The objective of this study was to evaluate agricultural technologies that may improve N management for profitable corn production and mitigate negative effects of NO_3-N in groundwater. From 2011 to 2014 corn was grown at two sites in Minnesota on sandy soils, Dakota County, MN with a continuous corn (CC) rotation and Pope County, MN with a CC, corn after soybeans (CSB), and soybean after corn (SbC) rotations. Twelve treatments were applied including urea broadcast at rates of 0, 45, 90, 135, 180, 225, 270, and 315 kg N ha^{-1} as a split application, half at pre-plant and half at the V4 development stage, pre-plant Super U at 180 kg N ha^{-1}, and pre-plant ESN at 180 and 225 kg N ha^{-1}. Canopy sensing with SPAD, GreenSeeker, and Crop Circle was done at V8 and V12 and NO_3-N basal stalk measurements at R6 development stage. Soil water NO_3-N samples were collected weekly throughout the growing season below the rooting zone using suction lysimeters. The mean Maximum Return to N (MRTN) was 231 kg ha^{-1} and produced a mean-yield increase above the unfertilized check of 6.5 Mg ha^{-1}. Canopy sensors and plant measurements provided limited utility and generally under-predicted N needs. Nitrogen use efficiency and yields were increased with split-applied urea compared to all other pre-plant sources at 180 kg N ha^{-1}, but no reduction in NO_3-N leaching occurred. Season-long NO_3-N concentrations ranged from 10 to 46 mg L^{-1} and overall annual loss was 27 to 41 kg NO_3-N ha^{-1}. Reducing N rate below the MRTN substantially reduced yield without reducing NO_3-N leaching losses.

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Chapter 1

Maize Yield and Nitrogen Use Efficiency in Upper Midwest Irrigated Sandy Soils

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1.1 Overview

Corn (*Zea mays* L.) in irrigated coarse-textured soils can be very productive with N applications, but excess N can increase groundwater contamination. Our objectives were to (i) determine the economic optimum N rate (EONR) for continuous corn (CC) and corn after soybean [*Glycine max* (L.) Merr.] (CSb), (ii) evaluate corn yield and N use efficiency (NUE) of split urea-N and single pre-plant application of enhanced-efficiency fertilizers, and (iii) determine the utility of canopy sensors and basal stalk nitrate-N test to manage N. Rotations of CC in Dakota County, MN and CC, CSb , and soybean after corn (SbC) in Pope County, MN were established in 2011-2014 with 0, 45, 90, 135, 180, 225, 270, and 315 kg urea-N ha^{-1} as split-application (half at pre-plant and half at V4), and pre-plant applications of SuperU at 180 kg N ha^{-1}, ESN/urea blend 90/90 kg N ha^{-1}, and ESN at 180 and 225 kg N ha^{-1}. The EONR for CC was 231 kg N ha^{-1}. The fertilizer replacement value in CSb was 77 kg N ha^{-1} and the EONR was 30 kg N ha^{-1} less than in CC. Canopy sensors and basal stalk nitrate-N generally under estimated N rate. A split-urea application increased corn grain yield by 5.4% (0.63 Mg ha^{-1}), partial factor productivity (PFP) by 6% and agronomic efficiency (AE) by 12% relative to mean single pre-plant application of enhanced-efficiency fertilizers. In irrigated sandy soils, applying high rates of N needed for economic optimum yield is best accomplished by splitting the application.

Abbreviations: AE, agronomic efficiency; AONR, agronomic optimum N rate; BMPs, best management practices; CC, continuous corn; CSb, corn after soybean; EONR, economic optimum N rate; FRE, fertilizer recovery efficiency; NDRE, Normalized difference red edge; NDVI, normalized vegetation index; NIR, near-infrared spectroscopy; NUE, N use efficiency; PFP, partial factor productivity; RSN, residual soil nitrate-N; SbC, soybean after corn.

1.2 Introduction

Minnesota has approximately 7 million ha in agricultural production of which nearly 3% (approximately 202,500 ha) are irrigated sandy soils (USDA/NASS, 2012). Even though this is only a small portion of the total agricultural land, these soils are important because of their high productivity potential and environmental sensitivity. These soils are formed from glacial outwash, and are characterized by their coarse texture, low nutrient holding capacity, and high water infiltration rate. At least half of these hectares are in corn production each year. Nitrogen fertilization is critical for profitable corn production on these soils because N is often the most limiting nutrient for the crop and corn has large N requirements. Further, because these sandy soils have high infiltration rates and low water holding capacities, corn 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 though the soil profile and below the rooting zone (Smika et al., 1977). Once nitrate moves below the rooting zone, it cannot be taken up by the crop. This not only reduces N use efficiency by the crop, but it can lead to groundwater contamination with nitrate.

Nitrate contamination of groundwater is an important concern as a large number of cities in the Upper Midwest depend on ground water for their drinking water supply (Gehl et al., 2005). Once ground water is contaminated, to make it suitable for human consumption it must undergo costly treatment. According to Compton et al., (2011) the cost is $0.54 per ha. Nitrate in drinking water possess potential human health concerns. The drinking water standard for water nitrate concentration is 10 mg kg^{-1} (US EPA, 2012). Infants who ingest water containing nitrate levels above the drinking water standard may suffer shortness of breath and methemoglobinemia, also known as Blue Baby Syndrome, which can be fatal (US EPA, 2012). For these reasons, to help ensure a safe drinking water supply, best management practices (BMPs) should be identified and followed (Klocke et al., 1999).

Nitrogen fertilizer management for corn production has been studied at length for many different production systems, including irrigated sands. However, there has been a renewed interest in sensitive sandy soils because of environmental and health risks and the need to improve nutrient use efficiency. Because fertilizer rate substantially influences productivity and environmental quality, this variable has been studied most extensively. However, continual research is needed to assess and re-assess corn response under current management and growing-season conditions. For example, in 2015 the University of Minnesota updated their N rate guidelines for corn grown in irrigated sandy soils based on recent findings indicating a substantial increase in N rate was needed relative to the previous guideline (Lamb et al., 2015).

In addition to rate, however, there are other practices and tools that can be used to enhance N management. Timing of application can be especially useful in sandy soils where there is large potential for leaching losses if all the N needed is supplied early in the growing season, and where fertigation can effectively be used to provide N at different times in the season. In Kansas, at least one fertigation application of N at the V6 development stage resulted in improved yield components and corn grain yields relative to no fertigation (Lamm and Shlegel, 2013). Another study, also in Kansas, showed that on average split-applications can reduce N rate by 88 kg N ha^{-1} (approximately 40%) relative to a single application (Gehl et al., 2005). Minnesota's N BMPs also identified split-applications of N as more effective than a single pre-plant application (Lamb et al., 2015).

Crop canopy sensing technologies can aid the decision making process for in-season N applications, but further refinements are needed. For example, Martin et al. (2007) found that measurements taken from the V8 to the V12 development stages are the best indicators of corn grain and plant biomass yields in comparison with measurements taken earlier or later than that in the growing season. After the V12 stage, NDVI is generally lower and more variable because tassels begin to turn yellow and some leaves start to senesce. Conversely, before the V8 stage, variability in NDVI measurements is high because of the low canopy signal to soil noise ratio as the crop canopy has not filled in the inter-rows (Martin et al., 2007). The orientation of the sensor may be another refinement needed to use these technologies. Scharf and Lory (2009) found higher correlation values at various reflectance wavelengths in the straight down orientation than with angled orientations. While canopy sensing technologies are being used extensively for in-season N management, these technologies have not been investigated at length for N management for corn in irrigated soils, but some studies indicate these technologies hold promise (Blackmer & Schepers, 1995; Dellinger et al., 2008; Osborne et al., 2002).

Lastly, the source of N is another important management decision that can aid in improving NUE. Traditionally granular urea and to a less extent anhydrous ammonia have been the most common N sources for irrigated sands and the sources most intensively investigated. A recent survey in Minnesota indicated that 67% of farmers used urea as their primary N fertilizer source in coarse-textured soils (Bierman et al., 2011). Many studies have shown that on coarse textured soils, high corn yields can be achieved with high NUE and low residual soil nitrate-N (RSN) by implementing proper management (Wortmann et al., 2011). In addition to split-N applications, other alternatives such as the use of polymer-coated urea or urea with urease and nitrification inhibitors may provide benefits when a single pre-plant application is desired. However, research needed to document the efficiency of these sources to improve NUE in irrigated sandy soils is lacking. A study by Halvorson and Bartolo (2014) comparing granular urea, ESN, and SuperU on a coarse textured soil in a continuous corn rotation located in western Arkansas, found ESN had a grain yield advantage over granular urea two out of three years and resulted in 4 to 14% greater economic return. Conversely, SuperU had no yield or economic advantage over urea (Halvorson and Bartolo, 2014). Also, Zhao et al. (2013) found different coated urea products produced 10-14% greater grain yields than granular urea, and NUE increased from 6.66 kg grain kg $^{-1}$ N for granular urea to 14.50 kg grain kg $^{-1}$ N for the resin coated urea in Eastern China. Several studies have been done in Central Minnesota comparing ESN to urea applied for irrigated potatoes. While ESN has no significant difference in tuber yields, ESN reduced nitrate leaching (Waddell et al., 1999; Wilson et al., 2010; Zvomuya et al., 2003) as well as decreased nitrous oxide (N_2O) emissions from approximately 1.36 kg N_2O-N ha^{-1} with a conventional split-application of urea to 1.13 kg N_2O-N ha^{-1} with ESN (Hyatt et al., 2010).

These studies illustrate the potential of alternative N sources and timing of application to improve NUE or increase yield on irrigated sands, while also having potential environmental benefits. However, these technologies and management practices have not been investigated at length for irrigated sandy soils for corn production in the Upper US Midwest. Additional work is needed to better understand the potential benefit of these sources and timing of N application under different climatic and soil conditions in the region. Undoubtedly, an improved understanding on the use of alternative N sources and the role of timing of N application along with the ability to predict N needs in-season is important to increase NUE in irrigated sandy soils of the Upper US Midwest.

The objectives of this study were to (i) determine the EONR for corn in irrigated sandy soils, (ii) evaluate and compare corn grain yield and NUE of traditional split urea-N applications to single pre-plant ESN, ESN/urea blend, and SuperU applications, and (iii) determine the utility of canopy sensing technologies to predict yield in-season. An additional objective was to evaluate the effect of soybean grown in rotation with corn under irrigated sandy soils on corn yield and NUE.

1.3 Materials and Methods

1.3.1 Site Description

Field trials were conducted from 2011 to 2014 in two counties in Minnesota, USA. In Dakota County (44°42'09.9"N 92°56'26.9"W) the study was established on a Sparta loamy fine sand (Sandy, mixed, mesic, Entic Hapludolls) in 2011 through 2013. In 2014 the study was conducted on a new location (44°41'53.7"N, 92°56'33.2"W) on a

Waukegan silt loam (Fine-silty over sandy or sandy-skeletal, mixed, superactive, mesic Typic Hapludolls). Both locations were in farmer's fields. In Pope County (45°42'49.1"N, 95°10'16.2"W) the study was established in the same location for four years on an Arvilla sandy loam (Sandy, mixed, frigid Calcic Hapludolls) with a sandy/ gravelly outwash parent material. The slope at all locations was between 0 and 2%. The Dakota Co. locations were in continuous corn. The Pope Co. location was divided into three adjacent blocks (West, Center, and East) to accommodate CC on the West block and a corn-soybean rotation with both crops growing each year with the corn phase (CSb) on the Center block in 2011 and 2013 and on the East block in 2012 and 2014 with the soybean phase (SbC) on the alternate block. While both sites were irrigated, irrigation data were only collected for Pope Co. from 2012-2014. Irrigation was applied 13 times in 2012 (332 mm), 11 times in 2013 (310 mm), and 6 times in 2014 (136 mm). Mean irrigation water nitrate levels were <10 mg L^{-1}. Thus, total N applied with irrigation water was less than 30 kg N ha^{-1} yr^{-1}. Because of the small amount of N this represents and the fact that nitrate levels <10 mg L^{-1} can be considered background levels in many places in Minnesota, we did not make adjustments to our N rate calculations.

1.3.2 Treatments

All plots were 4.56 meters (six-76 cm row spacing) by 12.2 meters. The same 12 fertilizer treatments were applied in all site-years as a broadcast application incorporated by rain or irrigation. The treatments remained in the same plots every year. Eight treatments included granular urea (46-0-0) (N-P-K) at 45 kg N ha^{-1} rate increments from

45 to 315 kg N ha^{-1} and a check with no N applied. Each of these rates were split-applied with half of the rate at pre-plant and the other half at the V4 development stage. The remaining four treatments were applied at pre-plant: 180 and 225 kg N ha^{-1} as polymer-coated urea, ESN (44-0-0) (Agrium Advanced Technologies, Loveland, CO); 180 kg N ha^{-1} as urea with N-(n-butyl) thiophosphoric triamide (NBPT) and Dicyandiamide (DCD), Super U (46-0-0) (Koch Fertilizer LLC, Wichita, KS); and 90-90 kg N ha^{-1} as a blend of ESN-urea. The 12 treatments were arranged in a randomized, complete block design with four replications for a total of 48 plots. In Pope Co. treatments were only applied to the corn crop.

