Corn and Soybean Production on Irrigated Coarse-Textured Soils: Integrating Winter Rye and Kura Clover to Reduce Nitrate Leaching

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

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

Fabián Fernández

January 2019

ACKNOWLEDGEMENTS

This thesis would not have been possible without the support of Dr. Fabian Fernandez. Your patience was unmatched, and I can never thank you enough for your thoughtful edits and suggestions. Working with you made me a better writer, researcher, and agricultural steward. Thank you for your time, mentorship, and friendship.

A special acknowledgement is also needed for Andy Scobbie, Thor Sellie, and the field crew. I am so grateful for all the moments you each took to teach me.

My experience at the University of Minnesota would not have been the same without John Baker, John Nieber, Jeppe Kjaersgaard, Kari Jarcho, Stacy Nordstrom, professors, and fellow graduate students. Thank you for being my support system.

Finally, I would like to thank my family. To my dad, who inspired my love for the outdoors and always encouraged me to invest in my education. To my mom, for always answering my phone calls no matter how hard the wind was blowing. To my husband, thank you for always supporting me in this endeavor. I will always be grateful we started our marriage in Minnesota and for the wonderful moments we shared there, I love you.

ABSTRACT

Best management practices for N fertilizer such as rate, timing, source, and placement are suggested to support crop yield and mitigate N loss. However, high risk conditions, like irrigated coarse-textured soils in corn (Z*ea mays* L.) and soybean [*Glycine max* (L.) Merr.] production which are highly prone to NO_3–N leaching, require additional management to balance production and environmental impact. The objective of this study was to evaluate winter rye (*Secale cereal* L.) cover crop (Rye–Cover) and kura clover (*Trifolium ambiguum* M. Bieb.) living mulch (Kura) systems as alternative management tools to reduce NO_3–N leaching in corn and soybean crop rotations. Rye–Cover and Kura were established in Pope county, Minnesota from 2016–2017 on an irrigated coarse-textured soil in three cropping rotations: continuous–corn (CC), corn–soybean (CSb), and soybean–corn (SbC). Rye was aerially seeded each fall into standing corn (CC and CSb) or soybean (SbC) and terminated with glyphosate two weeks before crop planting. Kura was drilled in the spring and managed for establishment for one year (Stage 1). The following year, Kura was strip-tilled and managed with corn or soybean (Stage 2). Corn received 0, 100, 200, 250, and 300 kg N ha^{-1} applied in four spilt applications at corn development V2, V6, V8, and V12. During Stage 1, Kura received 100 kg N ha^{-1} in four split applications and no N was ever applied to soybean. Weekly below root zone NO_3–N leaching was measured with permanently installed porous suction-tube lysimeters and drainage was calculated using a water balance equation and evapotranspiration (ET) was adjusted for treatments. Soil N, plant N, above-ground biomass, corn economic optimal N rate (EONR), and crop yield for corn and soybean were also measured. Spring rye biomass and N uptake were greatest in CSb and cumulative NO_3–N load leached below the root zone was reduced by 48% compared to CSb with No–Cover. The

EONR for CSb with Rye–Cover required 58 kg N ha^{-1} less (2016) or 53 kg N ha^{-1} more (2017) compared to No–Cover. When seeded into standing corn (CC and SbC rotations) Rye–Cover biomass was respectively 81% and 71% less than in CSb. Compared to No–Cover treatments Rye–Cover in CC and SbC did not reduce NO_3–N leaching and consistently increased the EONR in CC. Rye–Cover did not impact corn or soybean yield. During Stage 1, Kura leached 140 kg NO_3–N ha^{-1} but when managed with corn or soybean in Stage 2, NO_3–N load leached was reduced by 92%, 88%, and 84% in CSb, CC, and SbC, respectively. During Stage 2 NO_3–N leaching did not exceed 15 kg NO_3–N ha^{-1} in any rotation with Kura. Kura reduced yield by 38%, 31%, and 22% in CSb, CC, and SbC, respectively. These data indicate that Rye–Cover is best suited for management in CSb to reduce NO_3–N leaching. Additionally, Kura is a promising option for NO_3–N leaching reduction after the establishment year, but management to minimize yield loss requires further refinement.

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LIST OF ABBREVIATIONS

AE, agronomic efficiency

BMP, best management practice

C:N, carbon to nitrogen ratio

CC, continuous corn cropping rotation

CSb, corn following soybean cropping rotation

EONR, economically optimum nitrogen rate

ET, evapotranspiration

FRE, fertilizer recovery efficiency

K_c, crop coefficient

Kura, kura clover living mulch

NDRE, normalized difference red edge index

NDVI, normalized difference vegetative index

No-Cover, no cover crop or living mulch

NUE, nitrogen use efficiency

Rye-Cover, winter rye cover crop

SbC, soybean following corn cropping rotation

SREE, standardized reference evapotranspiration equation

CHAPTER 1: Corn and Soybean Agronomic Response to Nitrogen in Irrigated Sands with Rye Cover Crop

1.1. SYNOPSIS

Cover crops, such as winter rye (*Secale cereal* L.), are potential N management tools for coarse-textured soils in corn (*Zea mays* L.) and soybean [*Glycine max* (Merr.) L.] production. The objectives of this study were to evaluate the impact of a rye cover crop (Rye–Cover) and N rate on rye biomass, N uptake, and soil N availability; as well as corn and soybean yield, economic optimum N rate (EONR), and N use efficiency (NUE). Rye was seeded into standing corn and soybean, terminated two weeks before crop planting, and N rates of 0, 100, 200, 250, and 300 kg N ha^{-1} were applied to corn in four equal split applications between the V2 and V12 development stages. Little benefit was seen in fall soil N reduction from Rye–Cover, likely because soil N levels were low. The benefit from Rye–Cover was seen in spring when rye residue immobilized N that otherwise would have been vulnerable to loss. Rye–Cover had no impact on yield in CC or CSb but had variable results on corn EONR. In CC, Rye–Cover consistently increased the EONR by approximately 17 kg N ha^{-1} on average. The EONR for CSb with Rye–Cover required 58 kg N ha^{-1} less (2016) or 53 kg N ha^{-1} more (2017) compared to No–Cover. The results of this study indicated there was no agronomic advantage to integrate Rye–Cover into CC or SbC. CSb was better suited for Rye–Cover integration but beneficial interactions from Rye–Cover may be dependent on growing season conditions that affect immobilization and mineralization processes.

1.2. INTRODUCTION

In Minnesota there are approximately 200,000 hectares of irrigated, coarse-textured soils in row crop cultivation (USDA, 2015). Production on coarse-textured soils continues to expand because high yields are achievable when crops are supplemented with nutrients and water. Nonetheless, nutrient and water management in coarse-textured soils is complicated because of the low water holding capacity of these soils that result in rapid water and NO_3–N movement below the root zone. Nitrate leaching and groundwater contamination in the Midwest is a major concern since a majority of the public drinking water is sourced from groundwater (Gehl et al., 2005). Struffert et al. (2016) noted that NO_3–N leaching was greatest with spring precipitation when there is limited vegetation to uptake water or nutrients. This is an important issue as trends indicate springs will become increasingly wetter in the upper Midwest region (Seeley, 2015), which could exacerbate NO_3–N loss.

The above-mentioned challenges are partly responsible for a renewed interest in determining best management practices (BMP's) for N in irrigated sandy soils. The BMP's for corn production on irrigated sandy soils were updated by University of Minnesota Extension in 2015(Lamb et al., 2015). One of the changes in the 2015 revision was an increase in the economic optimal N rate (EONR), which raised concerns over increased environmental contamination of NO_3–N in groundwater. However, Struffert et al. (2016) showed that merely decreasing N rate below the EONR did not adequately reduce NO_3–N leaching in irrigated coarse-textured soils. These finding are synonymous with results from other studies investigating the relationship between N rate and NO_3–N leaching (Beaudoin et al., 2005). Additionally, these studies showed substantial NO_3–N loss even when crops were not amended with N, such as in soybean and corn check plots. These results highlight that standard BMP's (such as management of N rate, timing, source, and placement) may not be enough to substantially reduce NO_3–N leaching and alternative management strategies are needed. Cover crops for corn production in irrigated coarse-textured soils was suggested as a potential alternative management strategy that needs to be investigated to meet agronomic and environmental goals (Struffert et al., 2016).

Cover crops have been associated with many desirable benefits such as reduced soil erosion, scavenging and recycling residual soil NO_3–N, and improved soil organic matter (Dabney et al., 2001; Jewett and Thelen, 2008). There are also reports of rye sequestering soil organic carbon (Olson et al., 2010) and reducing NO_3–N losses (Mcracken et al., 1994; Kaspar et al., 2012). While the benefits are promising, there are also the drawbacks of increased management, yield suppression, and allelopathic characteristics (Dabney et al., 2001). Decreases in crop yield have been attributed to allelopathy (Raimbault et al., 1990; Tollenaar et al., 1993) and N deprivation (Johnson et al., 1993; Vaughan and Evanylo, 1998).

The selection of a cover crop greatly depends on the cropping system, hardiness zone, and management practices such as tillage. For coarse-textured soils under irrigation in corn and soybean production in the upper Midwest, a winter rye cover crop is a suitable option (Stoskopf, 1985). Rye is an effective N scavenger, is winter hardy, and can be chemically or mechanically terminated; however, more research is needed to determine the extent to which rye, as a cover crop, alters N management and corn and soybean production. Even with decades of research focused on rye cover crops, management techniques are still being refined. Corn grain and silage yields when managed with a rye cover crop have been reported to decrease (Raimbault et al., 1990; Johnson et al., 1998; Vaughan and Evanylo, 1998), increase (Ball-Coelho and Roy, 1997; Andraski and Bundy, 2005), or have no difference (Dhima et al., 2006; Krueger et al., 2011). Similarly, when planted with rye soybean yields were observed to decrease (Reddy, 2003), increase (Moore et al., 1994), or have no difference (Pantoja et al., 2015).

Management of rye biomass accumulation is very important to obtain the intended benefits of this cover crop. If too little biomass is present to reduce environmental impacts, then the addition cost of the practice is not justified (Snapp et al., 2005). If there is too much biomass it becomes difficult to manage and has an increasingly negative impact on crop yield (Vaughan and Evanylo, 1998). It is estimated that at least 0.3 Mg ha^{-1} of rye biomass is needed to take up 10 kg N ha^{-1} and that uptake is closely tied to biomass accumulation (Wilson et al., 2013). However, biomass accumulation is extremely variable ranging from 0.5–1.3 (Pantoja et al., 2015) and 2.2–5.2 Mg ha^{-1} (Ruffo and Bollero, 2003). Several studies involving rye cover conclude that rye should be terminated approximately 1–2 weeks before corn planting to avoid yield loss (Dhima et al., 2006; Krueger et al., 2011; Kaspar, T.C.; Jaynes, D.B.; Parkin, T.B.; Moorman, T.B.; Singer et al., 2012; Swanton et al., 2018).

An additional consideration in rye cover systems is the effect of rye cover on soil N storage. One study, which delayed crop planting for two weeks after rye termination, determined that during rye residue decomposition only a small amount of N was recycled, thus having minimal impact on the supply of plant available N (Pantoja et al., 2016). The minimal effect was linked to the low post-harvest soil N tests and thus minimal N uptake by the rye. In another study, which planted corn two days after rye termination, found that rye cover reduced corn yield by 2.8 Mg ha^{-1} (Johnson et al., 1993). This result was attributed to reduced soil N availability after rye termination due to immobilization caused by residue decomposition (Thomas and Frye, 1984). Thomas and Frye (1984) also noted visual N stress even with ample fertilizer and determined that the rye residue was immobilizing soil N. The contrasting results of these studies highlight that management practices can have important impacts on soil N storage and cycling that ultimately impact crop response.

Most rye cover cropping system studies have been conducted in warmer regions of the Midwest and are almost exclusively on fine-textured soils. Less is known regarding the impact of a rye cover crop on the yield and N needs of corn and soybean in colder regions of the upper Midwest and on coarse-textured soils. Therefore, this study was conducted on an irrigated, coarse-textured soil under continuous corn (CC) and both phases of a corn-soybean (CSb and SbC) rotation in the upper Midwest. The objectives of this study were to evaluate the impact of a rye cover crop and N rate on (1) rye biomass and N uptake, (2) soil N availability and (3) corn yield, EONR, and NUE in CC and CSb rotations, and soybean yield in a SbC rotation.