In Dakota Co. from 2011 to 2013 a starter with ammonium sulfate (21-0-0-24) was applied to all plots at a rate of 28 kg ha^{-1} because of a field history of sulfur deficiency likely related to the low organic matter content of this sandy soil. Phosphorus, potassium, and sulfur fertilizers with no N were added at the beginning of each growing season at the Pope Co. location to ensure adequate availability of these nutrients. Other agronomic practices included pest and weed control as deemed needed and irrigation at each location was scheduled based on rainfall, plant water use, and soil conditions to maximize yield. Primary tillage was done with a chisel plow in the fall and with a field cultivator in the spring before planting at both locations. In Dakota Co., hybrid Dekalb DKC 4812 was planted on 6-May-2011, 4-May-2012, and 10-May-2013, and hybrid Pioneer P0533AMI on 7 May 2014. In Pope Co., corn plots were planted with hybrid Croplan Acceleron 339OUT3/P on 11-May-2011 and 25-April-2012 and with corn hybrid Dekalb DKC 50-77 RIB on 20-May-2013 and 15-May-2014. At both locations corn was planted at a population of 86,500 plants ha^{-1}. The soybean rotation for Pope Co. was planted with soybean variety Croplan R2T 1193 with a population of 445,000 plants ha^{-1}, on the same planting dates as corn.

1.3.3 Plant Tissue Sampling

Stand counts were taken after emergence by counting the number of plants in 12.2 meters of row. Crop development stages were determined after Abendroth et al., (2011) for corn and after Licht, (2007) for soybean. Total N uptake was measured from whole plant samples at the V8, V12 and R6 development stage in corn by cutting six random representative plants at the soil surface from rows two and five of each plot. Plant samples were passed through a chipper with a 0.5 cm screen, dried at 60°C, and weighed. The dry samples were thoroughly mixed and a subsample was ground with a Thomas Wiley mill with a 2mm-sized screen. Total N of the ground-plant samples was measured at the University of Minnesota Research Analytical Laboratory by combustion analysis with a LECO FP-528 N Analyzer (Simone et al., 1994). Corn basal stalk samples were collected during harvest by cutting a 20cm section of the corn stalk 2cm above the soil surface. Samples were dried at 60°C, weighed, and analyzed for total nitrate-N as described by Gavlak et al. (2005). Grain harvest was done on 20-Oct-2011, 11-Oct-2012, 02-Oct-2013, and 07-Oct-2014 at Dakota Co. and on 27-Oct-2011, 17-Oct-2012, 05-Nov-2013, and 14-Oct-2014 at Pope Co. for corn, and on 03-Oct-2011, 11-Oct-2012, 24-Sept-2013, and 08-Oct-2014 for soybean, by harvesting 6.1 m of the center two rows of each plot. Corn ears were shelled and moisture content determined. Grain samples were oven-dried at 50°C, ground as described above for biomass samples, corn grain yield was corrected to 155 g kg^{-1} and soybean grain yield to 130 g kg^{-1} moisture and analyzed for N using Near-Infrared Spectroscopy (NIR) (Simone et al., 1994), at the University of Minnesota Research Analytical Laboratory.

1.3.4 Optical Canopy Sensing

We conducted optical canopy sensing for corn with three devices at V8 and V12 development stages. Corn plants were measured with the GreenSeeker model 505 (Trimble Navigation Limited, Sunnyvale, CA) at 656 nm (red) and 774 nm (NIR) that allowed us to calculate NDVI; Crop Circle model 470 (Holland Scientific Inc., Lincoln, NE) at 670 nm (red), 780 nm (NIR), and 730 nm (red edge) that allowed us to calculate NDVI and NDRE; and with the SPAD chlorophyll meter at 650 nm (red) and 940 nm (NIR) (Konic Minolta, Inc., Tokyo, JP). The Greenseeker and Crop Circle measurements were done by holding each device approximately 40 cm above the canopy directly on top of the center rows (row three and four) for the entire length of the plot. For SPAD chlorophyll meter measurements we sampled the leaf opposite and below the ear at halfway between the tip and the collar and halfway between the margin and the midrib of the leaf of 30 randomly selected plants within the two center rows.

1.3.5 Soil Sampling

Soil samples were collected after grain harvest for the control, urea rates of 135, 180, 225, 270 kg N ha^{-1}, and 180 kg N ha^{-1} rate for ESN, SuperU, and ESN/urea blend. Soil samples for the 225 kg N ha^{-1} rate for ESN were also collected, except in 2011 in CSb in

Pope Co. and CC in Dakota Co. in 2012. Two soil cores per plot (six meters apart) were taken with a 5 cm diameter hydraulic soil probe and mixed into one composite sample. At the Dakota Co. location the cores were taken to a depth of 120 cm in 2011 through 2013, and only to 60cm in 2014 because of a dense gravel layer. Similarly, because the subsoil at the Pope Co. site is gravelly, soil cores were only taken to 60 cm depths, cores were divided into 30 cm depth increments, dried at 35°C to consistent weight, ground through a 2 mm sieve, and analyzed for nitrate-N (Gelderman and Beegle, 1998).

1.3.6 Nitrogen Use Efficiency Calculations

Treatment efficiency was calculated as fertilizer recovery efficiency (FRE) and as agronomic efficiency (AE) as described by Wortmann et al. (2011). All units in these equations are in kg ha^{-1}. Recovery efficiency was calculated according the following equation:

$$FRE = (UN_N - UN_0)/ N\ rate$$

where UN_N is the total plant N uptake at physiological maturity for a specific N fertilizer treatment, and UN_0 is the total plant N uptake at physiological maturity for the unfertilized treatment (0 N check). The AE was calculated according to the following equation:

$$AE = (Y_N - Y_0) / N\ rate$$

where Y_N is the grain yield at physiological maturity for a specific N fertilizer treatment, and Y_0 is the mean grain yield at physiological maturity for the unfertilized treatment (0 N check). Partial Factor Productivity (PFP) or amount of yield produced per unit of N applied was also calculated as a measure of efficiency, as outlined with the following equation by Cassmen et al 1996:

$$PFP = Y_N / N\ rate$$

where Y_N is the grain yield at physiological maturity for a specific N fertilizer treatment.

1.3.7 Statistical Analysis

Data were analyzed with the MIXED procedure as well as the CORR procedure of SAS (SAS Institute, 2009) with block and location and their interactions with treatment variables as random effects, and N source, year, and fertilizer rate were fixed effects. Optimum N rate was determined with regression analysis using PROC REG and PROC NLIN models in SAS. The N rate at which different predictive canopy sensors methods reached a plateau (canopy sensors) or 2000 mg kg^{-1} (basal stalk) compared to the actual agronomic optimum rate (AONR) was calculated using the PLOT NLIN function using the average sensed value from each tool at each N rate level. EONR was calculated with a N-to-Corn price ratio of 0.0056, reflecting a fertilizer to corn price ratio calculated from prices of \$1.10 kg^{-1} fertilizer N (\$0.50 $pound^{-1}$) and \$196.84 Mg^{-1} of corn (\$5.00 $bushel^{-1}$). Mean separation for comparison of N sources was preformed using PROC GLM, first comparing treatments at each location separately across years and then comparing treatments at all locations/cropping systems and years combined for an overall mean. Statistical significance was declared at $p < 0.05$.

1.4 Results and Discussion

Both the Dakota Co. and Pope Co. sites were wetter than the 30-yr normal in April through June except in May 2011 in Dakota Co. and June 2011 in Pope Co. where precipitation amounts were close to normal (Table 1.1). Weather was drier than normal for both locations in July through September except for July 2011 at both locations and August 2014 in Pope Co. where precipitation amounts were greater than normal. In general across locations and years the period April-June was 196 mm above normal while the period July-September was 133 mm below normal. Temperature conditions also showed a similar behavior as precipitation with consistent trends across locations and years departing from the normal. April through July was warmer than the 30-yr normal at both sites across years, whereas September was cooler than normal and August was slightly cooler but near the normal average every year (Table 1.1). Temperatures averaged across the period April-July ranged between 4.0 and 7.8°C warmer than normal during our study (mean 5.5°C above normal) and for the period August-September the range was between 1.4 and 3.8°C cooler than normal (mean 2.6°C below normal). This trend for wetter springs followed by drier summers and warmer springs and summers is predicted to become the new normal for Minnesota (USEPA, 2013). If this trend truly becomes the new normal, and since N management is largely influenced by weather conditions, these weather observations highlight the need for continuing research to produce the information needed to better adjust N management to changes in climate. This is true even for irrigated systems where although irrigation ensures no water limitations, large rain events in the spring soon after N is applied can imposed a larger potential for leaching losses of N. Similarly, warmer springs and summers can impact N management and should be continually investigated because warmer temperatures can result in increased rates of N cycling from the soil and applied fertilizers.

Irrigated sandy soils can be very productive if properly managed. In these irrigated systems, corn is typically responsive to N as this is often the most limiting nutrient. In our study, we used the quadratic plateau model as grain yield had the best fit (greater R^2 values) to N rate (Table 1.2). The EONR (ratio = 0.0056) varied between years and sites, ranging from 170 and 297 kg N ha^{-1}, with a median of 237 kg N ha^{-1} and a mean of 228 kg N ha^{-1} (±10 SE) with a mean grain yield of 13.5 Mg ha^{-1}. The Δ yield to the EONR (difference between grain yield at EONR and yield at the 0 N check) ranged from 2.5 to 10.8 Mg ha^{-1} and the overall mean was 6.5 Mg ha^{-1} (Table 1.2). There was no relationship between EONR and Δ yield and we could not decipher whether greater N requirements in a given year over another were the result of growing season conditions that increased N loss, enhanced grain yield potential, or some other factor. A survey of Minnesota farmers in 2010 found the mean N rate for corn on irrigated soils across multiple rotations was 169 kg N ha^{-1} and produced 10.6 Mg ha^{-1} of yield (Bierman et al. 2011). This is 59 kg N ha^{-1} less N and 2.9 Mg ha^{-1} less yield than the overall mean economic optimum in our study. The survey highlights that farmers were following university guidelines. However, updated guidelines for N application for corn after corn in course textured soils suggest applications of 234 kg N ha^{-1} at a 0.0056 N-to-Corn price ratio and acceptable range of 215 to 252 kg N ha^{-1} (Lamb et al., 2015). Our mean EONR of 231 kg N ha^{-1} for CC agree with the updated guidelines. The earlier recommendations for irrigated sandy soils were based on the rate needed for highly productive fine-textured soils because at the time there was a limited amount of data for sandy soils. Our results and the recent update in guidelines illustrate the importance of current and local research to optimize corn production in different regions.

There was no residual effect of the previous N treatments applied to corn in the Pope Co. soybean crop, but there were differences caused by year (Table 1.3). Grain yield increased over time with the last year (2014) yielding 54% more (4.0 Mg ha^{-1}) than the first year. Beyond differences in growing season conditions, we can only speculate that increasing soybean yields with consecutive years it may be the result of a cumulative effect of the rotation on enhancing rhizobium activity since treatments remained in the same plots for the duration of the experiment. Rhizobium activity was not measured in this experiment but has been shown to increase yields after multiple years of planting (Furseth et al. 2012). Regardless, we were mainly interested in quantifying the impact of soybean on corn response to N. Most research conducted to quantify N credit from soybean has been done for fine textured soils (Varvel, 1994; Gentry et al., 2013). Little information is available on soybean N credit to corn in sandy soils, especially under irrigation. In a study in irrigated loamy sand soil by Bundy et al. (1993) they observed no soybean N contribution to corn and attributed this finding to possible N loss before the corn crop could utilize the released N. Across years in our study, CSb yield was consistently greater than the CC rotation (Fig. 1.1) in contrast to the results from Bundy et al. (1993). The fertilizer replacement value has been used to calculate the soybean N credit by determining the N rate needed to achieve the same yield in CC as with CSb when no N is applied (Varvel and Wilhelm, 2003). We determined that the fertilizer replacement value was 77 kg N ha^{-1} (23 kg N ha^{-1} per each Mg ha^{-1} increase in yield) (Fig. 1.1). The average EONR (ratio = 0.0056 for CC was 251 kg N ha^{-1} with a grain yield at the EONR of 13.0 Mg ha^{-1}, compared with CSb with an EONR of 221 kg N ha^{-1} and a grain yield at the EONR of 13.2 Mg ha^{-1} (Table 1.2 and Fig. 1.1). This soybean credit of 30 kg N ha^{-1} is similar to the 34 kg N ha^{-1} suggested in the new University of Minnesota guidelines (Lamb et al., 2015). This N credit has long being linked to greater N immobilization with corn residue than soybean residue (Green and Blackmer, 1995). Beyond N dynamics, other possible reasons for the differences observed between CC and CSb is that in CC greater amounts of residue can reduce soil temperatures and create emergence and establishment delays and greater sensitivity to weather stress later in the season (Wilhelm and Wortmann, 2004), allelopathic interactions can affect growth and development (Yakle and Cruse, 1983), and the lack of rotation can adversely impact soil microorganisms that enhance N mineralization and N use by corn (Vanotti and Bundy, 1995).