1.3. MATERIALS AND METHODS

1.3.1. Site Description

The study was conducted during 2016 and 2017 at the Rosholt Research Farm in Westport, Minnesota (45°42’49.1” N, 95°10’16.2” W) on an Arvilla sandy loam soil (sandy, mixed, frigid Calcic Hapludolls) with a sandy/gravelly outwash parent material. The top 15–cm of soil had the following mean characteristics: organic matter 46 g kg^{-1}, pH 6.8, and dry bulk density 1.64 g cm^{-3}. This study was part of a larger long-term project established in 2011 with three adjacent rotations: continuous corn (CC) and both phases of a corn–soybean rotation, corn (CSb) and soybean (SbC). From 2011–2014 the field site was used for an N rate and source study (Rubin et al., 2016). In 2015, the site received a uniform application of N and was amended with P and K to maintain optimum soil test values for these nutrients in preparation for this study.

1.3.2. Weather and Irrigation

From 2015 to 2017 an onsite weather station recorded hourly air temperature and precipitation (Table 1. 1). Whenever there was a malfunction with the onsite weather station, missing data were substituted with local NOAA (National Oceanic and Atmospheric Administration) data. The 30-year normal temperature and precipitation was determined using local NOAA weather stations (Table 1. 1). Irrigation was scheduled using an irrigation checkbook (Steele et al., 2010) and was applied with a linear irritation system. In both years, the irrigation system was run seven times, 100–mm was applied in 2016 and 114–mm was applied in 2017. Irrigation water contained <10 mg NO_3–N L^{-1} and per University of Minnesota guidelines (Lamb et al., 2015) N rates were not adjusted by NO_3–N in irrigation water because of the low N concentrations.

1.3.3. Treatments

Ten treatments were arranged in a randomized complete block design within each rotation with four replications. Individual plots measured 4.56–m wide by 12.2–m long and consisted of six crop rows planted at 76–cm spacing. Treatments were Rye–Cover (*Secale cereal* L.) and No–Cover with 0, 100, 200, 250, and 300 kg N ha^{-1} applied to the CC and CSb rotations and no N was applied to the SbC rotation. This enabled us to measure the residual effect of N treatments applied on the previous year corn. The N rates were divided in four equal split applications at corn development stages V2, V6, V8, and V12 (Abendroth et al., 2011). Nitrogen was applied as urea (46–0–0) (N–P–K) treated with a urease inhibitor [N– (n–butyl) thiophosphoric triamide (NBPT)] to avoid volatilization losses, though treatments were incorporated with at least 6–mm of irrigation or precipitation within three days of fertilizer application.

1.3.4. Rye Establishment

Rye was initially planted into all rotations in 2015 at corn and soybean development stage V6 on 16 June 2015 at the rate of 84 kg ha^{-1}. Rye seed was broadcast by hand to mimic aerial planting and was incorporated with irrigation. Due to poor rye stand in late August, likely caused by crop shading on the rye, rye was re-seeded. On 17 Sept. 2015, rye was re-seeded at 84 kg ha^{-1} only into the SbC rotation because late corn maturity in fall 2015 prevented re-seeding rye in CC and CSb before soils froze. The method of hand broadcasting rye at corn development R6 and at soybean 50–75% leaf-drop then incorporating with irrigation proved effective and was adopted for the remainder of the study. In 2016, rye was seeded into corn and soybean stands on 1 Sept. 2016 at 126 kg ha^{-1} and in 2017 was seeded at 126 kg ha^{-1} into soybean on 29 Sept. and into corn on 12 Oct. Depending on precipitation, irrigation was also applied after rye germination to prevent plant loss from water stress. Each spring, 21 Apr. 2016 and 9 May 2017, rye was terminated chemically with glyphosate, N– (phosphonomethly) glycine at 1.2 kg a.i. ha^{-1} plus 4.7 L ha^{-1} non–ionic surfactant (NIS) at 2.5% v/v. After rye termination in 2016, a disk and field cultivator were used for seedbed preparation and in 2017 the fields were strip-tilled to better accommodate other crops present in the larger long-term study that are not part of this study. Rye treatments remained in the same plots across years.

1.3.5. Crop management

Corn hybrids and soybeans varieties were planted 3 May 2016 (Croplan 3611SS/RIB and Northrup King Syngenta S12–H2) and 25 May 2017 (DKC46–20RIB and Genuity S12–H2). Corn was planted at 88,700 seeds ha^{-1} and soybeans at 350,000 seeds ha^{-1}. Corn stand counts were measured at approximately V4. Other than N, standard agronomic practices were used to maximize yield.

Corn was harvested 6 Oct. 2016 and 26 Oct. 2017 and soybean was harvested 7 Oct. 2016 and 17 Oct. 2017.

1.3.6. Plant Sampling

Rye above-ground biomass was sampled from a 0.25-m^2 area before termination each spring when rye was tillering; Zadoks cereal growth stage 25 to 30 (Zadoks et al., 1974). Rye biomass carbon to nitrogen ratio (C:N) was analyzed using a vario MAX cube (Elementar). Corn whole plant samples were collected at V8, R1, and R6 by collecting six whole plant samples per plot. During the corn R6 sampling the ear was removed from the plant, dried, shelled, and weighed to determine moisture content and dry biomass. Soybean whole plants were collected at R6 development stage by sampling 1.5–m of plants per plot. At harvest, grain sub-samples were collected from each corn and soybean plot. All plant samples were dried in a forced-air oven at 60°C, ground through a 2–mm sieve, and analyzed for total N by combustion analysis using a Carlo Erba 1500 elemental analyzer (Horneck and Miller, 1998).

Optical canopy sensing at V8 was collected from corn plots using a Crop Circle model 470 (Holland Scientific Inc.) at 670–nm (red), 780–nm (NIR), and 730–nm (red edge). Data were collected for the length of the plot on the center two rows by holding the sensor directly on top of the crop-row 40–cm above the canopy. These measurements were used to calculate the Normalized Difference Vegetative Index (NDVI) and Normalized Difference Red Edge Index (NDRE). NDRE values were compared to the greatest reading from the Rye–Cover and No–Cover systems of each rotation to determine a 95% threshold (Blackmer and Schepers, 1995). This value was compared to the other treatments to determine crop stress. Treatments below the 95% threshold indicated that they were likely N deprived, while those above 95% had adequate N at the time of sensing.

1.3.7. Soil Sampling

Soil samples were collected from the 0–15 cm and 15–30 cm depth increment at corn V8 and R1 development stage and at post-harvest from all plots in CC and CSb and in SbC from the 0–N check and 200 kg N ha^{-1} treatments applied to the previous corn crop. A 4–core (2–cm diameter hand probe) composite sample was collected at V8 and R1 and a 2–core (5–cm diameter truck mounted hydraulic probe) composite sample was collected post-harvest. Because of a gravely subsoil, it was not possible to collect deeper samples. Also, due to an impermeable layer caused by dry soil conditions, R1 samples in 2017 were only collected from the 0–15 cm depth increment. In addition, a 6–core (2–cm dimeter) composite sample of the 0–7.5 cm depth was collected from each replication at post-harvest to measure Bray P1 (Frank et al., 1998), ammonium acetate extractable K, Ca, and Mg (Thomas, 1982), and pH (Watson and Brown, 1998). Soil samples were dried in a forced-air oven at 32°C, ground through a 2–mm sieve, and analyzed for NO_3–N (Gelderman and Beegle, 1998) and NH_4–N (Bremner and Mulvaney, 1982).

1.3.8. Efficiency Calculations

Economic optimum N rate (EONR) for CC and CSb was calculated using the regional N rate guideline approach described by Sawyer et al. (2006). The EONR was calculated with an N fertilizer to corn price ratio of 0.0056 (Sawyer et al., 2006). This ratio reflects the mean market urea and corn prices from 2016–2017.

Fertilizer recovery efficiency (FRE) (Equation 1) and agronomic efficiency (AE) (Equation 2) were calculated as follows (Wortmann et al., 2011):

Eq.1.

$$\text{FRE} = \frac{\text{NU}_\text{N} - \text{NU}_0}{\text{N}_\text{rate}}$$

Eq.2.

$$\text{AE} = \frac{\text{Yld}_\text{N} - \text{Yld}_0}{\text{N}_\text{rate}}$$

where FRE is how much of the applied N was taken up by the plant (%) and NU_N is total plant N uptake at physiological maturity at a specified N fertilizer treatment, UN_0 is the total plant N uptake at physiological maturity for the 0–N rate treatment, and N_{rate} is the N rate corresponding to NU_N. Agronomic efficiency is the increase in grain (kg ha^{-1}) yield per unit of N applied and Yld_N is the end of season yield for a specific N fertilizer treatment, Yld_0 is the end of season yield for the 0–N rate treatment, and N_{rate} is the N rate corresponding to Yld_N. Nitrogen uptake at physiological maturity was calculated by summing the N uptake from the R6 biomass and the N uptake from the R6 grain. Grain N uptake for R6 was calculated using the mass of the six ears collected at R6 and the N concentration from a sub-sample collected at corn harvest.

1.3.9. Statistical Analysis

Data were analyzed with SAS software version 9.4 (SAS Institute, 2012) using MIXED and GLMMIX procedures. Nitrogen rate and cover were considered fixed effects and replications were considered a random effect. Year and rotation were run independently for all analyses. For the analysis of soil NO_3–N and NH_4–N a repeated measures analysis was performed where N rate, cover, time, and depth and their interactions were fixed effects while replication was a random effect. A compound symmetry covariance structure produced the smallest AIC, AICC, and BIC values. Optimum N rate was calculated using the PROC REG and PROC NLIN models with the modified Gauss–Newton method (SAS Institute, 2012). Where appropriate, differences between treatment means were determined using the PDIFF function and were considered significant at $P<0.05$.

1.4. RESULTS AND DISCUSSION

1.4.1. Weather and Irrigation

Conditions in 2015 had favorable moisture and temperature for fall rye establishment, with adequate precipitation and irrigation and the post-harvest temperature was on average 2.7°C warmer than normal (Table 1.1). Precipitation in 2016 was 56–mm greater than the 30-year normal and July received 179–mm of precipitation which was 81–mm greater than normal. Of the 606–mm of in season precipitation (April – October), 27% was received in the spring (April – June). Temperatures were average with the exceptions of March and November that were 5°C warmer than normal. In 2017, the site received 79–mm precipitation more than the normal and received 43% of the growing season's precipitation in the spring (April – June). Greater than normal rainfall occurred in June (153–mm) and August (176–mm). August was 2.8°C cooler than normal and delayed plant senescence. Warmer and wetter springs occurred more regularly than normal for the upper Midwest and extreme precipitation events occurred more frequently than normal. This trend is predicted to persist in the future (Seeley, 2015).

Supplemental irrigation was applied when soils reached 45% maximum allowable depletion. Irrigation was also used to incorporate fertilizer or rye seed when precipitation was not in the forecast. In 2016, irrigation events were timely and were never closely followed by precipitation. In 2017, two irrigation events were closely followed by unexpected precipitation events. On 10 June, 23–mm of irrigation was followed by a 76–mm precipitation on 14 June and on 1 Aug 25–mm of irrigation was followed by 41–mm of precipitation on 3 Aug. Despite best efforts to manage irrigation correctly, this illustrates a major issue for regions where precipitation is a common occurrence but crops still need irrigation because of the low water holding capacity of the soil. This issue may become increasingly more important if the frequency and intensity of erratic weather events in the upper Midwest increase as predicted (Seeley, 2015).

1.4.2. Rye Establishment and N Uptake

In CSb (the only rotation where rye was seeded into soybean) rye had the greatest spring biomass and N uptake compared to the other rotations (SbC and CC) in both years (Table 1.2). When averaged across years, rye in CSb accumulated 5 times more biomass and 5 times more N than CC and 4 times more biomass and 3 times more N than in SbC. These results were similar to those in Pantoja et al. (2016) where spring rye biomass was greater following soybean than corn at three of four locations. Regardless of rotation, rye had an average C:N of 15:1. Rye was seeded into soybean when leaf-drop was between 50 and 75%, which was a more favorable environment for rye growth than seeding into corn. Seeding rye into standing soybean allowed rye to utilize as much time for development as possible which is usually the limiting factor for cover crop establishment in northern climates (Snapp et al., 2005). At leaf-drop the canopy begins to open as more leaves fall and more sunlight can reach the soil surface which would benefit rye development compared to when seeded into corn. It is possible that once rye was seeded, that the remaining soybean leaves also covered the seeds. This would potentially protect the seeds from predation while also providing moisture and an environment conducive to germination (Sivy et al., 2011). Finally, soybean biomass has low C:N (20:1) and rapidly decomposes (Mannering, J.V., 1981). Rapid crop residue decomposition would reduce physical interference for rye root and shoot development and provide nutrients for the seedlings.

Rye biomass and N uptake in the CSb rotation showed no response to N rate (data not shown). This was expected since the previous soybean crop received no N and post-harvest soil N tests following soybean were low (Table 1.3). Further, across all variables and years rye N concentration was poorly correlated to N uptake ($R^2 = 0.05$) and biomass accumulation ($R^2 = 0.19$) but N uptake was well correlated to biomass production ($R^2 = 0.91$) (Fig. 1.1). This illustrates the importance of managing cover crops for biomass production when the end goal is N uptake. These findings agree with Wilson et al. (2013) who found N uptake was correlated with rye biomass.

Under CC, Rye–Cover had poor biomass production and N uptake in both years of the study (Table 1.2). The poor rye stand in CC was most likely due to restrictive vegetative barriers from corn residue in and on the soil. These residue barriers may have inhibited root and shoot growth. Corn residue typically has a C:N of 70:1 (Mannering, J.V., 1981) which decomposes slowly and in CC residue can often accumulate in the soil

(Broder and Wagner, 1988). Additionally, after corn harvest an abundance of residue remains in the field; this residue may have smothered the rye and further suppressed rye growth. Without an established root system, rye may have had limited establishment in this restrictive environment. Under CC, rye biomass increased as N rate decreased. This likely occurred because corn plants were smaller and less developed in the low N plots, corn plant biomass increased with N rate ($P<0.001$). Corn plots with low N rates may have had more light penetration and less buildup of restrictive residue that potentially supported better rye development compared to plots with greater N rates.

In SbC (where rye was seeded into corn in the fall) rye biomass in the spring was substantially less than when seeded into soybean for the CSb rotation but was greater than in CC (Table 1.2). Unlike in CC where rye seeds fell on top of corn residue from previous seasons and then were covered by corn residue after harvest, rye seeds in SbC likely had the advantage of better soil contact to enhance germination, but ultimately were adversely affected by corn residue cover after corn harvest. Unlike CC, rye biomass in the spring for SbC was not affected by residual N rate from the previous corn crop. This is likely because corn in CSb had a larger canopy and more biomass at low N rates compared to CC, thus eliminating the advantage of more light penetration observed under low N rates in CC. Greater biomass and leaf development in CSb relative to CC has been reported by others (Rubin et al., 2016; Kazula and Lauer, 2018)(Kazula and Lauer, 2018).

1.4.3. Soil N Response to Cover

Our primary interest in soil analysis was to observe the effect of Rye–Cover on soil N availability. There were only four instances where the cover variable, or its interactions with other variables, was significant in the soil data analysis (Appendix 1–4). For the first instance, under CC in 2016, Rye–Cover showed 24% (81 kg N ha^{-1}) greater soil NO_3–N than No–Cover (65 kg N ha^{-1}) (Appendix 1). For the second, under CSb in 2016 there was a significant Cover by N Rate interaction where N rate from 0 to 200 kg N ha^{-1} resulted in an increase from 37 to 58 kg NH_4–N ha^{-1} in Rye–Cover and only an increase from 35 to 44 kg NH_4–N ha^{-1} in No–Cover (Appendix 3). These two significant variables may indicate that for the overall growing season, rye might have immobilized N early in the season, when the potential for loss was greater, and mineralized N during the later portion of the growing season. In the third instance, under CC in 2016 there was a significant Cover by N Rate by Time of sampling interaction where the early season soil sample at V8 showed No–Cover had 64% (34 kg N ha^{-1}) greater NH_4–N levels than Rye–Cover at the highest N rate (300 kg N ha^{-1}) (Appendix 1). This likely indicates immobilization by rye. This was observed at the highest rates only likely because N application was greater than what was needed by corn at that stage. In contrast to V8, there was more NH_4–N in Rye–Cover at the two highest N rates at R1 with the 250 and 300 kg N ha^{-1} rates measuring 2.1 times (42 kg N ha^{-1}) and 1.3 times (17 kg N ha^{-1}) greater NH_4–N than No–Cover, respectively. This indicates that N that was previously immobilized by rye at V8, later mineralized and provided needed N for the corn crop. Finally, for the fourth, under CSb in 2017 the Cover by N rate interaction for NH_4–N in the top 30–cm of soil showed that No–Cover had 2–7 kg N ha^{-1} more than Rye–Cover with rates 200 kg N ha^{-1} or lower and Rye–Cover had 2–4 kg N ha^{-1} more than No–Cover with rates 250 kg N ha^{-1} or greater (Appendix 4). Overall, changes in soil N due to Rye–

Cover were inconsistent and in general small in magnitude, making it difficult to make a direct connection to the response reported for other parameters.

Typically, Rye–Cover had greater mean soil N than No–Cover for all three crop rotations (CC, CSb, and SbC) but differences were small and generally lack practical importance (Table 1.3). Beside the effect of Rye–Cover, with a few exceptions, soil N increased with N rate, decreased with depth, and in-season soil N tests were greater then at post-harvest (Appendix 1–4). Soil profile post-harvest N tests at 0.6 m averaged <50 kg N ha^{-1} for NO_3–N and <30 kg N ha^{-1} for NH_4–N (Table 1.3). This indicates that most N is likely taken up by the crop, leached below the root zone, or immobilized into organic forms, and implies that end of season N uptake by cover crops may not be as important since total inorganic N (NH_4–N. and NO_3–N) in the soil profile is <10 mg kg^{-1}. However, successful fall rye establishment is needed to ensure vigorous cover and N uptake in the spring when N (mostly generated by mineralization) is most susceptible to loss.

1.4.4. Yield Response to N and Cover

Rye–Cover had no impact on corn yield in CC or CSb (Table 1.4). The timing of Rye–Cover termination during this study (13 and 16 days before planting) likely helped eliminate the negative effects of allopathy and N stress often associated with Rye–Cover (Raimbult et al., 1991; Tollenaar et al., 1993; Duiker and Curran, 2005). Duiker and Curran, (2005) noted that the negative effects of rye were usually mitigated when planting was delayed by two weeks after rye termination.

Corn yield had a positive response to N rate and there was no significant interaction of cover crop and N rate (Table 1.4). Further analysis showed a quadratic plateau response to N across years in both CC and CSb crop rotations (Table 1.5). There were small (≤0.3 Mg ha^{-1}) differences in yield at the EONR between Rye–Cover and No–Cover but EONR response differed substantially between years. In 2016 under CSb, the EONR for Rye–Cover was 58 kg N ha^{-1} lower than for No–Cover and differences in grain yield were minimal (0.3 Mg ha^{-1} less with Rye–Cover) (Table 1.4). Similar results were found in Andraski and Bundy (2005) where Rye–Cover reduced EONR by 30 kg N ha^{-1}. In contrast to 2016, the EONR for the 2017 CSb Rye–Cover was 53 kg N ha^{-1} greater than for No–Cover with no difference in yield. These contrasting differences in EONR may be due to several factors including differences in rye biomass, temperature, and precipitation between years.

A related study (Struffert et al., 2016), observed that early season precipitation in May and June drives NO_3–N leaching. In this study, 2016 had lower potential for leaching relative to 2017 since precipitation during May and June was 54–mm below the normal in 2016 and 50–mm above normal in 2017. Mineralized N can quickly nitrify and be subject to loss when there is excess precipitation and the corn crop is not yet accumulating large amounts of N. As described, rye seeded into SbC produced 1.6 times more biomass and accumulated 2 times more N in 2016 than 2017 (Table 1.2), effectively removing more N from the soil that otherwise could be subject to loss. In addition, in 2016 the residue was fully incorporated into the soil by tillage, relative to 2017 where strip-till only incorporated a small portion of the residue. Full incorporation of Rye–Cover and warmer temperatures in spring 2016 likely promoted rapid immobilization of soil N, which would also prevent N from leaching. One potential drawback of rye induced immobilization is if N mineralization is delayed in relation to the time when corn has large N demands (Abendroth, LJ et al., 2011). Rye–Cover had a low C:N ratio (15:1) likely resulting in a short immobilization period followed by accelerated decomposition and mineralization allowing N to become available in a timely manner for the corn crop. These results illustrate that rye can be an effective tool to manage N by protecting N from leaching losses early in the spring through N uptake and immobilization and later supplying N through mineralization when corn needs it. However, as contrasted by the 2017 results, alignment of the different variables that impact N availability may hinder a consistent response.

In contrast to CSb, the CC rotation had minimal differences in EONR between Rye–Cover and No–Cover (Table 1.5). The differences in yield between years are likely not driven by Rye–Cover but are likely a reflection of increased N loss potential due to greater precipitation in 2017 than 2016. Relative to No–Cover, the Rye–Cover EONR required an additional 14 kg N ha^{-1} in 2016 and 20 kg N ha^{-1} in 2017. With merely 6 kg N ha^{-1} difference in EONR requirements between years, Rye–Cover in CC consistently required additional N. These data, and similar results from other studies (Raimbault et al., 1990; Thelen and Leep, 2002), support the need for strategic cover crop use depending on cropping rotation. Corn residue appears to drive N availability more than Rye–Cover making a Rye–Cover less effective at N management following corn. Integrating Rye–Cover into CSb for N management showed more promise than CC, but the decision to implement Rye–Cover in CSb is still uncertain based on the inconsistent EONR results.

Additionally, the magnitude of NO_3–N leaching reduction and other potential benefits of having the cover need to be taken into consideration.

Soybean yield averaged 4.47 Mg ha^{-1} in 2016 and 3.84 Mg ha^{-1} in 2017. In 2016, Rye–Cover reduced yield by 0.12 Mg ha^{-1} relative to No–Cover but no difference was present in 2017 (Table 1.4). While unclear, the yield reduction due to Rye–Cover was potentially from reduced soil moisture as seen in (Liebl et al., 2017) and (Westgate and Singer, 2005). Cumulative precipitation for May and June 2016 was 54–mm below average and rye may have contributed to soil moisture depletion. While some irrigation was applied in spring, since the application was uniform across the entire study area, it may not have been enough to sufficiently recharge the soil profile of treatments with Rye–Cover. Differences were likely not seen in 2017 because there was above normal spring precipitation. There was no yield response to residual N rate from the previous corn crop, the same results were found in a related study (Rubin et al., 2016). From a strategic management standpoint SbC does not seem to be an ideal rotation for Rye–Cover integration. As with CC, the residue from the previous corn crop appears to have overshadowed any uptake impact from rye. Additionally, soybean’s symbiotic relationship with rhizobia likely helps to counter N immobilization from residue, but soybean may be more susceptible to yield loss from early season soil water depletion caused by rye.

1.4.5. Crop N Use Efficiency

Across all years and rotations, Rye–Cover did not impact FRE or grain N concentration (Table 1.6 and 1.7). In 2017 under CSb, total N uptake averaged 13 kg N ha^{-1} more in treatments with Rye–Cover and AE was improved under No–Cover (8 kg kg^{-1} N). However; corn yield was not different between rotations (Table 1.4) and all AE values exceeded, or were within, the typical acceptable range of 15–30 kg kg^{-1} N as described by Fixen et al. (2012). So, while cover was significant in a few instances, the differences were generally small and likely not meaningful in terms of production.