1.4.1 Sensing

Canopy sensing technology can be used as a tool to more accurately predict in-season crop N needs (Blackmer & Schepers, 1995; Dellinger et al., 2008; Martin et al., 2007; Osborne et al., 2002). We evaluated the N rate at which different predictive methods reached a plateau as a way to evaluate their relative effectiveness compared to the calculated AONR based on grain yield response to N fertilizer rate at harvest (Table 1.2 and 1.4). In general, relative to the AONR calculated at harvest, at V8 sensors under predicted AONR by 81 kg N ha^{-1} but the prediction improved by V12, though AONR was still under predicted by 47 kg N ha^{-1}. Only in four occasions was the AONR over predicted relative to the calculation at harvest: two times with Crop Circle (NDRE) in CC once at V8 (64 kg N ha^{-1}) and once at V12 (10 kg N ha^{-1}), Crop Circle (NDVI) at V8 in CSb (79 kg N ha^{-1}), and GreenSeeker at V12 in CSb (102 kg N ha^{-1}). In Pope Co. canopy sensors overall were unable to detect the "soybean N credit." At V8 averaged across all sensors the sensors predicted virtually the same amount of N needed for CC than CSb, and at V12 they actually predicted 94 kg N ha^{-1}greater N requirements for CSb than CC, which is the opposite of the calculated AONR at harvest for these two rotations (Table 1.4). This indicates that using these sensors to predict N needs in CC potentially carries greater risk of grain yield penalty than in CSb. While Crop Circle under predicted the calculated AONR, NDRE calculations provided a better estimate than NDVI calculations. Overall NDRE values under predicted AONR only by 13% (32 kg N ha^{-1}) compared to 26% (66 kg N ha^{-1}) with NDVI (Table 1.4). In relative terms on the sensor's capacity to predict AONR, Crop Circle NDRE ranked consistently on top (best) and Crop Circle NDVI was second best. The SPAD measurement ranked last at V8 but was ranked on top (similar to Crop Circle NDRE) at V12. NDVI determined by the GreenSeeker consistently ranked lowest at both V8 and V12.

Averaged across location and crop rotation, canopy sensor readings were well correlated to N rate (Table 1.4); but just as with prediction to AONR calculated at harvest, the sensors had low or no correlation to grain yield or biomass and total plant N uptake at V8, V12, or R6 (data not shown). We also observed that correlation to N rate was low (R^2=0.52) at V12 for the GreenSeeker but not for the other sensors. Lower correlation later in the season with the GreenSeeker highlights the fact that the instrument may have reached canopy saturation. This follows results by Shaver et al. (2011) that indicated that the GreenSeeker could reach saturation at earlier crop development stages than the Crop Circle. While we observed greater correlation coefficient of the sensors to N rate for CC than CSb (Table 1.4), as mentioned before relative to the AONR calculated at harvest, the sensors in general under predicted N needs to a greater extent in CC than CSb. This finding further illustrates that canopy sensors may have limited utility for our conditions. We suspect this difference highlights the fact that these soils have limited natural ability to supply N and soybean in the rotation may be providing additional benefits for establishment, development, and N availability to the corn crop, as already discussed.

The increase in basal stalk nitrate-N concentrations with increasing N rate was best explained (greater R^2) with a power regression function and it was similar for all years, so we present this relationship averaged across years for each location and crop rotation and also as a mean across all variables (Fig. 1.2). Basal stalk nitrate-N interpretations based on research conducted in Iowa indicate that corn will not respond to N when nitrate-N values are above 2000 mg kg^{-1} N (Blackmer and Mallarino, 1996). Using this interpretation and the relationships in Fig. 1.2 we estimated that basal stalk nitrate-N would be 2000 mg kg^{-1} at 221, 249, 223, and 232 kg N ha^{-1} for CC in Dakota Co., CC in Pope Co., CSb in Pope Co., and averaged across all locations and crop rotations, respectively (Table 1.4). The basal stalk nitrate-N test under estimated the

AONR by 27 kg N ha^{-1} under CC (means of Dakota and Pope Co.) and by 20 kg N ha^{-1} for CSb with an overall under estimation of 24 kg N ha^{-1}. The test was poorly correlated to N rate ($R^2 = 0.43$) (Table 1.4 and Fig. 1.2) and, as with canopy sensors, had similar or lower coefficient of determination when correlated to yield (data not shown). As with canopy sensors, the basal stalk nitrate-N test provided limited utility to improve N management for corn in the irrigated sandy soils of our study.

1.4.2 Corn Response to Nitrogen Sources

Across years, sites, and crop rotations a split-application of urea (half rate pre-plant and half rate at V4) yielded 5.4% (0.63 Mg ha^{-1}) greater than the mean single pre-plant application of ESN, ESN/Urea blend, and SuperU at the same rate of 180 kg N ha^{-1} (Table 1.5). Likewise, averaged across years, sites, and crop rotations PFP was 6% greater and AE was 12% greater for the split-urea treatment compared with the mean of the other pre-plant applied N sources at the rate of 180 kg N ha^{-1}. There were no significant interactions with N source. Our results agree with the University of Minnesota BMP for irrigated sandy soils stating that a split-application of urea is superior to a single application (Lamb et al., 2015). Further, the use of a single pre-plant application of enhanced efficiency products (ESN or SuperU) does not enhance grain yield, PFP or AE compared to the BMP. Differences were not large enough to be significant for grain yield, PFP and AE when analyzed by individual locations and crop rotations. In Pope Co. averaged across N sources with 180 kg ha^{-1} the CC rotation had greater AE (30 kg ha^{-1}) than the CSb rotation (23 kg ha^{-1}). This is likely caused by the soybean N credit previously discussed. At the 225 kg N ha^{-1} rate, we observed no difference between split-applied urea and single pre-plant ESN applications for yield, PFP or AE. This is likely because the 225 kg N ha^{-1} rate is in the less responsive (flatter) portion of the yield response curve very close to, and sometimes greater than, the EONR (Table 1.2).

No differences as a result of N source or N rate were observed for grain N concentration, total plant N uptake, basal stalk nitrate-N, RSN, and FRE (Table 1.5). The large variability in basal stalk nitrate-N measurements relative to more uniform values for total plant N uptake indicates that this test may have limited use for our soil conditions. The fact that FRE values were small (range of 29 to 59% of the fertilizer accumulated in aboveground tissues) and RSN at the end of the growing season were also small (range of 1.8 to 3.9 mg kg^{-1}) regardless of N source, N rate, or crop rotation, indicate that these soils have very little potential to retain N and leaching loss potential below the root zone is great. Since these soils have high permeability, it is unlikely that substantial N loss could have occurred by other mechanisms besides leaching. Similar results were observed when comparing various N rates averaged across all years, locations, and crop rotation where RSN in the 0-60 cm depth was 1.9 mg kg^{-1} for the unfertilized check and at the highest N rate measured (270 kg N ha^{-1}) it was only 3.4 mg kg^{-1} (data not shown). We also know that nitrate was not stored at deeper layers since in those sites where deeper soil samples (60-90 and 90-120 cm) were collected, mean nitrate-N concentration was only 1.2 mg kg^{-1} (data not shown). These results highlight that using enhance efficiency fertilizers (ESN and SuperU) in a single pre-plant applications are not as effective as the urea split-application BMP. These enhanced efficiency fertilizers did not increase grain yield, PFP, or AE relative to the BMP and did not offer improvements above the BMP to increase FRE or RSN after the growing season.

1.5 Conclusion

Irrigated sand soils can be very productive if corn receives a substantial amount of N. These soils, generally speaking, have little ability to supply N, and N loss potential for the applied N can be substantial as a result of high water infiltration rate. The potential for loss was clear. Regardless of the amount or source of N applied, crop rotation, or FRE measured, soil nitrate-N concentrations were very small at the end of the season. Recently the University of Minnesota revised its guidelines for corn production in irrigated sands and increased the N rate needed to optimize corn productivity. Our results show very close agreement to the new guidelines and illustrate the importance of regularly conducting studies to quantify N response under local conditions. Moreover, the fact that N is needed in large quantities in irrigated sands and that the soil is not able to retain excess N, highlights the importance of managing N to supply only what the corn crop needs. Crop rotation has an important impact on how much N may be needed. Corn after soybean required less N than CC to produce the same level of grain yield. Unfortunately, canopy sensing technologies or basal stalk nitrate-N measurements showed little utility in improving N management in these soils as they overall under estimated the amount of N needed to maximize crop grain yield. There could be important advantages to supplying N with a single application of fertilizer. However, the use of enhanced efficiency fertilizers such as ESN and SuperU to accomplish this goal for a single pre-plant application did not provide advantages in terms of increasing grain yield or improving NUE relative to a split-N application of urea. This study clearly showed that splitting the N application is a BMP to increase yield and improve NUE in irrigated sandy soils. Managing N with split applications may become increasingly more important if the weather pattern we observed during the study for wetter and warmer than normal conditions in the spring become the new normal.

Table 1.1 The 30-yr normal (1980-2009) and 2011 to 2014 growing season monthly cumulative precipitation and monthly mean air temperature for Pope Co. and Dakota Co., MN.

Location	Year	Apr.	May	June	July	Aug.	Sept.	Year avg.
		Precipitation (mm)						
Pope Co.	30-yr avg.	35	58	76	104	90	91	671
	2011	54	123	73	227	63	11	666
	2012	67	195	90	71	31	2	600
	2013	47	126	150	52	22	73	732
	2014	146	136	220	38	133	28	816
Dakota Co.	30-yr avg.	52	75	98	113	112	113	843
	2011	65	73	141	122	45	17	632
	2012	92	205	152	76	43	17	810
	2013	144	157	140	66	50	41	792
	2014	147	126	272	69	86	42	886
		Temperature avg. (°C)						
Pope Co.	30-yr avg.	-1.9	6.8	13.7	18.7	21.4	20.1	5.9
	2011	5.4	12.7	17.7	23.5	20.9	14.6	5.6
	2012	7.9	15.5	19.9	24.2	19.5	14.4	7.8
	2013	0.7	12.2	18.7	21.6	20.8	16.6	4.3
	2014	3.4	12.5	19.2	19.7	20.4	14.6	3.7
Dakota Co.	30-yr avg.	-0.5	7.9	14.3	19.7	22.2	21.0	7.1
	2011	6.4	13.4	19.6	25.2	22.3	16.4	7.5
	2012	9.2	16.5	21.1	25.6	21.4	16.9	9.6
	2013	3.3	13.2	19.3	22.7	22.0	18.3	6.2
	2014	5.3	13.9	20.4	21.2	22.3	16.5	5.4

Source: National Oceanic and Atmospheric Administration

Table 1.2. Quadratic-plateau regression models for grain yield (y) in relation to N fertilizer rate (x) and economic and agronomic optimum N rate (EONR rate = 0.0056 and AONR) and corn grain yield at EONR and AONR for corn as affected by location, crop rotation: corn after corn (CC) and corn after soybean (CSb), and year.

Location-crop rotation	Year	Regression model	Pr > *F*	EONR	Yield at EONR	AONR	Yield at AONR
				kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}	Mg ha^{-1}
Dakota-CC	2011	$y = 9.8820 + 0.0427x - 0.00008x^2$	< 0.0001	206	15.5	230	15.6
	2012	$y = 6.9729 + 0.0479x - 0.0001x^2$	< 0.0001	177	12.2	200	12.3
	2013	$y = 6.2251 + 0.0796x - 0.0002x^2$	< 0.0001	170	14.6	184	14.7
	2014	$y = 4.1274 + 0.0664x - 0.0001x^2$	< 0.0001	297	15.0	315†	15.1
Pope-CC	2011	$y = 5.5723 + 0.0592x - 0.0001x^2$	< 0.0001	235	13.4	269	13.5
	2012	$y = 6.3433 + 0.0621x - 0.0001x^2$	< 0.0001	239	14.5	262	14.5
	2013	$y = 4.9759 + 0.0571x - 0.00009x^2$	< 0.0001	277	13.8	314	13.9
	2014	$y = 4.7463 + 0.0378x - 0.00006x^2$	< 0.0001	251	10.2	307	10.4
Pope-CSb	2011	$y = 8.0877 + 0.0388x - 0.00008x^2$	0.0035	174	12.3	203	12.4
	2012	$y = 11.123 + 0.0217x - 0.00005x^2$	0.0051	265	13.7	315†	13.7
	2013	$y = 8.5982 + 0.0351x - 0.00006x^2$	< 0.0001	264	14.1	315†	14.4
	2014	$y = 7.7131 + 0.0455x - 0.0001x^2$	< 0.0001	181	12.7	202	12.8

†AONR was above maximum N rate of 315 kg N ha^{-1}.

Table 1.3 Soybean grain yield as affected by N fertilizer rate applied to the previous corn crop and year in Pope Co., MN.

Residual rate	2011	2012	2013	2014
kg N ha^{-1}		———— Mg ha^{-1} ————		
0	2.8	3.7	3.4	4.0
45	2.8	3.7	3.7	4.0
90	2.2	3.7	3.7	4.2
135	2.4	3.7	3.7	4.0
180	2.6	3.7	3.7	4.0
225	2.7	3.7	3.6	3.9
270	2.5	3.8	3.7	4.1
315	2.4	3.7	3.7	4.0
Mean	2.6c†	3.7b	3.7b	4.0a

†Within row, values followed by the same letter are not significantly different $p>0.05$.

Table 1.4 Mean four-year (2011-2014) predicted agronomic optimum N rate (AONR) and coefficient of determination (R^2) based on response to N fertilizer rate for canopy sensors at V8 and V12 development stage and basal stalk nitrate-N at physiological maturity (R6), and calculated AONR and grain yield at AONR at harvest based on response to N fertilizer rate for Dakota and Pope Co., MN and crop rotation: corn after corn (CC) and corn after soybean (CSb).

Method	Develop. stage	Dakota-CC	Pope-CC	Pope-CSb	Mean
		kg N ha^{-1}†			
SPAD	V8‡	124	177	124	142
GreenSeeker (NDVI)		136	150	174	153
Crop Circle (NDVI)		89	132	322	181
Crop Circle (NDRE)		134	352	186	224
SPAD	V12§	216	219	241	225
GreenSeeker (NDVI)		143	69	345	186
Crop Circle (NDVI)		228	171	199	199
Crop Circle (NDRE)		246	187	238	224
Basal Stalks	R6	221	249	223	232
AONR	Harvest	236	288	243	256
Yield at AONR (Mg ha^{-1})		14.4	13.1	13.3	13.6
		R^2			
SPAD	V8	0.88	0.87	0.56	0.91
GreenSeeker (NDVI)		0.81	0.82	0.16	0.86
Crop Circle (NDVI)		0.75	0.72	0.24	0.85
Crop Circle (NDRE)		0.87	0.83	0.64	0.91
SPAD	V12	0.97	0.88	0.52	0.91
GreenSeeker (NDVI)		0.29	0.32	0.40	0.52
Crop Circle (NDVI)		0.91	0.43	0.36	0.77
Crop Circle (NDRE)		0.93	0.34	0.28	0.71
Basal Stalks	R6	0.41	0.48	0.46	0.43

†Sensor predictions at N rate where variable reaches a plateau value as predicated by linear plateau regression model. Basal Stalk N increased linearly with no maximum; N rate was predicted by the linear model to produce 2000 mg kg^{-1}, $p < 0.05$.

‡Absolute maximum overall sensor unit-values for V8 were 53, 0.87, 0.37, and 0.38 for SPAD, GreenSeeker, Crop Circle NDVI, and Crop Circle NDRE, respectively.

§ Absolute maximum overall sensor unit values for V12 were 65, 0.86, 0.47, and 0.48 for SPAD, GreenSeeker, Crop Circle NDVI, and Crop Circle NDRE, respectively.

Table 1.5 Mean four-year (2011-2014) values for corn grain yield, grain N concentration, total N uptake, basal stalk nitrate-N, Residual Soil Nitrogen (RSN), Fertilizer Recovery Efficiency (FRE), Partial Factor Productivity (PFP), and Agronomic Efficiency (AE) for Dakota and Pope Co., MN as affected by crop rotation: corn after corn (CC) and corn after soybean (CSb), N fertilizer source, and N rates.

Location	Source	Rate	Grain Yield	Grain N	Total uptake	Basal Stalk nitrate -N	RS N†	FRE‡	PFP§	AE¶
		kg ha^{-1}	Mg ha^{-1}	g kg^{-1}	kg N ha^{-1}	—mg kg^{-1}—			———kg ha^{-1}———	
Dakota-CC	Urea	180	13.3	1.00	198	964	2.2	47	74	38
	ESN		12.6	0.98	191	529	2.6	43	70	34
	SuperU		12.7	1.02	217	2330	2.5	58	70	34
	ESN/Urea	90/90	12.9	0.99	192	360	2.0	44	72	35
	Urea	225	13.5	1.08	208	1949	2.3	42	60	31
	ESN		13.7	1.06	215	1905	2.7	45	61	32
Pope-CC	Urea	180	11.6	1.09	218	722	2.5	56	64	33
	ESN		11.2	1.12	202	623	2.0	48	62	31
	SuperU		10.7	1.05	200	419	2.1	47	60	28
	ESN/Urea	90/90	10.6	1.07	194	125	1.8	44	59	28
	Urea	225	12.5	1.19	247	1068	3.1	59	56	31
	ESN		12.1	1.19	232	1106	2.6	52	54	29
Pope-CSb	Urea	180	12.3	1.11	243	1264	2.4	52	69	25
	ESN		11.7	1.13	225	881	2.6	43	65	22
	SuperU		12.0	1.15	228	1211	3.1	44	66	23
	ESN/Urea	90/90	11.4	1.13	201	858	3.9	29	63	20
	Urea	225	12.5	1.21	244	2272	3.1	40	56	21
	ESN		12.1	1.16	254	1970	3.7	47	54	19
Mean	Urea	180	12.4a	1.07	220	983	2.4	52	69a	32a
	ESN		11.9b	1.08	206	677	2.4	45	66b	29b
	SuperU		11.8b	1.08	215	1320	2.6	50	65b	29b
	ESN/Urea	90/90	11.6b	1.06	196	448	2.6	39	65b	28b
	Urea	225	12.9	1.16	233	1763	2.8	47	57	28
	ESN		12.7	1.14	233	1661	3.0	48	56	27

†Residual soil nitrate-N (60cm, depth to gravel) after grain harvest.

‡ Fertilizer recovery efficiency is the difference of total plant N uptake at physiological maturity for a specific N fertilizer treatment and the total plant N uptake at physiological maturity for the unfertilized treatment divided by the N fertilizer rate.

§Partial Factor Productivity is the grain yield produced per unit of N applied.

¶Agronomic Efficiency is the difference in grain yield at physiological maturity for a specific N fertilizer treatment and the grain yield at physiological maturity for the unfertilized treatment divided by the N rate.

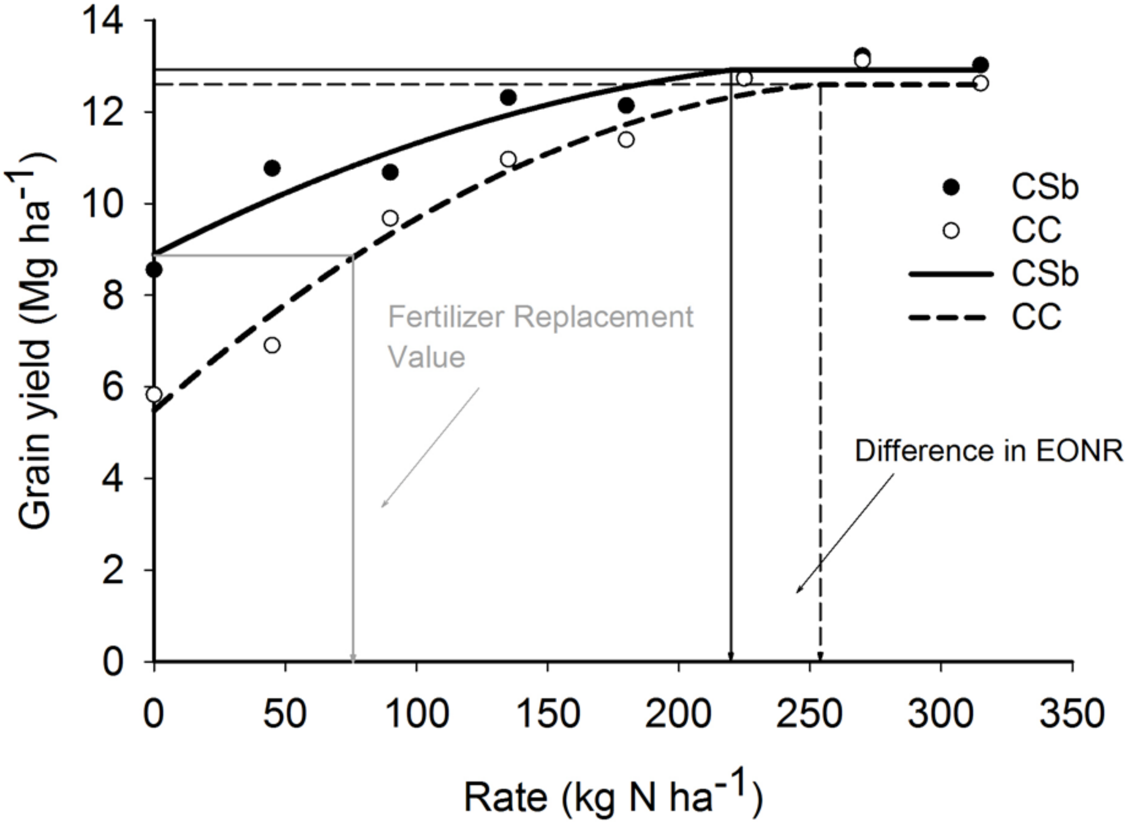

Figure 1.1 Relationship between grain yield and N rate, and difference in economic optimum N rate (EONR ratio = 0.0056) needed to achieve the economic optimum yield at Pope Co. for continuous corn (CC) and corn soybean (CSb) rotation averaged across four years (2011-2014).

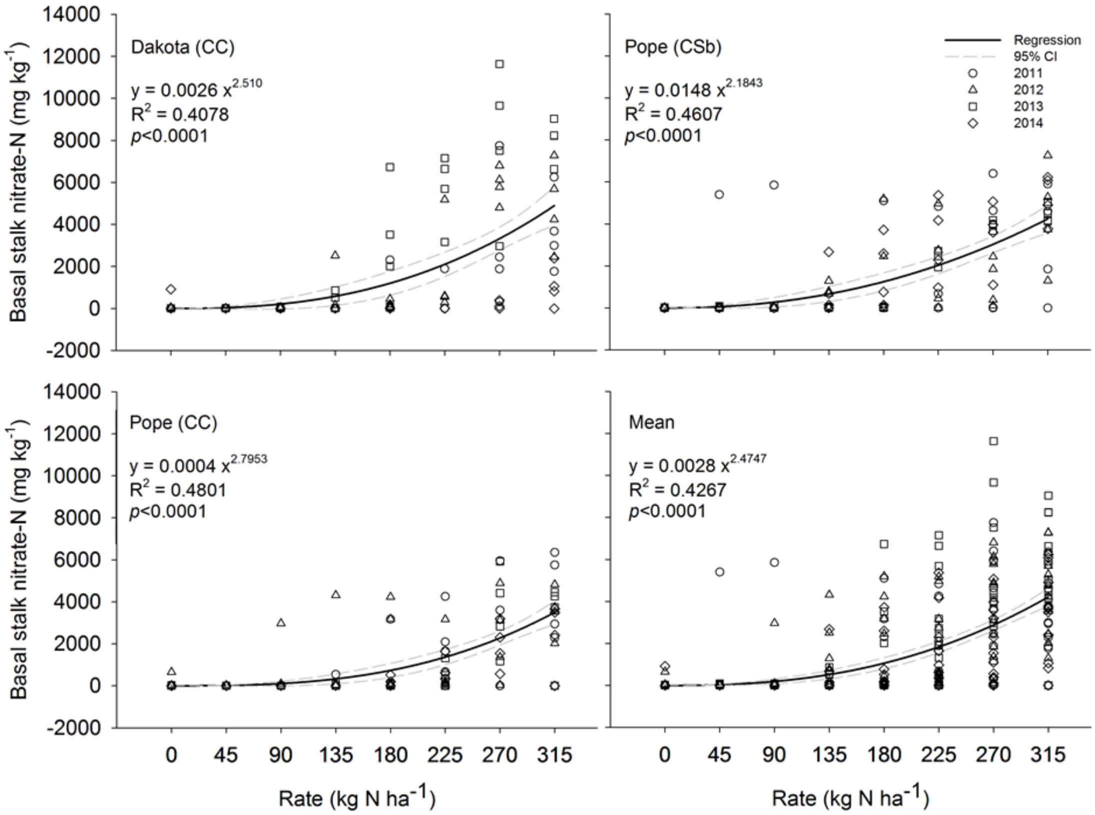

Figure 1.2 Relationship between corn basal stalk nitrate-N and N rate across four years (2011-2014) for Dakota Co. and Pope Co., MN for continuous corn (CC) and corn after soybean (CSb). Dotted lines show 95% confidence interval.

Chapter 2

Nitrogen Management for Maize and Groundwater Quality in Upper Midwest Irrigated Sands

2.1 Overview

Groundwater contamination from nitrate (NO_3-N) leaching in corn (*Zea mays* L.) production areas with coarse textured soils is a problem. Our objectives were to evaluate NO_3-N leaching losses in continuous corn (CC) and corn after soybean (CSb) cropping systems in irrigated sandy soils in Minnesota in relation to (i) best management practice (BMP) of split urea applications and single pre-plant applications of enhanced efficiency fertilizers (EEFs), and (ii) N rate using the BMP of split urea applications. An additional objective was to evaluate residual N treatment effect on NO_3-N leaching for soybean after corn (SbC). Granular urea (0 to 315 kg N ha^{-1} in 45 kg increments) was broadcast as a split-application (half at preplant and half at V4 development stage) and ESN, ESN/Urea, and SuperU at preplant at a rate of 180 kg N ha^{-1} on an Arvilla sandy loam soil. In May and June excess precipitation at the time of N application resulted in 75% of the total leaching and 73% of the total NO_3-N load below the root-zone. Reducing the economic optimum N rate (EONR) produced limited benefits towards reducing NO_3-N losses. In CC reducing the EONR by 20% reduced grain yield by 4% and NO_3-N load by 9% to 78 kg ha^{-1}; reducing the EONR by 25% reduced grain yield by 6% and NO_3-N load by 11% to 76 kg ha^{-1}. No significant NO_3-N load reduction was achieved by reducing the EONR for CSb. Enhanced efficiency fertilizers produced no improvement in reducing NO_3-N load. After four years of no N application the check plots had 9 to 20 mg NO_3-N L^{-1} and load of 21 to 51 kg NO_3-N ha^{-1}. The study highlights the difficulty of achieving substantial reductions in N loss in our cropping systems towards meeting water quality goals for the drinking water standard.