Nitrogen rate stimulated differences in grain N, total N uptake, and AE in both rotations and years. Additionally, FRE in CSb always responded to N rate, but FRE did not respond to N rate in CC, likely because the low check values inflated the efficiency values. Grain N and total N uptake increased with N rate, while AE and FRE, when significant, decreased with N rate. It is typical for FRE and AE to decrease with N rate since the increase of yield per unit of N decreases as N rate approaches an optimal or maximum response (Wortmann et al., 2011). However, the four-split N application timing used in this study appear to have improved efficiency values compared to a related study. In Rubin et al., (2016) granular urea (46–0–0) was split applied at preplant and V4 for total N rates of 180 and 225 kg N ha^{-1}. The average FRE at 180 kg N ha^{-1} was 56% in CC and 52% in CSb and at 225 kg N ha^{-1} FRE was 59% in CC and 40% in CSb. In our study the average FRE for CC at 200 kg N ha^{-1} was 69.5% in CC and 68% in CSb. There were other differences between the studies besides N application timing but the overall increase in FRE with the four-split timing is encouraging for improving N use efficiency on coarse-textured soils.

Due to the low water holding capacity of coarse-textured soil, most of the N loss occurs through leaching and is exacerbated by high precipitation when water and N uptake from plants is limited. The loss of N not only reduces fertilizer efficiency, but can directly contaminate groundwater supplies (Pollution Control Agency, 2013). Splitting fertilizer applications to correspond with corn N uptake needs may help improve fertilizer efficiency while limiting the total amount of fertilizer susceptible to leaching at one time. Additionally, delaying the initial application until after germination may help to avoid loss to spring precipitation (Nigon, 2018). One concern with delaying and splitting N fertilizer is the risk of depriving corn of N early in the season.

Canopy sensing was used to determine crop N stress at V8, or at the point after half of the intended fertilizer amount had been applied to the plots. Adjusted NDRE values below a threshold 0.95 (Blackmer and Schepers, 1995) indicated that a yield reduction was likely to occur while values above 0.95 predicted that there was adequate N (Table 1.8). Canopy sensing readings predicted that in 2017, Rye–Cover was going to negatively impact yield in CSb. At the time of canopy sensing, only half of the fertilizer had been applied, since 2017 was a wetter than normal year, it is likely that some of the earlier applied N had leached or was otherwise unavailable. However, seeing that there was no difference in yield, it is likely that the remaining N applications remedied this deficiency. It is likely that by splitting fertilizer applications less fertilizer was potentially lost early in the season but that the applications after V8 were timely enough to meet crop needs. Cover did not otherwise impact NDRE readings in 2016 or in CC in 2017. Rate was always significant and predicted that yield increased with N rate. The 200 and 250 kg N ha^{-1} fertilizer rates were included in this study because they represent typical EONR for CSb and CC, respectively, for irrigated sandy soils in Minnesota (Lamb et al., 2015). As a general observation the adjusted NDRE values (+/- 0.03) indicated that in CSb, the N rates at or above the typical EONR of 200 kg N ha^{-1} predicted that there was sufficient N and that in CC N rates at or above 250 kg N ha^{-1} also has sufficient N. In contrast, N rates below the typical EONR values for each rotation typically fell below the 0.95 threshold and predicted yield reductions. This observation helps to validate the recommended EONR's suggested in Lamb et al. (2015). Proper N rate is a main component to increasing fertilizer efficiency, but these data indicate that the timing of N applications can be equally impactful in increasing efficiency and reducing N loss on coarse-textured soils.

1.5. CONCLUSIONS

While cover crops can be important for nutrient management in row crop production, not all cropping systems may benefit in the same manner. This study found that rye seeded into standing soybean before a corn crop was the best situation to allow rye to accumulate biomass and N and therefore best serve as a management tool. Rye seeded into standing corn had poorer rye stands and minimal N uptake. Additionally, corn residue likely overshadowed any benefits associated with rye in terms of N immobilization because of the large C supply from corn stover relative to the smaller dry biomass accumulation of rye. In CC, while Rye–Cover did not reduce corn yield, the increase in EONR by 14 and 20 kg N ha^{-1} indicates that unless there are other benefits associated with the cover crop (such as improved soil conditions, nutrient and soil loss reduction, etc.) that compensate for the increase N requirement (and added management complexity of having a cover crop), rye cover crop may hold limited utility in CC. Additionally, seeding rye into soybean shows promise as an N management tool but the impact on crop production is variable and needs further investigation. Compared to No–Cover, Rye–Cover had no influence on corn yield but EONR values varied by approximately +/- 50 ka N ha^{-1} depending on the year. The amount of rye biomass and the capacity for immobilization and mineralization seems to impact EONR, but other factors such as precipitation are also very important but ultimately difficult to separate from treatment effects in our study. Additional management practices such as N fertilizer timing and rate may increase system efficiency, but further research is needed to refine specific recommendations.

Table 1. 1. Monthly cumulative precipitation and irrigation and mean monthly temperature for 2015–2017 and 30-year normal precipitation and temperature (1987-2017).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
						Precipitation (mm)							Sum
30-yr mean†	15	13	33	57	81	100	98	95	70	61	26	16	666
2015‡	5	7	8	39	166	104	147	133	35	51	29	10	732
2016†‡	10	8	37	35	53	74	179	126	70	68	35	27	722
2017‡	8	8	3	76	78	153	53	176	91	89	8	2	745
						Irrigation (mm)							Sum
2015							47	49	17				113
2016					11	22	33	33					100
2017						23	31	25	34				114
						Temperature (°C)							Mean
30-yr mean†	-11.2	-9.0	-1.7	6.6	13.8	19.2	21.6	20.4	15.7	8.1	-0.7	-8.4	6.2
2015‡	-9.2	-13.7	-0.5	7.8	12.9	19.1	20.9	19.0	17.8	8.9	2.7	-4.4	6.8
2016‡	-10.0	-5.5	3.4	6.5	14.2	19.4	20.7	20.1	15.6	8.8	4.7	-8.9	7.4
2017‡	-9.2	-3.5	-1.3	7.6	13.0	19.1	21.1	17.6	16.1	8.0	-1.6	-9.9	6.4

†Data collected from National Oceanic and Atmospheric Administration (NOAA).
‡Data from onsite weather station.

Table 1. 2. Spring above-ground Rye-Cover biomass in dry matter basis and N uptake.

Year	Rotation	Biomass kg ha^{-1}	N Uptake kg N ha^{-1}
2016	CSb†	2885a§	70a
	CC	438b	12b
	SbC‡	581b	17b
2017	CSb	1523a	43a
	CC	367b	9b
	SbC	591b	16b

† Rye biomass in CSb was fall seeded into standing soybean.
‡Rye biomass in SbC was fall seeded into standing corn.
§ Significantly different at P = 0.05.

Table 1. 3. Annual post-harvest NO_3–N and NH_4–N values from 0.6-m soil depth profile.

N rate kg N ha^{-1}	CSb–Rye†	CSb–No	CC–Rye	CC–No	SbC–Rye	SbC–No
	kg NO_3–N ha^{-1}					
0	17	18	13	15	31	21
100	26	23	15	17	-	-
200	38	32	22	24	32	34
250	70	54	66	59	-	-
300	90	97	62	41	-	-
Mean	48	45	36	31	32	28
	kg NH_4–N ha^{-1}					
0	32	36	16	17	20	16
100	23	24	15	18	-	-
200	33	33	18	23	31	26
250	26	24	28	23	-	-
300	29	30	36	25	-	-
Mean	29	29	23	21	26	21

†Denotes rotation (CSb: corn-soybean, CC: continuous-corn, and SbC: soybean-corn) and cover.

Table 1. 4. Corn yield as impacted by cover and N rate and soybean yield as impacted by cover and N rate from the previous corn crop.

		2016		2017			ANOVA	
Rotation†	N Rate	Rye–Cover	No–Cover	Rye–Cover	No–Cover		2016	2017
	kg N ha^{-1}	Mg ha^{-1}					P>F‡	
CSb	0	9.8	10.3	6.5	5.4	Cover (C)	0.6345	0.2533
	100	14.8	14.4	11	11.9	Rate (R)	<.0001	<.0001
	200	15.8	15.8	12.8	12.6	C x R	0.7131	0.1883
	250	16.1	16.9	12	12			
	300	16.5	16.3	12.9	12.9			
CC	0	5.9	6	3.5	4	Cover (C)	0.8991	0.8403
	100	11.5	11.9	7.1	8.1	Rate (R)	<.0001	<.0001
	200	15.9	15.7	10.8	10.3	C x R	0.9849	0.3306
	250	15.7	15.8	11.2	10.9			
	300	16.3	16.2	9.8	11.5			
SbC	0	4.35	4.54	3.74	3.99	Cover (C)	0.0106	0.6519
	100	4.33	4.55	3.88	3.87	Rate (R)	0.2417	0.8229
	200	4.34	4.45	3.75	3.87	R x C	0.4743	0.3758
	250	4.49	4.56	3.84	3.72			
	300	4.53	4.54	3.92	3.48			

† Rotations: CSb (corn-soybean), CC (continuous-corn), SbC (soybean-corn).

‡Significantly different at P = 0.05.

Table 1. 5. Yearly quadratic-plateau regression models for grain yield (y) in relation to N rate (x) as well as the economic optimum nitrogen rate (EONR) and yield at EONR across rotations and cover systems. N cost to corn price ratio=0.0056.

Year	Rotation†–Cover	Regression Model	P>F	EONR	Yield at EONR
				kg N ha^{-1}	Mg ha^{-1}
2016	CSb – Rye	$y = 9.764 + 0.076x - 0.00023x^2$	<0.0001	171	16.1
2016	CSb – No	$y = 10.32 + 0.053x - 0.00011x^2$	<0.0001	229	16.4
2017	CSb – Rye	$y = 6.459 + 0.067x - 0.00018x^2$	<0.0001	185	12.5
2017	CSb – No	$y = 5.429 + 0.113x - 0.00045x^2$	<0.0001	132	12.5
2016	CC – Rye	$y = 5.791 + 0.081x - 0.00016x^2$	<0.0001	266	16.2
2016	CC – No	$y = 5.947 + 0.083x - 0.00017x^2$	<0.0001	252	16.0
2017	CC – Rye	$y = 3.318 + 0.052x - 0.00013x^2$	<0.0001	299	11.1
2017	CC – No	$y = 4.025 + 0.052x - 0.00009x^2$	<0.0001	279	11.3

† Rotations: CSb (corn-soybean and CC (continuous-corn).

Table 1. 6. 2016 growing season mean values for grain N concentration, total N uptake, fertilizer recovery efficiency (FRE), and agronomic efficiency (AE) as affected by rotation, cover, and N rate.

Rotation† – Cover	Rate	Grain N	Total N Uptake	FRE	AE
	kg N ha^{-1}	g kg^{-1}	kg ha^{-1}	%	kg kg^{-1}
CC – Rye	0	0.94	84	.	.
	100	1.00	155	71	56
	200	1.18	226	71	50
	250	1.22	255	69	39
	300	1.21	252	56	35
CC – No	0	0.90	88	.	.
	100	0.95	157	69	59
	200	1.27	238	75	49
	250	1.25	261	69	39
	300	1.25	279	64	34
			P>F‡		
Cover		0.7403	0.2162	0.6805	0.9795
Rate		<.0001	<.0001	0.4580	0.0006
Cover x Rate		0.6192	0.8499	0.9445	0.9719
CSb – Rye	0	0.97	141	.	.
	100	1.12	197	56	50
	200	1.20	256	58	30
	250	1.26	285	58	25
	300	1.32	273	44	22
CSb – No	0	0.98	143	.	.
	100	1.17	224	81	41
	200	1.19	249	53	28
	250	1.28	288	58	27
	300	1.28	291	49	20
			P>F†		
Cover		0.8148	0.2570	0.1978	0.1346
Rate		<.0001	<.0001	0.0351	<.0001
Cover x Rate		0.7721	0.5996	0.1883	0.3545

† Rotations: CC (continuous-corn) and CSb (corn-soybean).

‡Significantly different at P = 0.05.

Table 1. 7. 2017 growing season mean values for grain N concentration, total N uptake, fertilizer recovery efficiency (FRE), and agronomic efficiency (AE) as affected by rotation, cover, and N rate.

Rotation† – Cover	Rate	Grain N	Total N Uptake	FRE	AE
	kg N ha^{-1}	g kg^{-1}	kg ha^{-1}	%	kg kg^{-1}
CC – Rye	0	0.90	51	.	.
	100	1.05	128	78	35
	200	1.16	180	65	36
	250	1.27	221	64	31
	300	1.24	219	56	21
CC – No	0	0.88	56	.	.
	100	0.94	124	69	41
	200	1.15	189	67	32
	250	1.27	222	66	28
	300	1.20	221	55	25
			P>F‡		
Cover		0.1712	0.4760	0.8346	0.7938
Rate		<.0001	<.0001	0.3351	0.0002
Cover x Rate		0.6930	0.9518	0.9203	0.2383
CSb – Rye	0	0.86	86	.	.
	100	1.06	172	86	45
	200	1.21	234	74	32
	250	1.27	231	58	22
	300	1.23	246	54	21
CSb – No	0	0.84	69	.	.
	100	0.97	155	86	65
	200	1.20	211	71	36
	250	1.24	224	62	26
	300	1.17	245	59	25
			P>F		
Cover		0.0847	0.0388	0.8217	0.0035
Rate		<.0001	<.0001	0.0092	<.0001
Cover x Rate		0.7980	0.7843	0.9592	0.0680

† Rotations: CC (continuous-corn) and CSb (corn-soybean).

‡Significantly different at P = 0.05.

Table 1. 8. Normalized Difference Red Edge Index (NDRE) values compared to the highest reading for each cover system per rotation. Values ≥0.95 predicted that there was sufficient N while values ≤0.95 may indicate crop stress and potential yield loss.

		2016		2017	
Cover	kg N ha^{-1}	CC†	CSb	CC	CSb
No	0	0.68	0.92	0.75	0.80
	100	0.85	0.95	0.83	0.90
	200	0.93	0.96	0.87	0.98
	250	0.95	0.98	0.94	0.96
	300	0.95	0.95	0.93	0.97
Rye	0	0.66	0.89	0.71	0.79
	100	0.87	0.95	0.78	0.87
	200	0.92	0.96	0.89	0.92
	250	0.94	0.94	0.92	0.93
	300	0.98	0.96	0.95	0.96
			P>F‡		
	Cover	0.9202	0.2807	0.1649	0.0046
	Rate	<.0001	0.0293	<.0001	<.0001
	Cover x Rate	0.5929	0.6482	0.0999	0.412

† Rotations: CSb (corn-soybean), CC (continuous-corn), SbC (soybean-corn).

‡Significantly different at P = 0.05.

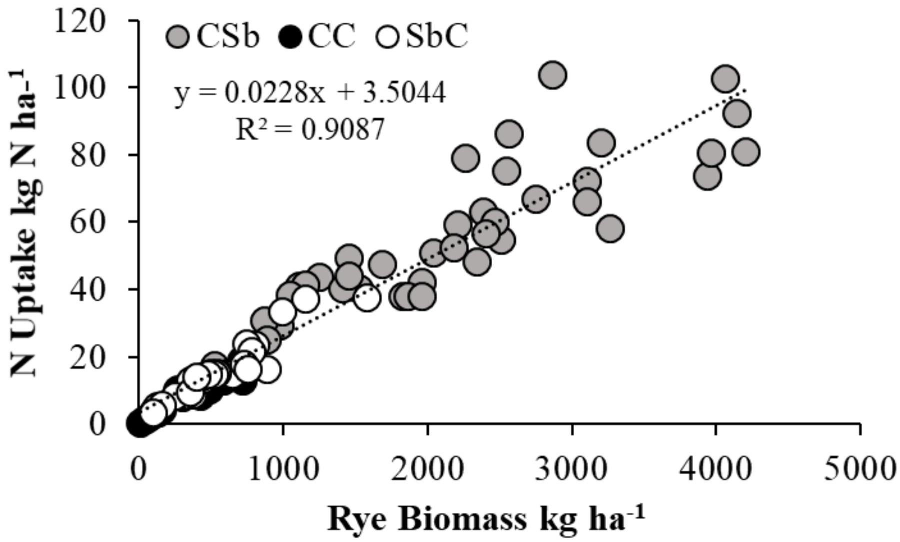

Figure 1.1. Spring above-ground rye biomass as related to total N uptake.

CHAPTER 2: Nitrate Leaching Mitigation on Irrigated Coarse-Textured Soils with Nitrogen Rate and Rate Cover

2.1. SYNOPSIS

Irrigated coarse-textured soils in corn (*Zea mays* L.) and soybean (*Glycine max* Merr. L.) production are highly susceptible to NO_3–N leaching and groundwater contamination. The objectives of this study were to evaluate the concentration and load of NO_3–N leaching in continuous–corn (CC), corn–soybean (CSb), and soybean–corn (SbC) in response to a winter rye (*Secale cereal* L.) cover crop and N rate on irrigated coarse-textured soils. Rye was seeded into standing corn and soybean, terminated two weeks before crop planting, and 0–N, Optimal–N, and High–N rates were applied to corn in four equal split applications between the V2 and V12 development stages. From three drainage calculation methods the water balance equation with evapotranspiration (ET) values adjusted with a Standardized Reference Evapotranspiration Equation (SREE) was chosen because it was most sensitive to rotation and treatment variables. The 0–N treatments had 13 and 21% more drainage than Optimal–N and High–N rates, respectively, illustrating that crops were smaller and used less water than those with sufficient N availability. Rye had no impact on corn yield and substantially reduced NO_3–N leaching in CSb. On average NO_3–N concentration (mg NO_3–N L^{-1}) was reduced by 48% and NO_3–N load (kg NO_3–N ha^{-1}) was reduced by 50%. Load nor concentration was reduced by rye in CC or SbC, likely attributed to corn residue from the previous crop inhibiting rye growth. Also corn residue likely reduced N load through N immobilization in CC and SbC as the mean load for No–Cover plots was 1.7 times less than for No–

Cover plots in CSb where soybean was the previous crop residue. Load was not affected by N rate in CSb but in CC and SbC in 2017, where more drainage occurred, load increased with increasing N rate. These inconsistencies, along with the fact that season-long loads ranged from 38 to 135kg NO_3–N ha^{-1} when 0–N was applied, suggest that adjusting N rate alone may not suffice as a management tool to reduce NO_3–N loads that meet water quality protection goals. Further, this study illustrates that Rye–Cover on irrigated coarse-textured soils has potential as a management practice to reduce NO_3–N load but crop rotation and growing-season conditions can have substantial influence on its efficacy.

2.2. INTRODUCTION

Coarse-textured soils in corn and soybean production are one of the greatest contributors of agriculturally-sourced NO_3–N in groundwater supplies (Pollution Control Agency, 2013). Theses soils have characteristically low water holding capacity, leading to the rapid infiltration of water and nutrients through the soil profile. Additionally, in standard row crop production there is little to no live plant biomass in fields from harvest until spring. This period coincides with high precipitation and when NO_3–N leaching losses can be elevated (Randall and Vetsch, 2005; Qi et al., 2011; Struffert et al., 2016). The lack of crops that could utilizing excess water and nutrients during this period likely exacerbate the potential for loss of NO_3–N into groundwater and this has costly agricultural and environmental effects.

Row crop cultivation on coarse-textured soils persists and continues to expand because high yields are produced when crops are supplemented with water and nutrients. However, a NO_3–N leaching study on a coarse-textured soil found that when averaged across N rate approximately 68.0 kg N ha^{-1} leached under a CC cropping system, which represents approximately 42% of the applied N (Struffert et al., 2016). Considering the average price of N is approximately \$0.77 kg^{-1} N^{-1} and corn is very responsive to N, the overall economic and agronomic cost of NO_3–N leaching to producers can be large and highlights the benefit of reducing leaching losses.

The social and environmental costs of NO_3–N leaching are also difficult to quantify. Research conducted in Minnesota compared the average unit of N applied to the monetary value required to reclaim N contaminated groundwater and air emissions (Keeler et al., 2016). The study found that depending on location within the state, sources of contamination, and population that the cost of lost N ranges from \$0.001/kg N to \$10/kg N. Other reports estimate that reclaiming drinking water supplies with contamination levels >10 mg NO_3–N L^{-1} typically costs \$0.16 kg^{-1} N (Compton et al., 2011). There are firm standards for NO_3–N levels in water for human consumption (Avery, 1999; EPA, 2018), but acceptable NO_3–N levels for soil water in the root zone and water that leaches below the root zone are generally undefined, which lead to unclear expectations of what might be tolerable from an environmental perspective.

One of the primary methods employed to reduce NO_3–N leaching is to adjust N management that involves rate, timing, and source. The University of Minnesota guidelines for fertilizing corn in irrigated sandy soils suggests applying 215–250 kg N ha-

^{1} with a split application to obtain optimal yield in CC (Lamb et al., 2015). On irrigated sandy soils in Kansas, splitting N fertilizer not only increased yield but reduced the amount of total fertilizer generally required to meet yield goals (Gehl et al., 2005). Dinnes et al. (2002), determined that multifaceted management strategies of two or more practices, like timing and rate, best reduced NO_3–N leaching while maintaining yields. Under high rainfall regimes in Thailand, splitting N applications into three to four applications improved yield and N use efficiencies (Sitthaphanit et al., 2009). This scenario may adequately extrapolate to equally permeable soils receiving frequent irrigation or precipitation. However, not all fertilizer management strategies have been reported to significantly reduce leaching. Struffert et al. (2016) found that enhanced efficiency fertilizer such as polymer-coated urea (ESN), performed equally well at reducing leaching as split applied urea, and noted that reducing N rate did not significantly decrease leaching but negatively impact yield. However, some models have indicated that intensely managed irrigated sands can adequately reduce leaching with limited loss in profits; specifically, when adjusting N application timing and rates (Johnson et al., 1991).

Secondary NO_3–N reduction strategies integrate cover crops to utilize residual N, immobilize vulnerable nutrients, and water use (Dabney et al., 2001). Grasses, and brassicas have been found to be most effective at reducing NO_3–N losses while legumes have limited utility because they fix atmospheric N and have rapid mineralization rates (McCracken et al., 1994). Limitations to incorporating cover crops into traditional row crop agriculture include increased management and potential yield reduction (Raimbault et al., 1990; Snapp et al., 2005). Studies have shown that cover crops have promising potential to reduce NO_3–N leaching (Logsdon et al., 2002) but obtaining sufficient crop establishment needed to realize that potential, is inconsistent (Kaspar, T.C.; Jaynes, D.B.; Parkin, T.B.; Moorman, T.B.; Singer et al., 2012; Pantoja et al., 2015).

One of the greatest challenges of assigning the value to various management practices to reducing NO_3–N leaching losses is to correctly quantify the magnitude of reduction caused by those management strategies. Porous suction-tube lysimeters installed in sandy soil have been found to provide accurate and reliable NO_3–N measurements (Lord and Shepherd, 1993) but factors such as depth of installation (to be below the root zone), frequency of sampling, and amount of applied suction are important considerations (Lord and Shepherd, 1993; McCracken et al., 1994; Geibe et al., 2006). Lysimeters have been successfully used to quantify changes in NO_3–N leaching due to presence of cover crop or N rate (Logsdon et al., 2002).

The potential for NO_3–N leaching reduction with the use of rye cover crops in conjunction with N rate management has been extensively investigated on fine-textured soils (Krueger et al., 2012; Kaspar et al., 2011; McCracken et al., 1994). However, similar research in coarse-textured soils, where NO_3–N leaching can be most impactful to groundwater quality, is lacking. Therefore, the objectives of this study were to evaluate the concentration and load of NO_3–N leaching in CC, CSb, and SbC in response to a winter rye cover crop and N rate on irrigated, coarse-textured soils.

2.3. MATERIALS AND METHODS

2.3.1. Site Description

Data were collected in 2016 and 2017 at the Rosholt Farm in Westport, Minnesota (45°42'49.1" N, 95°10'16.2" W). The site was an Arvilla sandy loam soil (sandy, mixed, frigid Calcic Hapludolls) with a sandy/gravelly outwash parent material. The soil horizon contained sandy loam (0 to 500-mm), sand (500 to 700-mm) and coarse-sand and gravel (700 to 1200-mm) materials. This study was part of a long-term N study established in 2011 with three adjacent rotations: continuous corn (CC) and both phases of a corn–soybean rotation, corn (CSb) and soybean (SbC) (Rubin et al., 2016). Full details of the site description can be found in Chapter 1. In 2015, all corn plots received a uniform 280 kg N ha^{-1} fertilizer application to erase previous treatment effects in preparation for this study.