Abbreviations: BPM, best management practice; CC, continuous corn; CSb, corn after soybean; EONR, economic optimum N rate; EEFs, enhanced efficiency fertilizers; PCL, passive capillary lysimeter; SbC, soybean after corn; RSN, residual soil nitrate-N; WB, water balance.

2.2 Introduction

Over the past century much of the native prairie in the United States Midwest has been converted into intensive annual row crop production, specifically corn and soybeans (*Glycine max* L.). For example in Minnesota in 1909, there were approximately 809,000 ha in corn grain production and that number has risen to just over 3.4 million ha in 2012 (USDA-NASS, 2015). With increasing corn production in the landscape, N fertilizer application has also increased because of the high N use of the crop (Sawyer et al., 2006). However, N fertilization can lead to environmental concerns, particularly water quality degradation from NO_3-N. Coarse textured soils are of particular concern because of their small water holding capacity and large leaching potential. In Minnesota, there are approximately 202,500 ha of irrigated sandy soils (USDA NASS 2015). Even though these areas have a high risk for NO_3-N leaching, they are also highly productive with N fertilization.

Nitrate contamination of groundwater is an important concern, as a number of cities in the Upper Midwest depend on ground water for their drinking water supply (Gehl et al., 2005). Once groundwater is contaminated, it must undergo expensive treatment to be suitable for human consumption. This treatment has been estimated to be $0.54 per ha, Compton et al., (2011). Nitrate in drinking water can have potential human health concerns. The drinking water standard is 10 mg NO_3-N kg^{-1} (US-EPA, 2012). Babies and infants ingesting water containing nitrate levels above the drinking water standard may suffer shortness of breath and methemoglobinemia. This is known as Blue Baby Syndrome and can be fatal (US-EPA, 2012). To ensure a safe drinking water supply, best management practices for nitrogen use should be identified and followed (Klocke et al., 1999).

Timing of application is a fertilizer management practice that has been shown to reduce NO_3-N leaching and increase nitrogen use efficiency in corn (Jokela and Randall, 1988; Randall et al., 2001). However, many farmers have a limited amount of time to apply N fertilizer in northern regions of the US Midwest. The growing seasons are short; work loads are great over a short time period. Large areas of production can leave farmers conflicted about when is the best time to apply fertilizer (Scharf et al., 2002). With three main options of application timing, a survey done in Minnesota in 2010 showed that state wide, approximately 33% of farmers apply N in the fall, 59% in the spring, and 8% as sidedress. Depending on the fertilizer type, the application timing varied significantly, with 63% of all anhydrous ammonia applied in the fall, and 90% of all urea applied in the spring. (Bierman et al., 2012). In Southern Minnesota studies showed that a spring application increased nutrient use efficiency by more than 20% compared to fall application, and reduced NO_3-N losses by an average of 36% (Randall et al., 1997, Randall et al., 2001). Multiple split application treatments during the growing season, caused no significant difference between grain yield or NO_3-N leaching in Iowa (Jaynes, 2013). However, these and most studies on NO_3-N leaching have been conducted in fine-textured soils with subsurface tile drainage where the major concern is for contamination of surface waters. Similar studies focused on NO_3-N leaching but in coarse textured soils where groundwater contamination is the biggest concern are lacking for the Upper Midwest.

In addition to and in combination with the time of N application, the use of alternative N sources can be used to mitigate NO_3-N leaching into water. Different N fertilizers, such as polymer coated urea as well as additives such as nitrification inhibitors have shown potential to reduce NO_3-N leaching (Blaylock et al., 2004, 2005; Motavalli et al., 2008). Randall and Vetsch, (2005) found on a poorly drained clay loam soil the use of the nitrification inhibitor nitrapyrin (2-chloro-6-(trichloromethyl) pyridine) with anhydrous ammonia reduced NO_3-N losses by 14% with a spring application and 10% with a fall application compared to a fall application without nitrapyrin. However, in another study, Randall et al., (2003) found no significant difference in the amount of NO_3-N leachate with a fall anhydrous application with nitrapyrin when compared to a spring application of N without nitrapyrin. With mixed results of these products and costs up to eight times as much as non-treated fertilizers, these sources have yet to be considered a viable option for crop production and reducing NO_3-N leaching (Blaylock et al., 2004). Nelson et al., (2009) found on a claypan soil in Missouri, there was no yield difference between untreated and a polymer coated urea, however the polymer coated urea reduced subsoil NO3-N concentrations early in the season by 51 to 63%. As with timing of application studies, studies focused on N source to reduce NO_3-N leaching have been primarily focused in fine textured soils while research to determine the viability of alternative N sources to reduce NO_3-N leaching into groundwater in coarse textured soils is lacking.

The objectives of this study were to evaluate NO_3-N leaching losses in CC and CSb cropping systems in irrigated sandy soils in Minnesota in relation to (i) BMP of split urea applications and single pre-plant ESN, ESN/urea blend, and SuperU applications, and (ii) N rate using the BMP of split urea applications. An additional objective was to evaluate residual N treatment effect on NO_3-N leaching for SbC.

2.3 Materials and Methods

The study was established in 2011 and data collected from 2012 to 2014, at Westport, Pope County, in West Central Minnesota (45°42'49.1"N, 95°10'16.2"W) on an Arvilla Sandy Loam (Sandy, mixed, frigid Calcic Hapludolls) with a sandy/ gravelly outwash parent material. The slope was between 0 and 1% and the site was irrigated. The site was divided into three adjacent blocks (West, Center, and East) to accommodate CC on the West block and a corn-soybean rotation with both crops growing each year. The CSb was located on the Center block in 2011 and 2013 and on the East block in 2012 and 2014 and SbC on the alternate block.

A randomized complete block experimental design with four replications was used. The treatments included a 0 kg N ha^{-1} control; granular urea (46-0-0) (N-P-K) at rates of 45, 90, 135, 180, 225, 270, and 315 kg N ha^{-1}. All urea treatments were split applied with half of the rate at planting and the other half at the V4 development stage (2 June 2011, 22 May 2012, 12 June 2013, and 9 June 2014); and the following four treatments with a single pre-plant application of 180 kg N ha^{-1}: polymer coated urea, ESN (44-0-0) (Agrium Advanced Technologies, Loveland, CO); urea with N-(n-butyl) thiophosphoric triamide (NBPT) and Dicyandiamide (DCD) SuperU (46-0-0) (Koch Fertilizer LLC, Wichita, KS); and a ESN/Urea blend of 90/90 kg N ha^{-1}. All treatments were applied as a broadcast application incorporated by rain or irrigation and the treatments were applied to the same plots each year corn was grown. The plots were 4.56 meters (6 – 76 cm rows) by 12.2 meters.

Primary tillage was done by chisel plow in the fall and with a field cultivator in the spring before planting. Phosphorus, potassium, and sulfur fertilizers were added at the beginning of each growing season to ensure adequate availability of these nutrients. Other agronomic practices including pest and weed control were done as needed and irrigation was applied by using the checkbook method for scheduling (Steele et al., 2010). The coefficient of irrigation uniformity was at an acceptable level of at least 83% across the entire study area, based off of a uniformity test done in 2014. Corn plots were planted with hybrid Croplan Acceleron 339OUT3/P on 11 May 2011 and 25 Apr. 2012 and with corn hybrid Dekalb DKC 50-77 RIB on 20 May 2013 and 15 May 2014. Corn was planted at a population of 35,000 plants per acre. Soybean was planted as Croplan R2T 1193 at a population of 180,000 plants per acre, on the same planting dates as corn.

Soil samples were collected in the fall after grain harvest from the plots for the control, urea rates of 135, 180, 225, 270 kg N ha^{-1}, and for the ESN, SuperU, and the ESN/urea blend treatments in CC and CSb. Two soil cores (5 cm in diameter and approximately six meters apart, however distance was not directly measured) were taken per plot with a hydraulic probe and mixed into one composite sample. Because of gravelly subsoil, cores were only taken to a 60 cm depth and divided into 30 cm increments. Samples were dried at 35°C to a consistent weight, ground through a 2 mm sieve, and analyzed for nitrate-N (Gelderman and Beegle, 1998). Corn grain yields were determined by harvesting all ears from the middle two rows in each plot using a plot combine in 2013 and 2014, in 2011 and 2012 the center two rows were hand harvested 20 feet of each rows three and four for a total of 40 feet. Grain yields were corrected for moisture to155 g kg^{-1} for corn and 130 g kg^{-1} for soybean.

Suction tube lysimeters for nitrate-N leachate sampling were installed permanently in Apr. 2011 in selected treatments including the 0-N control, 135, 180, 220, and 270 kg N ha^{-1} split-applied urea, also the 180 kg N ha^{-1} SuperU, ESN, and ESN/urea blend treatments in three replications. Each plot contained three lysimeters in order to improve measurement accuracy. The three values were used to produce an average value for each plot and sampling time. The suction tube lysimeter consists of a polyvinylchloride pipe 3.8 cm in diameter with a porous ceramic cup fitted (0655X01-B1M3; Soilmoisture Equipment Corp., Santa Barabara, CA) at one end, as described by Linden (1977). Each lysimeter was connected through a series network of high density tubing to other lysimeters and ultimately to a vacuum source. The porous cup end was buried between 1.2 meters and 1.8 meters below the soil surface. Tubes used for water extraction and pressurizing were encased in additional polyvinylchloride piping in order to protect them from damage. The porous cup lysimeters were placed under vacuum pressure at 32 centibars in order to draw water from the soil into the lysimeter (Weihermüller et al., 2007). Water sampling was performed every seven to ten days for the entire growing season. The entire solution volume was removed from the samplers during each collection. We did not collect soil water samples during the winter (November - March) because of freezing temperatures. Also, during the establishment year in 2011, samples were collected but not used as this was an equilibrating year after excavation and the start of treatment variables. It is known that deployment of lysimeters during their first year of installation has limited value (Weihermüller et al., 2007).

The mass (load) of nitrate leached past the rooting zone was calculated by two methods: 1) passive capillary lysimeter (PCL) and 2) water balance (WB) model. For method 1, nitrate load leached was calculated from the depth of water that drained through the soil profile past the root zone, quantified with passive capillary lysimeters, and the concentration of nitrate in the water according to Smika et al., (1977). For this measurement, six passive capillary lysimeters, (Drain Gauges from Decagon Devices, Inc., Pullman, WA), were permanently installed in September 2011, evenly spaced every 62 meters at the beginning, middle, and end on both sides of the center block. Data was collected from the PCL during 19 dates in 2012, 21 dates during in 2013, and 19 dates during the 2014 growing season.

Nitrate load leaching below the root zone was calculated with the equation from Gehl et al. (2005).

$$N = C \, x \, q$$

where N is the load of nitrate-N lost through leaching, C is the nitrate-N concentration in the leachate, and q is the quantity of water leached. The load of nitrate leached per day was calculated by dividing the total nitrate loss in each drainage gauge sampling time period by the total amount of days in that period. The annual nitrate load leached below the root zone is calculated by adding the calculated loads for each sampling date.

For method 2, daily drainage was estimated using the following water balance model as described in Andraski et al. (2000):

$$\text{If } TSW_{(t\text{-}1)} + P_t - Et_t > TSW_{FMC}\text{, then}$$

$$(TSW_{(t\text{-}1)} + P_t - Et_t\ ) - TSW_{FMC} = D_t$$

where $TSW_{(t\text{-}1)}$ is the total stored water in the 1.2 meter soil profile at the end of the previous day (*t* - 1, where *t* is in days), P_t is the present-day water inputs from precipitation, Et_t is the present-day water loss from evapotranspiration, $TSW_{FMC\ (}$Total Stored Water $_{\text{Field Moisture Capacity}}$) is the total stored water in the 1.2 meter profile at field moisture capacity (FMC: 33 kPa), and D_t is the present-day water loss because of drainage. Each year the initial soil profile was at 88 mm, the TSW_{FMC} for an Arvilla sandy loam (Steele et al; 2010).

Data were analyzed with the MIXED procedure of SAS (SAS Institute, 2009) with block and the interaction with treatment variables as random effects, and N source, year, and fertilizer rate were considered fixed effects. The EONR was determined by using regression analysis using PROC REG and PROC NLIN models in SAS, with an N price/corn price ratio of 0.0056. Relationships between the N fertilizer applied and soil water NO_3-N concentration, soil water NO_3-N load, and end of season residual soil NO_3-N (RSN) concentration were analyzed by mean separation with the PROC GLM procedure of SAS (SAS Institute, 2009). Data were analyzed at alpha = 0.05 unless otherwise indicated.

2.4 Results and Discussion

2.4.1 Weather and Irrigation

On average, weather was wetter than normal from April through June compared to the 30 yr normal (Table 2.1). On the other hand, weather was drier than normal during July through September, except for August 2014 that was above normal but most of that rain came later in the month. Every year much of the irrigation water was applied in July and August except in 2012 when some irrigation was also needed in June because it was substantially drier than June 2013 and 2014 (Fig.2.1). In 2014, there were excessively wet conditions through June, but a dry July and early August required irrigation. There were a few instances (1 Sept. 2013, and 18 Aug. 2014) where irrigation (>30mm) was done the same day or a day after an important (>30mm) rain event. This was not considered ideal management. Also, there were a few instances where irrigation events were followed by rain events within a few days. Cumulative growing season (1 May to 31 Oct.) rainfall was 36 cm in 2012, 55 cm in 2013, and 130 cm in 2014 and was supplemented with irrigation with 17 cm in 2012, 31 cm in 2013, and 35 cm in 2014 for a total amount of water of 53 cm in 2012, 86 cm in 2013, and 165 cm in 2014. Finally, consistently for 2012 to 2014 the period April to July was warmer than normal followed by cooler than normal conditions for August and September (Table 2.1).

2.4.2 Nitrogen Rate and Soil Water Nitrate Concentration and Load Below the Root-Zone

In general for the CC and CSb rotation NO_3-N concentrations were low (approx. 16mg L^{-1}) at the beginning of the growing season, increased in June, remained high (approx. 63 mg L^{-1}) through July, declined in August, and remained low thereafter (Fig.

2.2). This was also observed for the unfertilized check but generally at lower concentrations. For the May-June period, the mean water nitrate-N concentration (averaged across all variables in Fig. 2.2) was 25 mg L^{-1} whereas a similar analysis for the period July-August showed a mean nitrate-N concentration of 39 mg L^{-1}. In the SbC rotation, where no N fertilizer was applied, NO_3-N concentrations were steadily low (<42 mg L^{-1}) through the growing season.

The low NO_3-N concentrations early in the season are likely a dilution effect as substantial drainage is occurring (Fig 2.2). Others have observed a similar dilution effects with increased drainage (Mariotti et al., 2015). By the end of June, 41% of the total water added (irrigation and precipitation averaged across the three growing seasons) had been received and measured cumulative drainage was 98% in 2012, 41% in 2013, and 86% in 2014 relative to the total season-long drainage (Fig. 2.3). In a fine-textured soil in south central Minnesota, Randall and Vetsch (2005) reported similar findings where 71% of the annual drainage occurs in April through June. The large amount of drainage at that early part of the season (Fig. 2.2 and 2.3) is the result of substantial amounts of precipitation (Fig. 2.1) when the soil profile is at or near full water holding capacity and crop growth and temperatures have a minimal effect on the evapotranspiration rate. We also believe it is a concentration dilution effect as during the May-June period substantial NO_3-N load leaching below the root-zone is occurring (Fig. 2.3) despite relatively lower NO_3-N concentrations (Fig. 2.2). By the end of June, measured NO_3-N load leaching was 98% in 2012, 34% in 2013, and 88% in 2014 relative to the total season-long accumulation (averaged across variables in Fig. 2.3). These values correspond closely to the cumulative drainage percent values during the same time-period mentioned earlier and follow similar results to those of Randall and Vetsch (2005). That research indicated 75% of the annual NO_3-N load occurs in April through June. The large amount of drainage occurring during this period also coincides with fertilizer application and likely results in the substantial increase in NO_3-N load leaching measured (Fig. 2.3).

During the July-August period, NO_3-N concentrations from the lysimeters were high (Fig. 2.2), but there was relatively little NO_3-N calculated load increase below the root-zone (Fig. 2.3). Even though substantial precipitation and irrigation was being added at this point in the growing season (43% of the total, averaged across the three growing seasons) (Fig. 2.1) , there was little drainage occurring because evapotranspiration is substantial and resulted in NO_3-N concentration in the soil solution in close proximity to the lysimeters to increase. Since excess water results in leaching losses below the root-zone and we are limited in our ability to prevent leaching early in the season, proper irrigation management would be important to minimize leaching during the middle of the season when substantial NO_3-N concentrations in the soils-water are present within the root-zone. Later in the season as water usage by the crop declined, drainage started to occur but at that point little NO_3-N remained in the soil, so the amount of NO_3-N load was relatively low (Fig. 2.3). In fact, RSN in the top 60 cm measured after harvest was not affected by N fertilizer rate (data not shown) and the overall mean soil NO_3-N concentration was low (2.6 mg kg^{-1}) indicating that by the end of the growing season the potential for N loss is low as N has already being used by the crop or leached below the root-zone. Our results agree with reported in Gehl et al. (2006). They found no differences in RSN caused by differing N application rate in sandy soils. One of the BMPs suggested for irrigated sandy soils by the University of Minnesota is the use of split applications of N fertilizer. The split application of N result in superior corn grain yields compared to single applications (Lamb et al., 2015). Given the fact that most of the drainage and NO_3-N load occurred by the end of June, this data supports this BMP. However, the split application used in this study where half of the N rate was applied at planting and the remainder at V4 development stage (22 May 2012, 12 June 2013, and 9 June 2014) might have been too early to avoid the high nitrate-N loss from leaching. While in dryland agriculture multiple split applications or a late split application can be costly and difficult to do, in irrigated sands it is feasible to supply N with the irrigation water. Supplying enough N early in the season to help with crop establishment and then supplying the majority of N through irrigation when water and N are rapidly being used by the crop (and the potential for leaching is low), is a way to reduce N loss and maintain productivity.

Season-long mean water nitrate concentration in general increased with increasing fertilizer N rate, especially for CC. There were some inconsistencies for which there is no clear explanation beside the fact that suction tube lysimeter data can be highly variable (Table 2.2). Similarly, in terms of absolute values, NO_3-N load below the root-zone increased with increasing fertilizer N rate for CC and CSb, but only in 2014 we found statistical differences (Table 2.2). The overall lack of statistical difference between treatments is not surprising as variability is compounded when calculating load from drainage amounts and NO_3-N concentrations (Randall and Vetsch, 2005). Our NO_3-N load values are within the range of 12 to 146 kg ha^{-1} reported by others for corn in sandy soils (Sexton et al., 1996; Hergert, 1986). Considering absolute values, every year the CSb rotation had the greatest concentrations with the SbC rotation having the least and the CC rotation having intermediate values. Statistical differences were observed only in 2012. The CSb rotation produced greater NO_3-N load than the SbC in 2012 and 2014 and in 2012 the CSb rotation also produced greater NO_3-N load than the CC rotation.

The unfertilized check plot provided a measurement of how much NO_3-N in the soil and through soil-water can be expected when no N is applied. Consistently, the CSb rotation had the absolute greatest concentrations followed by the SbC and CC rotations, because of large variability, the differences were only significantly different in 2012 and 2014. CSb had greater concentrations than CC and in 2014 CSb had also greater concentrations than SbC ($P<0.1$) (Table 2.2). Given the fact that the total amount of N uptake by corn and soybean is similar (Munson and Nelson, 1990), the only difference between the check plots for CSb and SbC is the crop residue present from the previous year. Because we did not measure N immobilization, we can only speculate that the reason the CSb rotation had greater absolute NO_3-N concentrations than the SbC may be an indication of greater N immobilization with the corn residue present in the SbC rotation. Greater immobilization might also be the reason why CC had the lowest absolute concentration values. Finally, after four consecutive years of no N applications, the check plot still had season-long mean NO_3-N concentrations in the leachate ranging from 9 mg L^{-1} in CC to 20 mg L^{-1} in CSb and produced a range of NO_3-N load below the root-zone of 21 to 51 kg ha^{-1}, respectively. These findings illustrate the difficulty of reducing potential negative effects of NO_3-N leaching to groundwater in corn cropping systems below the U.S. Public Health drinking water standards of 10 mg L^{-1}.

When averaged across years NO_3-N load below the root-zone increased with N fertilizer rate for CC by the relationship NO_3-N load = $-0.0004(N_{rate})^2 + 0.3319N_{rate} + 27.73$; $R^2 = 0.90$; P=0.0002. Based on this relationship and the quadratic plateau relationship of grain yield to N fertilizer rate at an EONR with a N-to-Corn price ratio of 0.0056 (chapter 1), we determined that at the EONR (251 kg N ha^{-1}) CC produced 12.6 Mg ha^{-1} of grain yield and resulted in a NO_3-N load of 86 kg ha^{-1}. Reducing the EONR by 20% to 201 kg N ha^{-1} would result in a grain yield of 12.1 Mg ha^{-1} (reduction of 4%) and a NO_3-N load of 78 kg ha^{-1} (reduction of 9%). Reducing the EONR by 25% to 188 kg N ha^{-1} would result in a grain yield of 11.9 Mg ha^{-1} (reduction of 6%) and a NO_3-N load of 76 kg ha^{-1} (reduction of 11%). A reduction in EONR of 20% and 25% would still produce a NO_3-N load of 29 kg ha^{-1} and 27 kg ha^{-1} above the unfertilized check. On the other hand, when averaged across years there was no relationship (P=0.1570) to NO_3-N load with N fertilizer rate for the CSb rotation (data not shown). Our data indicate that reducing nitrate load to an acceptable level to achieve pristine water quality goals while producing corn under the conditions of our study was not feasible, even if a substantial reduction in N fertilizer rate, and related grain yield reduction, were considered.

2.4.3 Nitrogen Source and Soil Water Nitrate Concentration and Load Below the Root-Zone

The University of Minnesota BMP for irrigated sandy soils suggests using split-applications of urea during the growing season (Lamb et al., 2015). One possible way to reduce leaching not researched extensively for sandy soil is the use of EEFs. Other studies investigating EEFs found that polymer-coated urea significantly reduced NO_3-N leaching over untreated granular urea, on a coarse textured and claypan soils (Nelson et al., 2009; Wilson et al., 2009) In our study, there was no significant difference between the products and the split N application of urea in NO_3-N concentrations or load below the root-zone for the different crop rotations or years (Table 2.3). The only exception was for CSb in 2013 with the ESN/Urea blend having the greatest NO_3-N concentrations and the split application of urea having the least. There is no clear explanation for this. Across the different seasons, NO_3-N concentration and load below the root zone for EEFs followed a similar pattern (data not shown) as observed for the urea treatment at the 180 kg N ha^{-1} rate (Fig. 2.2 and 2.3). This was surprising given the fact that the EEFs should have nitrified later in the season relative to urea. We also found no difference in RSN for N sources (data not shown). Since overall there was a 6.1% increase in grain yield with the split application over the average grain yield of the three EEF treatments (chapter 1) and no benefit exists for water quality goals, the enhanced efficiency products tested do not provide any clear benefit over the BMP tested in this study.

2.4.4 Evaluation of Two Measurement Methods for Water Drainage

We decided to use the WB method for our NO_3-N load calculations and analysis because it is the most widely used method and would provide ease comparisons of results with other studies. It was also felt the WB data more closely represented leaching losses for our study compared to the PCL. We determined it would be informative to conduct a comparison of methods since we measured NO_3-N loss with both methods. Both methods roughly mimic each other across the three growing seasons (Fig. 2.4). However, the WB method estimated consistently more total drainage and NO_3-N load (regardless of crop rotation) than the PCL method (Table 2.4). The PCL method produced substantially lower measurements than the WB method in 2012 (108%) but differences narrowed between the two methods for 2013 (17%) and 2014 (31%). The larger difference in 2012 is likely a reflection of the fact that for the PCLs 2012 was an equilibration year after excavation and installation in fall of 2011. For this reason, the last two years may provide a better comparison for these methods.

2.5 Conclusion

Sandy soils in MN are extremely valuable as they are highly productive when irrigated. There are concerns over N management as NO_3-N leaching below the root-zone in these soils can create groundwater quality issues. Recently the University of Minnesota revised its guidelines for corn production in irrigated sands and increased the N rate needed to optimize corn productivity. While BMPs are not just to meet production goals but also to improve efficiency and environmental protection, the increase in N rate called into question whether the new guidelines would exacerbate NO_3-N leaching below the root-zone. Seventy five percent of the total leaching and 73% of the total NO_3-N load we measured took place during May and June. Even though 41% of the total water (sum of irrigation and precipitation) was received during this time a similar amount (43% of the total) was received during the later period of July-August but little leaching and NO_3-N loading occurred during the later period. Most of the water in May and June was from precipitation and illustrates the challenge that excess water in the spring can create to protect N from leaching when the crop is not taking up large amounts of nitrogen and evapotranspiration rates are low. Excess precipitation is typical during the early portion of the growing season, and during our study, we also observed that this period was wetter than normal, following what is being predicted with climate change models. The excess precipitation and high-leaching period also overlapped with N fertilization timing, including early sidedress application at V4. Based on these results and other scientific literature we speculate that delaying N applications later into the season or splitting the application multiple times to ensure adequate N supply early in the season but hedging the risk for N loss may be a feasible way to reduce N loss and maintain productivity. Further, the fact that most of the leaching and loading occurs in May and June would suggest that having vegetation, such as a living mulch, that is actively using water may help reduce leaching losses and should be investigated to determine if environmental quality and production goals can be better achieved. The alternative of reducing N rate below the EONR produced limited benefits towards reducing NO_3-N losses in a way that would have a substantial impact in improving water quality, especially for the CSb rotation that produced overall greater NO_3-N load than CC. Further, using EEFs as a way to reduce NO_3-N load did not provide benefits above the BMP of slit-N applications. Finally, the fact that after four years of no N application the CC and CSb rotation had NO_3-N concentrations ranging from 9 to 20 mg L^{-1} and NO_3-N load of 21 to 51 kg ha^{-1} highlights the difficulty of achieving substantial reductions in N loss towards meeting water quality goals for the drinking water standard of a maximum of 10 mg NO_3-N L^{-1}.