2.3.2. Weather and Irrigation

Weather data were collected in 2016 and 2017 using an onsite weather station, data are summarized in Chapter 1. The weather station collected hourly precipitation, ambient temperature, wind speed, relative humidity, solar radiation, and solar flux data. Missing data due to equipment malfunctions were supplemented using National Oceanic and Atmospheric Administration (NOAA) data using the average values of three weather stations located less than 30 kilometers from the field site. The 30–year normal for the region was determined using the NOAA database.

Crop irrigation needs were determined using an irrigation checkbook (Steele et al., 2010) and applied with a linear irrigation system. Irrigation was applied 7 times for a total of 100–mm in 2016 and 114–mm in 2017. An irrigation uniformity test was run in 2016 and the coefficient of uniformity was ≥93%. Irrigation water NO_3–N concentrations were <10 mg NO_3–N L^{-1} and the amount of NO_3–N applied with irrigation water was <10 kg N ha^{-1}. These values were minimal and thus N rates were not adjusted for irrigation water NO_3–N following University guidelines (Lamb et al., 2015).

2.3.3. Treatments

The study was a randomized complete block design with four replications in each of the three cropping rotations: CC, CSb, and SbC. Treatments were applied to plots measuring 4.56 m wide (six crop rows 76–cm apart) by 12.2-m long and remained in the same plot for the duration of the study. Treatments included Rye–Cover or No–Cover and N fertilizer rates representing 0–N, Optimal–N, and High–N rates. These values were 0, 250, and 300 kg N ha^{-1} in CC and 0, 200, and 300 kg N ha^{-1} in CSb, respectively. Optimal N values were based on University of Minnesota guidelines (Lamb et al., 2015) and optimal N rates from the Rubin et al. (2016) study conducted on the same site. All rotations were treated with Rye–Cover and No–Cover comparisons but only CC and CSb received N treatments; no N was applied to SbC. The N rates were divided in four equal split applications at corn development stages V2 (19 May 2016 and 15 June 2017), V6 (16 June 2016 and 7 July 2017), V8 (26 June 2016 and 12 July 2017), and V12 (14 July 2016 and 26 July 2017). Nitrogen was applied as urea (46–0–0) (N–P–K) treated with the urease inhibitor Agrotain (Koch Fertilizer LLC) [N–(n–butyl) thiophosphoric triamide (NBPT)] and incorporated with irrigation within three days to avoid N volatilization loss.

2.3.4. Rye Establishment

Rye was broadcast by hand to mimic aerial seeding into standing corn and soybean and depending on precipitation, irrigation was applied to incorporate seeds and after germination. In 2015, rye was seeded into all rotations on 16 June at 84 kg ha^{-1}; however, by fall rye stand was sparse and rye was re-seeded into soybean at 50–75% leaf-drop. Late corn maturity in fall 2015 prevented re-seeding rye in CC and CSb before soils froze. For the remainder of the study rye was seeded at 126 kg ha^{-1} into corn at development stage R6 on 1 Sept. 2016 and 12 Oct. 2017 and into soybean at 50–75% leaf-drop on 1 Sept. 2016 and 29 Sept. 2017. The rye overwintered and after spring growth, it was terminated with 1.2 kg a.i. ha^{-1} glyphosate, N– (phosphonomethly) glycine with 4.7 L ha^{-1} non–ionic surfactant (NIS) at 2.5% v/v on 21 Apr. 2016 (12 days before row crop planting) and on 9 May 2017 (16 days before row crop planting). Chemical termination was followed by tillage. In 2016, the field was disked, and field cultivated and in 2017 it was strip-tilled to accommodate a long-term study also present at the site. Rye treatments remained in the same plots across years.

Above-ground rye biomass was sampled from a 0.25 m^2 area in every plot each spring when rye was tillering (Zadoks et al., 1974), dried in a forced-air oven at 60°C, ground through a 2–mm sieve, and analyzed for total N by combustion analysis using a Carlo Erba 1500 elemental analyzer (Horneck and Miller, 1998).

2.3.5. Crop Management

Corn hybrids and soybean varieties were planted 3 May 2016 (Croplan 3611SS/RIB and Northrup King Syngenta S12–H2) and 25 May 2017 (DKC46–20RIB and Genuity S12–H2).

Corn was harvested 6 Oct. 2016 and 26 Oct. 2017 and soybean was harvested 7 Oct. 2016 and 17 Oct. 2017. Other than N, standard agronomic practices were used to maximize yield.

2.3.6. Drainage

In 2011, six passive capillary lysimeters (Decagon Devices, Inc., Pullman, WA), were permanently installed at 1.2-m below the soil surface. Drainage measurements were collected weekly from April until frost, usually October or November. The passive capillary lysimeters provided weekly average drainage measurement across the site. Drainage was also calculated using a modified water balance model to better capture variations between cropping rotations and treatments (equation 1) (Steele et al., 2010):

Eq. 1.

$$\text{If } \mathrm{TSW_{t-1} + P_t + I_t - ET_t > TSW_{FMC}}, \text{ then}$$

$$\mathrm{D_t = TSW_{t-1} + P_t + I_t - ET_t - TSW_{FMC}}$$

where $TSW_{(t\text{-}1)}$ is the total stored water in the 0.8-m soil profile at the end of the previous day (t-1 where "t" is days), P_t is the present-day water inputs from precipitation, I_t is the present-day water inputs from irrigation, Et_t is the present-day water loss from evapotranspiration, TSW_{FMC} is the total stored water in the 0.8-m profile at field moisture capacity (FMC, 33 kPa), and D_t is the present-day water loss through drainage. Each year the initial soil profile was at 82mm, the TSW_{FMC} for an Arvilla sandy loam (Steele et al., 2010).

Two methods were used to calculate ET for equation 1. One method utilized an irrigation checkbook (Checkbook) for Minnesota which used inputs of temperature, precipitation, crop parameters, and soil properties to calculate ET (Steele et al., 2010). The other method (Penman) utilized the Standardized Reference Evapotranspiration Equation (equation 2) to calculate a reference ET (ET_{ref}) using alfalfa as a reference crop (Walter et al., 2000):

Eq. 2.

$$ET_{ref} = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T + 273} u_2 (e_s^o - e_a)}{\Delta + \gamma(1 + C_d u_2)}$$

where Δ is slope of the saturated vapor pressure curve (kPa $°C^{-1}$), R_n is net radiation (MJ m^{-2} d^{-1}), G is solar heat flux (MJ m^{-2} d^{-1}), γ is psychrometric constant (kPa $°C^{-1}$), C_n = 1600 for tall reference crop (mm d^{-1}), T is mean daily temperature (°C), u_2 is mean wind speed (m s^{-1}), e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa), C_d = 0.34 for tall reference crop (mm d^{-1}). In order to calculate actual ET, Et_{ref} was multiplied by a crop coefficient (K_c).

The ET values from the Checkbook and Penman methods were factored into equation 1 to calculate drainage. The Checkbook method calculated individual drainage values for corn and soybean rotations and the Penman method calculated drainage for N-limited and non-N-limited treatments in corn and overall drainage in soybean. The two calculated methods were compared along with the measured drainage from the passive capillary lysimeters.

2.3.7. Crop Coefficients

For this study, K_c values from Appendix E of ASCE–EWRI (Walter et al., 2000) were used and were adjusted according to in-season biomass measurements. Mean ET K_c for field corn and beans were used, where corn effective cover was at tasseling and soybean effective cover was flowering. The K_c values in ASCE–EWRI Appendix E are those for crops under ideal management. In order to adjust for treatments that were stressed due to insufficient N, 0–N treatments, equation 3 (FAO Paper No. 33, equation 103) was used to adjust K_c:

Eq. 3.

$$K_s = 1 - \frac{1}{K_y}(1 - \frac{Y_a}{Y_m})$$

where K_s is adjusted value for K_c due to crop stress, K_y is a yield response factor from "Table 24" of Paper No. 33 (maize = 1.25) and (soybean = 0.85), Y_a is the actual yield of the stressed treatment, and Y_m is the maximum expected yield. The average crop yield for CC and CSb treatments at 0 and 100 kg N ha^{-1} (N-limited) were averaged to calculate Y_a and the average crop yield for 200 and 300 kg N ha^{-1} in CSb and 250 and 300 kg N ha^{-1} in CC (non-N-limited) were used to calculate Y_m. The K_s for N stressed crops was determined to be 0.7, or an average 30% yield decrease.

Values for Rye–Cover were determined using the mean ET K_c values for winter wheat. Where 0% time was the beginning of spring growth and K_c=0.25 and 100%-time represented rye termination and K_c=0.6. The expected mean K_c values for perennial rye grass in Appendix E were greater than the actual rye biomass present in the study. Kc values for winter wheat were more representative and were used to represent rye growth. A K_c of 0.2 was used for bare soil which was present before crop emergence with No–Cover, after rye termination in Rye–Cover, and after harvest. An average trend of K_c values for different crops and treatments used to calculate ET can be found in Fig. 2.1.

2.3.8. Nitrate–N Concentration

Suction-tube lysimeters were installed in 2011 in three of the four replications into each cropping rotation. Each plot contained three lysimeters and the plot average from each sampling period was used to determine the concentration of NO_3–N leachate from 1.2-m below the soil surface. Further specifications and installation details for suction-tube lysimeters were given in Struffert et al. (2016). Suction-tube lysimeter sampling typically occurred from April to November, when temperatures were above freezing, and were collected every 7 to 10 days. There were 31 sampling periods in 2016 (6 Apr. – 17 Nov.) and 30 samplings periods in 2017 (6 Apr. – 30 Oct.). A pressurized vacuum system (32 centibars) was used to empty the entire lysimeter column and collect 30–50 ml of water from each lysimeter. The samples were analyzed for NO_3–N concentration using a Hach DR 6000 spectrophotometer. Known standards were analyzed every 20–24 samples to ensure equipment accuracy. From each batch, duplicate samples and standards were sent to an independent lab to maintain a 10% QA/QC. Samples were run according to a standardized procedure developed by the Minnesota Department of Agriculture.

2.3.9. Nitrate–N Load

The load of NO_3–N leaching below the root zone was calculated using equation 4:

Eq. 4

$$\mathrm{NO_3 - N\ load} = \frac{[\mathrm{NO_3 - N}] * \mathrm{drainage}]}{1000000}$$

where NO_3–N load is in kg ha^{-1}, [NO_3–N] is the concentration of NO_3–N from the suction -tube lysimeters in mg L^{-1}, and drainage is the water moving below the root zone in L ha^{-}

[1]. Nitrate–N values were multiplied by weekly drainage values to calculate weekly load. The weekly loads were summed to calculate annual NO_3–N load leached.

2.3.10. Statistical Analysis

Data were analyzed with SAS software version 9.4 (SAS institute, 2012) using MIXED and GLMMIX procedures. Nitrogen rate and cover were considered fixed effects and replication was considered a random effect. Year and rotation were run independently for all analyses. Where appropriate differences between treatment means were determined using the PDIFF function and were considered significant at $P<0.05$.

2.4. RESULTS AND DISCUSSION

2.4.1. Weather and Irrigation

Compared to the 30–year normal, cumulative precipitation and mean temperature were above normal but monthly measurements varied between years (Chapter 1). In 2016, cumulative precipitation was 56–mm greater than normal but April – June monthly precipitations were 22 to 28–mm below normal, and July and August were 81 and 31–mm above normal, respectively. In 2017, cumulative precipitation was 79–mm above normal, March and July 2017 were 30 and 45–mm below normal, and June and August were 53 and 81–mm above normal, respectively. March 2016 was 5.1 C° warmer than normal and August 2017 was 2.8 C° cooler than normal. Monthly irrigation values are summarized in Chapter 1. Climate predictions indicate that early spring and in-season storms are likely to become more intense and frequent (Seeley, 2015). If these predictions become the norm, proper and timely irrigation applications will become more difficult to manage. Spring (April – June) conditions have a substantial impact on NO_3–N leaching because plants use limited amounts of water and nutrients during this time. During this study 27% (2016) and 43% (2017) of the total water received fell during the spring period (April – June).

2.4.2. Rye Cover and N Uptake

The full details of rye biomass and N uptake results can be found in Chapter 1. In summary, regardless of rotation, Rye–Cover had an average C:N of 15:1 with a range of 14:1–16:1. Rye biomass and N uptake were greatest in CSb (the only rotation where rye was seeded into soybean) followed by SbC and CC. When averaged across years, rye in CSb accumulated 5 time more biomass and N than CC and 4 times more biomass and 3 times more N than in SbC. Compared to other studies, rye biomass was low (Kaspar, T.C.; Jaynes, D.B.; Parkin, T.B.; Moorman, T.B.; Singer et al., 2012; Pantoja et al., 2016). The soybean stand was likely a more conducive environment for rye growth in contrast to the corn rotations where corn residue potentially restricted rye development.

Rye biomass and N uptake were strongly correlated (R^2=0.91). In contrast, N uptake was poorly correlated with tissue N concentration (R^2=0.05) as well as biomass accumulation (R^2=0.19), data not shown. Rye biomass and N uptake were not responsive to residual N rate. This illustrates the importance of managing cover crops for biomass production when the end goal is N uptake. Additionally, soil N values, discussed in Chapter 1, suggested fall soil N values were low <50 kg N ha^{-1}; indicating that rye N uptake in the fall would unlikely influence N loss. The benefit of fall cover crop establishment is to ensure vigorous cover crop growth in the spring when there is greater potential for NO_3–N loss and rye N uptake and immobilization may prevent such loss.

2.4.3. Crop Yield

Full details of crop yield are described in Chapter 1. Corn yield in both rotations was not affected by cover in either year of the study and yield always positively responded to N rate. In 2016, soybean yield averaged 4.53 Mg ha^{-1} with No–Cover but was reduced by 0.12 Mg ha^{-1} in Rye–Cover treatments. In 2017, cover did not impact soybean yield (3.85 Mg ha^{-1}) and N rate was not significant either year. Development in corn treatments with no N (0 kg N ha^{-1}) was delayed and ET was likely lower in these treatments, so drainage was adjusted accordingly.

2.4.4. Evaluation of Drainage Methods

Nitrate load is greatly influenced by drainage below the root zone. Because this study implemented varying cropping systems and N rate applications ET and drainage varied among treatments. In order to ensure reflective drainage values three methods were compared to calculate drainage (Fig. 2.2): drainage lysimeters (Drain Gauge), a water balance equation with ET values from an irrigation checkbook (Checkbook), and a water balance equation with ET values derived using the Standardized Reference Evapotranspiration Equation (SREE) (Penman).

Local measurements were used to calculate the parameters of the equation to ensure optimal estimates (Batchelor, 1984; Walter et al., 2000). With the Penman method we calculated that there was only a 1% difference for in-season (April – October) drainage between Rye–Cover and No–Cover treatments, similar results were seen in (Kaspar, T.C.; Jaynes, D.B.; Parkin, T.B.; Moorman, T.B.; Singer et al., 2012). In-season drainage does not capture the water use of Rye–Cover during pre-season (Rye–Cover growth until Rye–Cover termination). During this time conditions such as frozen soils limit drainage but the cover is still using soil water and potentially increasing the soil water storage deficit. Cumulative ET values were 27–mm with No–Cover and 49–mm with Rye–Cover in 2016 (1 Mar – 21 Apr.) and 41–mm with No–Cover and 75–mm with Rye–Cover in 2017 (1 Mar – 9 May) (Fig. 2.3). Early season water utilization by a cover crop may help reduce drainage in the spring by increasing the capacity of water storage. In-season values show that there was a 21% difference in 2016 and 13% difference in 2017 between N-limited (0 kg N ha^{-1}) and non–N-limited (200, 250, and 300 kg N ha^{-1}) corn treatments with N-limited treatments having greater drainage (Table 2.1). Additionally, on average there was a 6% difference between corn and soybean drainage in 2016 and a 1% difference in 2017.

The Checkbook method accounted for cropping rotation but did not adequately adjust for drainage variations due to N rate. Depending on year, drainage between the Checkbook and Penman methods varied by 7 and 10% in corn and 2 and 3% in soybean with the Checkbook method underestimating drainage. Finally, the Drain Gauge method, which used the average drainage under corn and soybean, was not selected because in 2016 drainage was under-estimated compared to the calculated methods and did not differentiate between rotation or treatment effect. The Drain Gauge method measured approximately 50% less drainage in 2016 and 15% less drainage in 2017 compared to the Penman method. These data suggest that the passive capillary drainage lysimeters may perform better in wetter conditions and can be highly variable from year to year. Other possibilities for the differences include impurities in the fiberglass wick (Knutson et al., 1993), uncalibrated pressure head (Knutson and Selker, 1994) or and inadequate number of lysimeters for the treatment area (Brandi-Dohrn et al., 1996).

Ultimately, the Penman method was selected because it accounted for the most variation including calculations for cropping rotations (corn vs soybean) and N rate (N-limited and non-N-limited treatments), (Table 2.1). Drainage trends followed precipitation and in 2016 36% of cumulative drainage in corn occurred from April – June and in 2017 spring drainage accounted for 45%. In soybean, spring drainage accounted for 29% in 2016 and 44% in 2017.

2.4.5. Nitrate–N Concentration

Mean in-season NO_3–N concentrations were greater in 2016 than 2017 (Table 2. 2), but 2017 had 111–mm more precipitation. In general, NO_3–N concentrations gradually increased from April – July, while in August concentrations generally started to decrease towards low values at the end of the season (Fig. 4; A-1, B-1). Large precipitation events seemed to create minor fluctuations in this general pattern. Low early-season concentrations were likely caused by dilution as an effect of increased drainage in the spring. Low end of season concentrations could be attributed to minimal drainage and limited leachable nutrients. Peak concentrations were likely influenced by the presence of fertilizer applied from May – July in combination with minimal drainage due to crop water use. The dilution effect on NO_3–N concentration where NO_3–N concentrations are less during times of increased drainage have been observed by others (Mariotti et al., 2015; Struffert et al., 2016). High NO_3–N concentrations during periods of limited or no drainage indicate that there is NO_3–N in the soil solution, but because there is little or no drainage, N present in the soil solution is available for crop uptake and poses little risk to groundwater contamination. Conversely, if excess water from precipitation, over irrigation, or both were to occur during the summer when soil NO_3–N concentrations were high, there would be a large potential for N loss. The atypically dry spring in 2016 (28% of total precipitation and 36% of total drainage occurred April – May) minimized the early season drainage dilution effect across rotations and may account for the relatively consistent NO_3–N concentrations across the season. The 2017 season had a more typical spring (40% of total precipitation and 45% of drainage occurred April – May) and NO_3–N concentration were similar to those found in Struffert et al., (2016).

Residual N rate was never significant in SbC (Table 2.2) and N rate was only significant in CSb in 2016 (Fig. 2.4, A-1) where the 0–N check plot was different from all N rates and CC in 2017 (Fig. 2.4, B-2) where all rates were different from each other. In CSb (Fig. 2.4, A-1 and B-1), differences across N rates were minimal from April – July where the average concentration across N rates was 29.4 mg N L^{-1}, but concentrations differentiated from August until the end of season where the 0–N treatments averaged 11.6 mg N L^{-1} and 200 and 300 kg N ha^{-1} treatments averaged 28.1 mg N L^{-1}. These results indicate that the previous soybean crop supplies mineralizable N to the check plots that is subject to leaching early in the season. Once the pool of rapidly mineralizable N is used up by the crop or lost through leaching, the concentrations in the check plots decrease significantly. In 2017 all N rates in CC were significantly different from each other (Fig. 2.4, B-2). With concentrations averaging 7.9, 18.1 and 24.1 mg N

L^{-1} for 0, 250, and 300 kg N ha^{-1} rates, respectively. Overall, N rate had a minimal impact on NO_3–N concentrations suggesting that integrated N management strategies will likely be required to minimize losses.

When averaged across N rate, Rye–Cover significantly reduced NO_3–N concentration in CSb by 49% in 2016 and 46% in 2017 (Table 2.2). In both CC and SbC there were minimal differences in average NO_3–N concentrations between Rye–Cover and No–Cover (+/- 2 mg N L^{-1}). The differences in NO_3–N concentration between covers within rotations is likely due to cumulative rye biomass present in the spring. There was significantly more Rye–Cover in CSb in 2016 and 2017 than in CC or SbC, and both of the later rotations had similar amounts of biomass and similar soil water NO_3–N concentrations (Table 2.2). Others have seen inconsistent relationships between Rye–Cover and NO_3–N reduction (Kaspar et al., 2007; Kaspar, T.C.; Jaynes, D.B.; Parkin, T.B.; Moorman, T.B.; Singer et al., 2012) and found that reductions in NO_3–N concentrations were not always proportional to total rye biomass. Similar conclusions can be made from this study because there was 89% more Rye–Cover in 2016 than 2017 but there was only a 37% difference in NO_3–N concentration reduction between years. It is largely unknown how much rye biomass is required to sufficiently reduce NO_3–N concentrations especially on different soil types. This study indicates that there may be substantial acceptable ranges for rye biomass accumulation that enable NO_3–N concentration reduction but that there are apparent thresholds where minimal biomass provides no NO_3–N concentration benefit as seen in CC and SbC. Where corn residue is present, N immobilization likely ties up N reducing the potential for leaching, but when there is no corn residue, Rye–Cover preforms as an acceptable substitute to limit N loss.

2.4.6. Nitrate–N Load

Rye–Cover significantly reduced total cumulative NO_3–N load in CSb in 2016 and 2017 (Table 2.3). Cumulative average load in 2016 CSb totaled 63 kg N ha^{-1} with Rye–Cover and 128 kg N ha^{-1} with No–Cover; a 51% reduction. In 2017, NO_3–N load was 68 kg N ha^{-1} with Rye–Cover and 130 kg N ha^{-1} with No–Cover; a 48% reduction. Studies like McCraken et al., (1994) had similar NO_3–N reductions from Rye–Cover on a silt loam. Unlike CSb, Rye–Cover had no impact in CC or SbC. The lack of response is likely due to the low biomass of rye fall seeded into standing corn. Under these conditions Rye–Cover produced >300 to <600 kg ha^{-1}, and the corresponding N uptake was low (9–17 kg N ha^{-1}) compared to CSb where Rye–Cover produced >1500 to <2900 kg ha^{-1} and N uptake was 43 to 70 kg N ha^{-1} (Chapter 1). Also, in the CC and SbC rotations, corn residue likely overshadowed N immobilization from rye residue. Corn residue has relatively high C:N, which would immobilize N early in the season, minimizing loss when N is most vulnerable. The amount of protection against NO_3–N loss given by corn residue seems to be dependent on weather conditions. In 2016, the year with less drainage in our study, NO_3–N load was approximately 28 kg N ha^{-1} less than for 2017 in both the CC and CSb regardless of the cover crop variable. This may be related to immobilization and mineralization processes and when they occurred in relation to precipitation events that result in drainage. Conversely, in CSb where there was little corn residue, NO_3–N loads were similar in both years (Fig. 2.5; A-1, B-1). An important difference was that the NO_3–N load in CSb with Rye–Cover was similar in 2016 and less in 2017 compared to those of CC and SbC. In contrast, in CSb No–Cover NO_3–N load was 2.1 times greater in 2016 and 1.4 times greater in 2017 relative to the mean value across CC, SbC and both Rye–Cover and No–Cover (Fig. 2.5; A-1, B-1).

Nitrogen rate significantly affected cumulative load in CC and SbC in 2017 (Table 2.3). All N rates or residual N rates were different from each other, where 300 kg N ha^{-1} had the greatest load followed by the Optimal N rate, and the Optimum N rate was greater than the 0–N rate (Fig. 2.5; B-2,3). These results indicate that N can impact potential loading in the current crop and subsequent crops as seen in SbC (Kaspar et al., 2012**)**. Nitrogen rate was likely non-significant in most cases due to the high inherent variability that comes from calculating load from drainage and concentrations values (Randall and Vetsch, 2005; Struffert et al., 2016). Dramatic increases in load always corresponded to precipitation and drainage events or as depicted in Struffert et al. (2016). Increases in drainage were frequent and intense early in the season and became more scattered as the season progressed.

The 0–N plots in CC clearly illustrated that organic matter mineralizes and continuously cycles N into the soil, which can then be vulnerable to leaching (Table 2.3). In Struffert et al. (2016) the CC 0–N plots had not received N for four years yet still averaged 29 kg NO_3–N ha^{-1} indicating that N rate alone is not sufficient to eliminate NO_3–N leaching. Irrigated coarse-textured soils are inherently leaky systems regardless of cropping rotation but CSb typically leaches the most. This is likely due to residual N from the soybean phase in combination with supplemental N applied in season. The data from this study suggest that a rye cover crop can reduce NO_3–N leaching in CSb both in load and concentration to similar values observed for non-fertilized CC.