Table 2.1 30-yr normal (1980-2009) precipitation and temperature and departure from normal for 2012 to 2014.

Year	Apr.	May	June	July	Aug.	Sept.	Year mean
	Precipitation (mm)						
30-yr mean	34	57	76	104	90	90	670
2012	31	136	14	-33	-58	-88	-70
2013	12	68	74	-52	-67	-17	61
2014	111	78	143	-66	42	-62	145
	Temperature avg (°C)						
30-yr mean	-1.8	6.7	13.7	18.7	21.4	20.2	5.9
2012	9.7	8.7	6.1	5.5	-1.9	-5.8	1.9
2013	2.5	5.4	5.0	2.9	-0.6	-3.5	-1.5
2014	5.2	5.7	5.5	1.0	-1.0	-5.5	-2.2

Source of 30-yr normal: National Oceanic and Atmospheric Administration. Yearly data collected at the research site.

Table 2.2 Season-long mean nitrate concentration and cumulative nitrate load below the root-zone and standard error means (SEM) during 2012 to 2014 for various N rates in continuous corn (CC) and corn after soybean (CSb), and residual N rate from the previous corn crop on soybean after corn (SbC).

N Rate	Year	CC	CSb	SbC	CC	CSb	SbC
kg ha^{-1}		———mg NO_3^--N L^{-1} (SEM)———			———kg NO_3^--N ha^{-1} (SEM)———		
	2012						
0		15.9c† (1.3)	44.6 (2.6)	23.8b(1.9)	32.8 (10.8)	92.7 (20.7)	50.7 (14.6)
135		30.4b (2.0)	56.5 (3.3)	26.0b (1.4)	54.2 (11.8)	113.3 (29.3)	41.3 (19.3)
180		34.7ab (3.5)	54.2 (5.8)	24.9b(2.9)	59.1 (25.9)	128.7 (46.4)	50.9 (17.3)
225		33.0ab (3.1)	57.3 (8.0)	35.4a(2.2)	69.8 (25.7)	94.9 (63.4)	71.6 (17.9)
270		40.1a (3.1)	48.0 (3.1)	27.4b(2.9)	76.4 (18.5)	78.2 (12.9)	69.8 (25.9)
Mean		30.5B‡ (1.3)	51.8A (2.1)	27.6B (1.1)	58.5B (8.4)	101.6A (15.5)	56.8B (8.0)
	2013						
0		8.8c (0.9)	23.4c (2.1)	18.2ab (1.7)	32.1 (15.3)	74.0 (14.3)	76.0 (23.7)
135		25.6b (2.1)	32.3b (3.6)	14.b (1.2)	67.7 (11.5)	100.8 (29.2)	51.1 (17.3)
180		23.9b (2.7)	29.3bc (2.7)	15.7b (1.8)	70.1 (22.0)	100.1 (48.3)	56.4 (35.4)
225		35.6a (2.6)	30.5bc (2.7)	15.8ab (1.3)	124.2 (20.1)	102.4 (14.7)	60.1 (20.7)
270		23.0b (2.8)	41.2a (3.0)	20.1a (1.5)	71.0 (33.6)	139.3 (26.3)	76.0 (23.0)
Mean		23.3 (1.1)	31.5 (1.3)	16.8 (0.7)	73.0 (11.4)	103.3 (12.4)	63.9 (9.8)
	2014						
0		8.8d (1.0)	19.7d (1.2)	10.6c (0.7)	21.3b (4.9)	50.6c (5.8)	25.4 (7.7)
135		28.2c (2.5)	42.9c (3.0)	10.9c (0.5)	63.3ab (11.0)	83.8b (7.3)	25.0 (3.7)
180		37.2b (3.0)	46.6bc (2.8)	15.6b (1.4)	82.5a (11.1)	91.7ab (1.6)	38.7 (16.4)
225		42.7ab (3.7)	55.8a (4.0)	25.0a (1.8)	93.5a (13.3)	113.6a (15.2)	61.8 (18.5)
270		44.3a (3.1)	53.6ab (3.2)	15.8b (1.4)	99.4a (21.5)	112.2a (2.0)	41.3 (15.8)
Mean		32.2 (1.4)	43.7 (1.5)	15.6 (0.6)	72.0A (9.1)	90.4A (6.9)	38.5B (6.3)

†Within year and crop rotation means followed by the same lowercase letter are not significantly different ($P < 0.05$).

‡Within year means followed by the same uppercase letter are not significantly different ($P < 0.05$)

Table 2.3 Season-long mean nitrate concentration and cumulative nitrate load below the root-zone and standard error means (SEM) during 2012 to 2014 for various N sources (urea, SuperU, polymer-coated urea (ESN), and a 1:1 blend of ESN and urea) applied at the rate of 180 kg N ha^{-1} in continuous corn (CC) and corn after soybean (CSb), and residual N from the previous corn crop on soybean after corn (SbC).

Product	Year	CC	CSb	SbC	CC	CSb	SbC
		mg NO_3^--N L^{-1} (SEM)			kg NO_3^--N ha^{-1} (SEM)		
	2012						
Urea		34.7 (3.5)	54.2 (5.8)	24.9 (2.9)	59.1 (25.9)	128.7 (46.4)	50.9 (17.3)
SuperU		31.3 (2.9)	67.9 (6.4)	28.7 (2.2)	49.0 (21.1)	137.9 (38.1)	66.8 (16.7)
ESN		29.5 (2.1)	48.2 (3.0)	24.7 (1.2)	62.9 (17.3)	77.7 (12.5)	45.4 (8.1)
ESN/Urea		24.0 (1.9)	43.3 (3.8)	36.2 (3.7)	39.5 (12.9)	78.1 (28.3)	67.9 (28.8)
	2013						
Urea		23.9 (2.7)	29.3b (2.7)	15.7 (1.8)	70.1 (22.0)	100.1 (48.3)	56.4 (35.4)
SuperU		30.0 (2.4)	42.4ab (3.7)	17.8 (1.6)	104.6 (31.8)	110.9 (37.1)	71.1 (24.6)
ESN		25.3 (2.4)	44.8ab (2.7)	18.2 (1.2	90.5 (42.5)	132.3 (32.6)	73.0 (7.5)
ESN/Urea		25.3 (2.4)	54.6a (5.0)	13.0 (0.9)	88.4 (10.5)	179.3 (5.2)	49.2 (17.4)
	2014						
Urea		37.2 (3.0)	46.6 (2.8)	15.6 (1.4)	82.5 (11.1)	91.7 (1.6)	38.7 (16.4)
SuperU		38.7 (3.7)	47.1 (3.4)	13.9 (1.0)	72.3 (19.6)	99.3 (13.2)	37.9 (9.2)
ESN		26.6 (2.4)	33.4 (2.2)	15.6 (0.9)	62.4 (20.9)	76.6 (10.2)	38.6 (8.2)
ESN/Urea		34.8 (2.7)	38.6 (2.1)	15.6 (1.2)	72.5 (4.2)	75.3 (7.3)	36.8 (15.7)

Table 2.4 Season-long cumulative drainage (cm) and nitrate-N load (kg ha^{-1}) below the root-zone calculated by the passive capillary lysimeters (PCL) and water balance (WB) methods and percent difference of WB compared to PCL for different years and for continuous corn (CC), corn after soybean (CSb), and soybean after corn (SbC).

Year	Rotation	PCL	WB	WB difference relative to PCL
		cm		%
2012		10	22	108
2013		31	36	17
2014		18	23	31
		kg ha^{-1}		
2012	CC	23	58	153
	CSb	42	102	143
	SbC	23	57	143
2013	CC	57	73	28
	CSb	84	103	23
	SbC	52	64	24
2014	CC	48	72	49
	CSb	67	90	34
	SbC	30	38	29

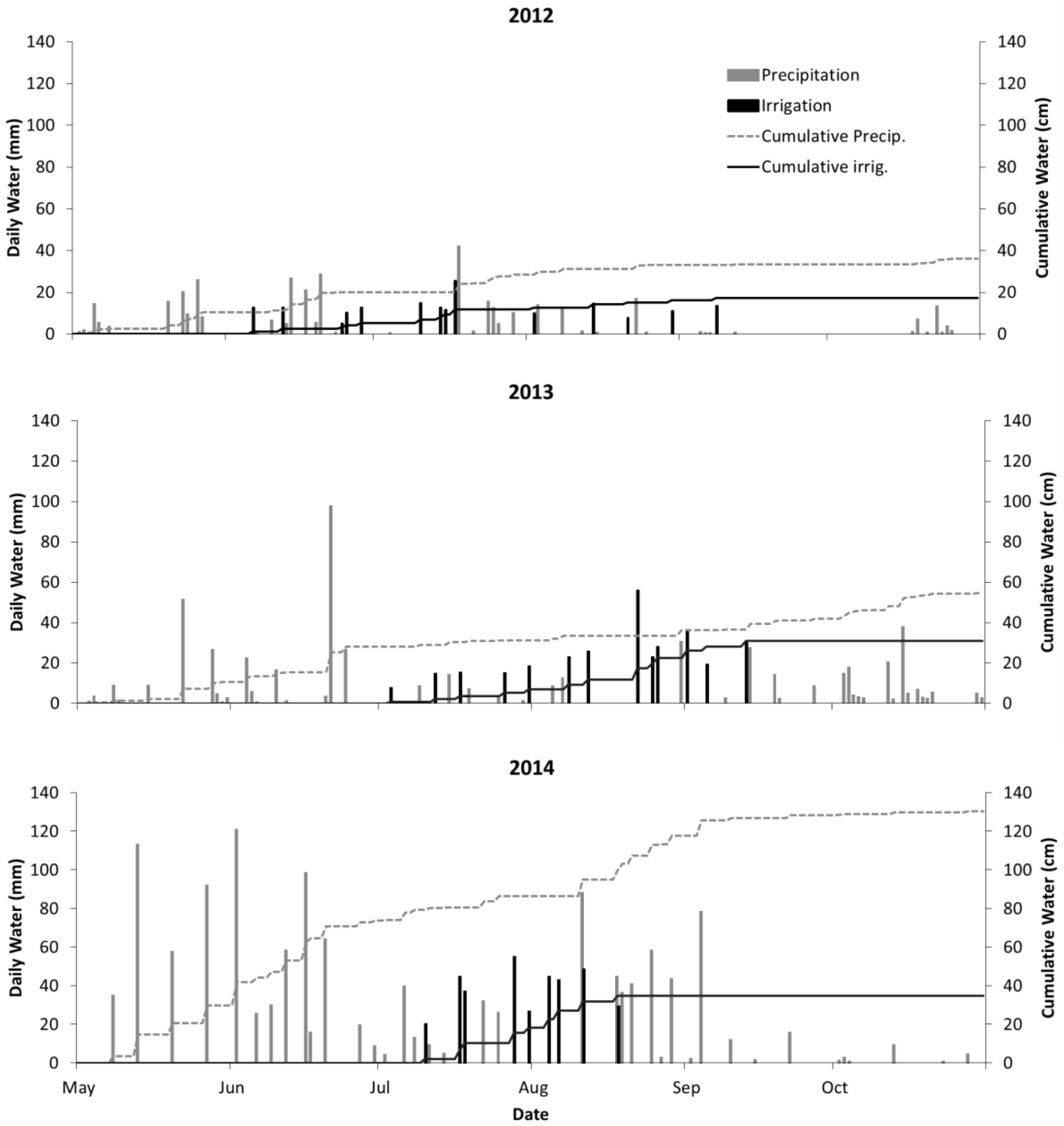

Figure 2.1 Daily precipitation and irrigation amounts in mm and cumulative precipitation and irrigation amounts in cm for 2012 to 2014.

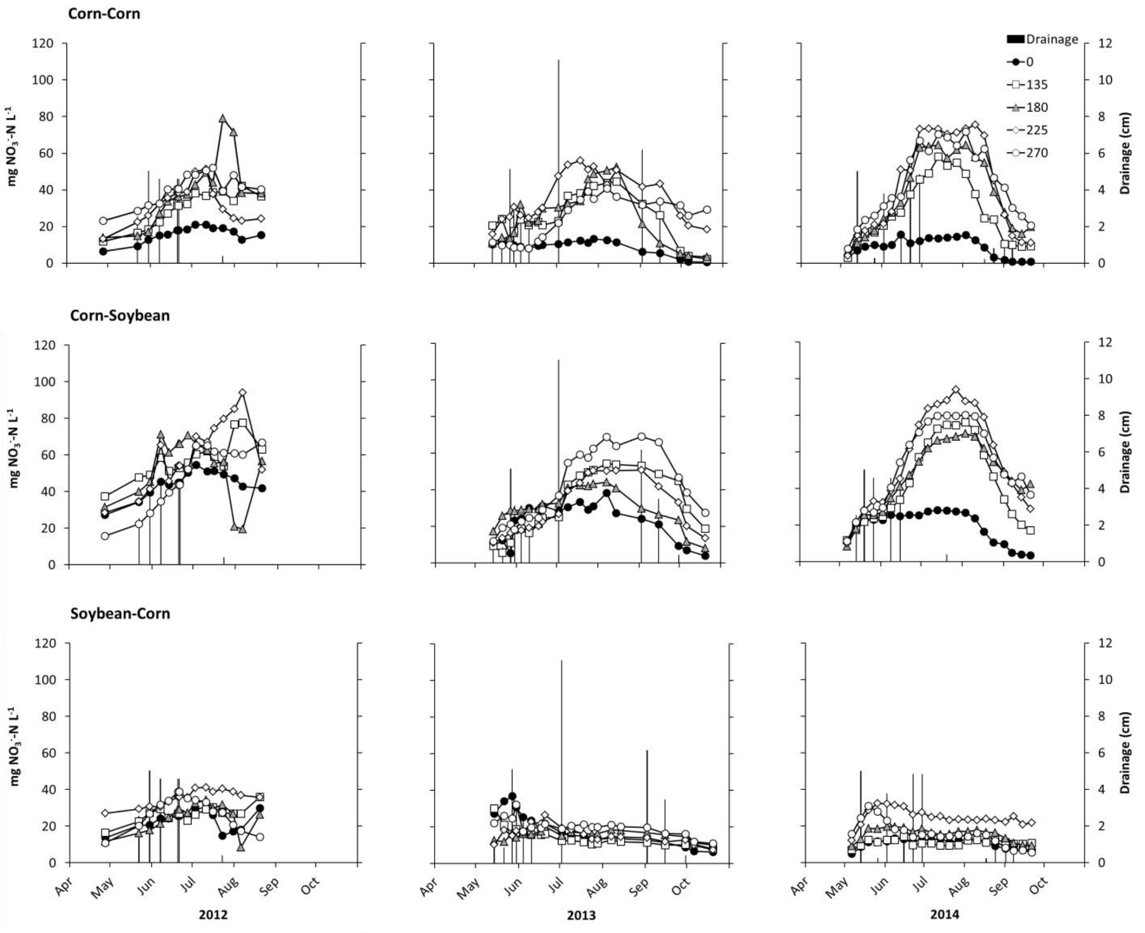

Figure 2.2 Season-long nitrate concentrations (mg NO$_3$-N L^{-1}) and water drainage (cm) below the root-zone during 2012 to 2014 for various N rates in continuous corn (CC) and corn after soybean (CSb), and residual N rate from the previous corn crop on soybean after corn (SbC).

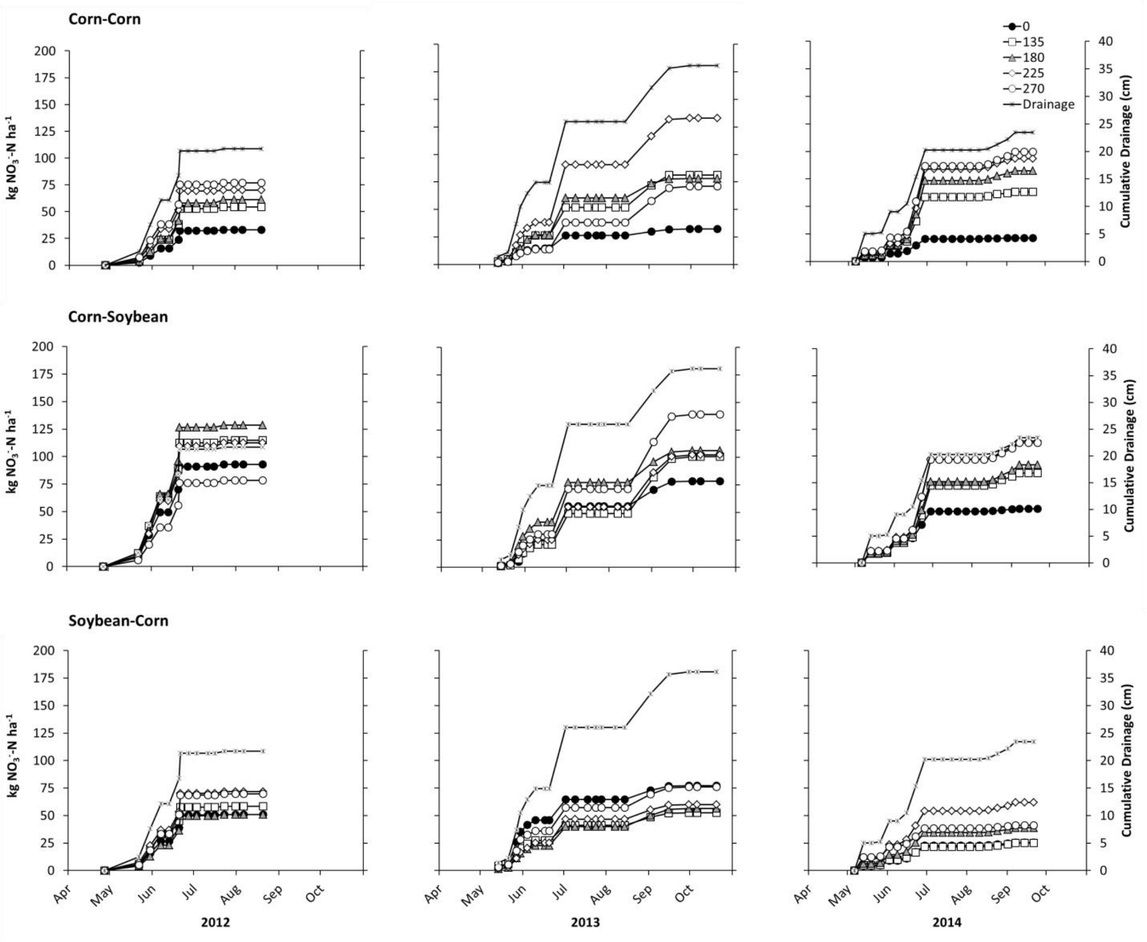

Figure 2.3 Season-long cumulative nitrate load (kg NO_3-N ha^{-1}) and water drainage (cm) below the root-zone during 2012 to 2014 for various N rates in continuous corn (CC) and corn after soybean (CSb), and residual N rate from the previous corn crop on soybean after corn (SbC).

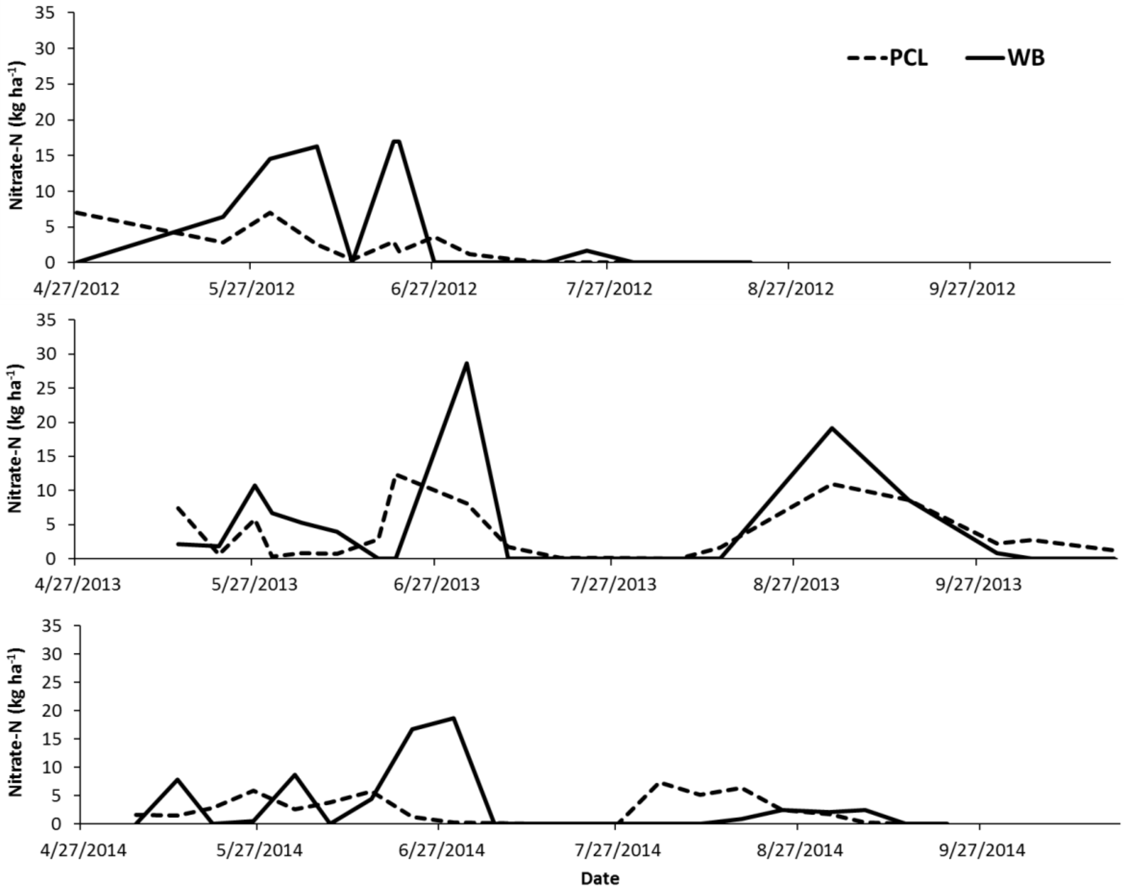

Figure 2.4 Season-long nitrate-N load during 2012 to 2014 averaged across N fertilizer rates and crop rotations calculated by the passive capillary lysimeters (PCL) and water balance (WB) methods.

3.0 Conclusions

This study found no benefit for use on sandy irrigated soils of ESN or SuperU compared to urea as a N source of nitrogen. Grain yields and the concentration of NO_3-N leached below the root zone was no different from the 180 kg N ha^{-1} and 225 kg N ha^{-1} rate of N applied as urea compared to ESN and Super U. These products may still be valuable on different textured soils or in years with different weather conditions. Also, since we know from combining totals of plant N uptake, NO_3-N load leached, and amount of residual soil nitrogen, we can calculate how much N was left the system because of these factors. This brings up the question to how much has gone into the atmosphere, since the slopes at both of these sites are minimal we assume that there is a very low to near zero amount of runoff, thus we assume some N has be volatilized but cannot be for certain how much. This study gives us a better knowledge of a solid number of what we left in the system and how much the plant has taken up, improving our understanding of nitrogen efficiency in these hybrids as well as N dynamics in these coarse textured soils.

There were a number of limitations to this study. One mentioned above, the lack of knowing how much may have been volatilized into the atmosphere. Without this number we cannot be certain if there is a considerable amount of N we did not catch leaching through the profile or if it did in fact volatilize. Many of the other limitations were realized when looking at results of the water study. Since the lysimeters were permanently installed at Pope Co. there was increasingly similar trends as the years went on, this was not the case for Dakota Co. because the lysimeters were removed each year the soil did not have time to settle back into place causing much of the data to be highly variable and questionable. To better understand what is driving leachate concentrations it would be preferable to sample the lysimeters more often than the seven to ten day average. Ideal we would have liked to sample every day, however that amount of work is not practical, but we could possibly sample every three to four days to giving us a more accurate timeline. The goal of this thesis was not to determine the effectiveness of a load measurement comparing the use of passive capillary lysimeters versus the use of a water balance method, although we believe that installation of more passive capillary lysimeters would improve this method, as well as increasing the amount of times these were sampled to the same timing as the suction cup lysimeters, this would give us more accurate flow measurements and give us a more precise time of when water is flowing through the soil.

When looking at other studies and scientific literature we know there is a time of high potential losses for. This time occurs before the time when a corn crop has its greatest need (V4) for nitrogen. In this study, the urea sidedress application was done at V4. Is this application time too early? In the future it would be interesting to examine multiple application times starting at V4 and continuing later into the season. Since these soils have a high potential for leaching applying smaller amounts of nitrogen more often than just one sidedress should have the potential to reduce leaching and increase grain yield.

In a future study it would be interesting to investigate at these concepts in a lab setting and compare it to the field data. Since there is greater accessibility in lab experiments and the lab experiments are usually on a smaller scale, there would be the ability to sample the suction cup lysimeters more often, as well as being able to collect all the water flowing through the soil profile. This information would be able to give us a better understanding of where the nitrogen is going in the system. Doing this and including more treatments with different sidedress timings would help confirm if two applications is our best option or if more would benefit the producer. Since the University of Minnesota's best management practices recommends a split application of 234 kg N ha^{-1}, I would like to have this be the main rate at which different treatments are tested, this would give us a good indication of if that is the best rate to apply in these soils.

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