Overall our study clearly shows that rye cover crops should be targeted to those rotations that have the greatest potential to benefit from NO_3–N load reduction (Fig. 2.5; A-1, B-1). The CSb rotation had the highest NO_3–N load, as also observed by others (Struffert et al., 2016), but Rye–Cover reduced load to values similar or less than those observed in SbC where no N was applied (Table 2.3). That said, NO_3–N load were generally similar between CC (where N fertilizer was applied) and SbC (where no fertilizer was applied). In the numerically best possible scenario to reduce NO_3–N load of our study (0–N Rye–Cover in SbC) 43.2 kg NO_3–N ha^{-1} was the mean load across 2016 and 2017. This scenario reduced NO_3–N load 66% relative to the numerically worst possible scenario to reduce NO_3–N load of our study (127.4 kg N ha^{-1}) (over-application with 300 kg N ha^{-1} in CSb with No-Cover averaged across years). Still, these data indicate that concerns over NO_3–N loads and groundwater contamination in sandy soils with high organic matter content may be largely related to N mineralization under annual cropping systems than N fertilization. Although not all NO_3–N leaching below the root zone end up in groundwater, if pristine groundwater quality is the goal, our results call into question if these highly productive soils should be converted to different cropping systems.

2.5. CONCLUSIONS

Leaching in corn and soybean cropping systems can contribute substantial amounts of NO_3–N below the root zone. The CSb rotation had the most potential for

NO_3–N leaching but NO_3–N leaching in concentration and load were significantly reduced when CSb was managed with Rye–Cover. On averaged NO_3–N concentrations were reduced by 47.5% and load was reduced by 49.5%. Neither CC nor SbC leaching was reduced by Rye–Cover likely due to corn residue from the previous crop reduced rye establishment while also immobilizing N. Rye–Cover did not reduce corn yield suggesting that rye has potential as a viable management practice that supports agronomic and NO_3–N loss reduction goals. When 0–N was applied NO_3–N load averaged 131.4 (CSb), 46.3 (CC), and 71.6 (SbC) kg NO_3–N ha^{-1}. Interactions with N rate were inconsistent in reducing NO_3–N leaching suggesting that independently reducing N rate does not suffice as a NO_3–N load reduction management tool. Drainage directly impacts NO_3–N leaching suggesting that as precipitation trends continue to increase the management of irrigation and N applications may also need to be refined to manage N loss. It was observed that even though rye biomass in CSb differed by approximately 1300 kg ha^{-1} between study years, equivalent levels of NO_3–N reduction occurred, suggesting that the amount of rye biomass required to reduce NO_3–N leaching has a wide range. Further research investigating the impact of rye establishment on leaching reduction would be necessary to create comprehensive management guidelines for rye cover in varying rotations and soil types.

Table 2. 1. Cumulative drainage (Penman) for corn and soybean with Rye-Cover and No-Cover. Drainage was calculated for non-N-limiting treatments and N-limiting treatments.

	Corn			
	No–Cover		Rye–Cover	
	non-N-limiting	N-limiting	non-N-limiting	N-limiting
	Cumulative Drainage (mm)			
2016	331	419	329	418
2017	504	576	498	570

	Soybean†	
	No–Cover	Rye–Cover
	Cumulative Drainage (mm)	
2016	351	349
2017	499	493

† No N was applied to soybean thus there were N treatment effects.

Table 2. 2. Mean in–season NO_3–N leaching concentrations under corn-soybean (CSb), continuous-corn (CC), and soybean-corn (SbC) for 2016 and 2017.

		CSb			CC			SbC		
Year	N Rate	Rye-Cover	No-Cover	Mean	Rye-Cover	No-Cover	Mean	Rye-Cover	No-Cover	Mean
	kg N ha^{-1}	mg NO_3-N L^{-1}								
2016	0	13	28	20b†	9	9	9a	13	21	17a
	200	20	37	28a	–	–	–	24	19	21a
	250	–	–	–	22	12	17a	–	–	–
	300	20	38	29a	22	37	30a	17	14	16a
	Mean	18B‡	34A		18A	19A		18A	18A	
2017	0	7	21	14a	7	9	8c	11	11	11a
	200	14	24	19a	–	–	–	23	19	19a
	250	–	–	–	19	17	18b	–	–	–
	300	19	30	24a	26	21	24a	25	25	25a
	Mean	13B	25A		17A	16A		19A	17A	
	Source of Variance				*P*>F					
2016	Cover (C)	<.0001			0.8069			0.5048		
	Rate (R)	0.0284			0.0894			0.1761		
	C x R	0.8757			0.3421			0.4199		
2017	Cover (C)	0.0036			0.8497			0.0747		
	Rate (R)	0.1018			0.0005			0.1239		
	C x R	0.4966			0.6627			0.6022		

Table 2. 3. Cumulative annual NO_3–N load leached under corn-soybean (CSb), continuous-corn (CC), and soybean-corn (SbC) for 2016 and 2017.

		CSb			CC			SbC		
Year	N Rate	Rye-Cover	No-Cover	Mean	Rye-Cover	No-Cover	Mean	Rye-Cover	No-Cover	Mean
	kg N ha^{-1}	mg NO_3-N L^{-1}								
2016	0	56	131	94a†	40	46	43a	48	72	60a
	200	67	125	96a	–	–		81	68	74a
	250	–	–		74	40	57a	–	–	
	300	64	128	96a	72	119	96a	61	50	56a
	Mean	63B‡	128A		62A	67A		55A	61A	
2017	0	44	135	90a	53	56	55c	38	60	49c
	200	67	127	97a	–	–		98	91	95b
	250	–	–		114	80	97b	–	–	
	300	92	127	109a	124	133	128a	139	112	125a
	Mean	68B	130A		97A	90A		88A	86A	
	Source of Variance				*P*>F					
2016	Cover (C)	<.0001			0.7794			0.6267		
	Rate (R)	0.9717			0.1537			0.6408		
	C x R	0.7544			0.3247			0.3304		
2017	Cover (C)	0.0098			0.9775			0.3220		
	Rate (R)	0.7387			0.0010			<0.0001		
	C x R	0.0935			0.4420			0.0682		

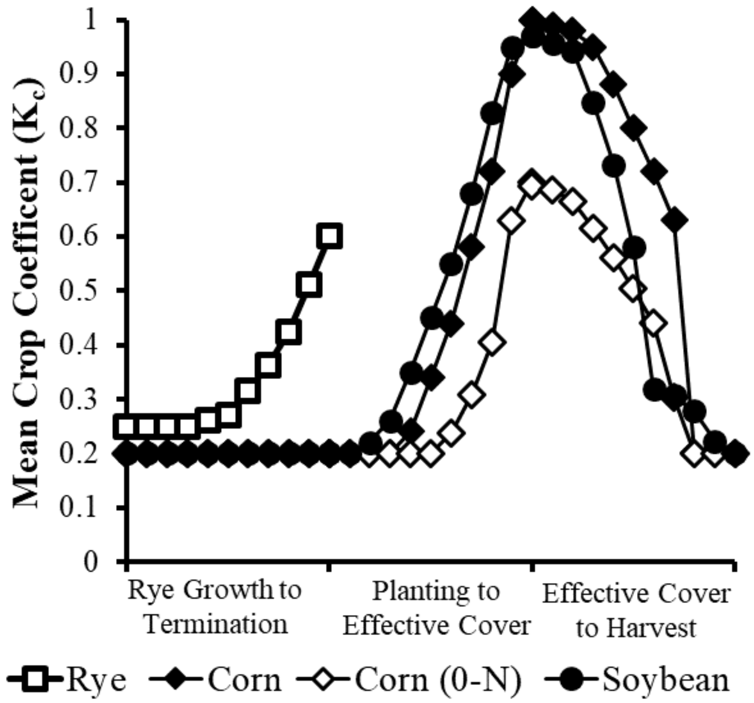

Figure 2. 1. Mean crop coefficients (K_c) for rye, non-N-limited corn "Corn", N-limited corn "Corn 0-N", and soybean according to the ASCE Standardized Penman-Monteith Reference Method.

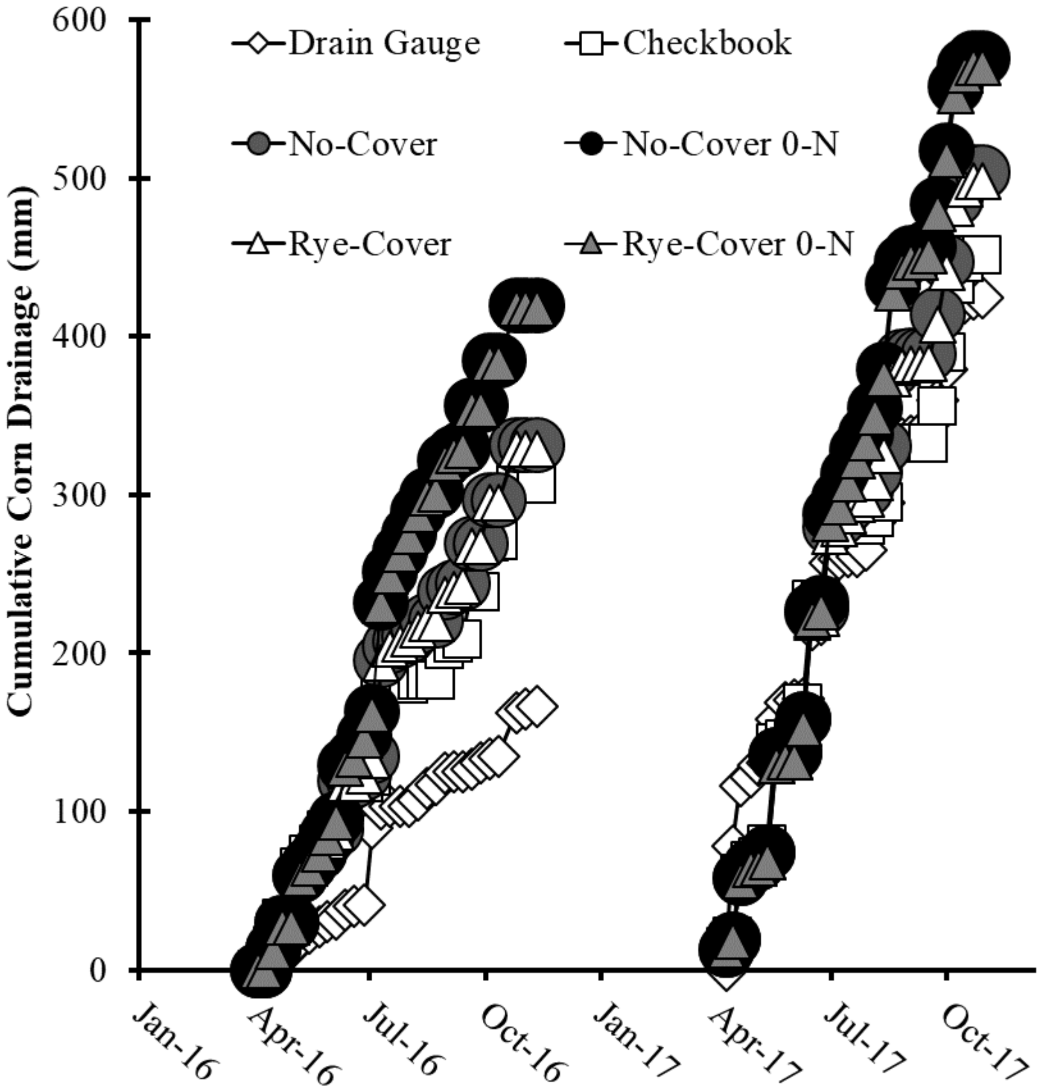

Figure 2. 2. Season–long cumulative drainage in corn measured from passive capillary drainage lysimeters (Drain Gauge) and calculated using ET measurements from an irrigation checkbook (Checkbook) or Standardized Reference Evapotranspiration Equation (SREE) for 2016 and 2017. Drainage was calculated for treatments with non-limiting N and limited N (0-N).

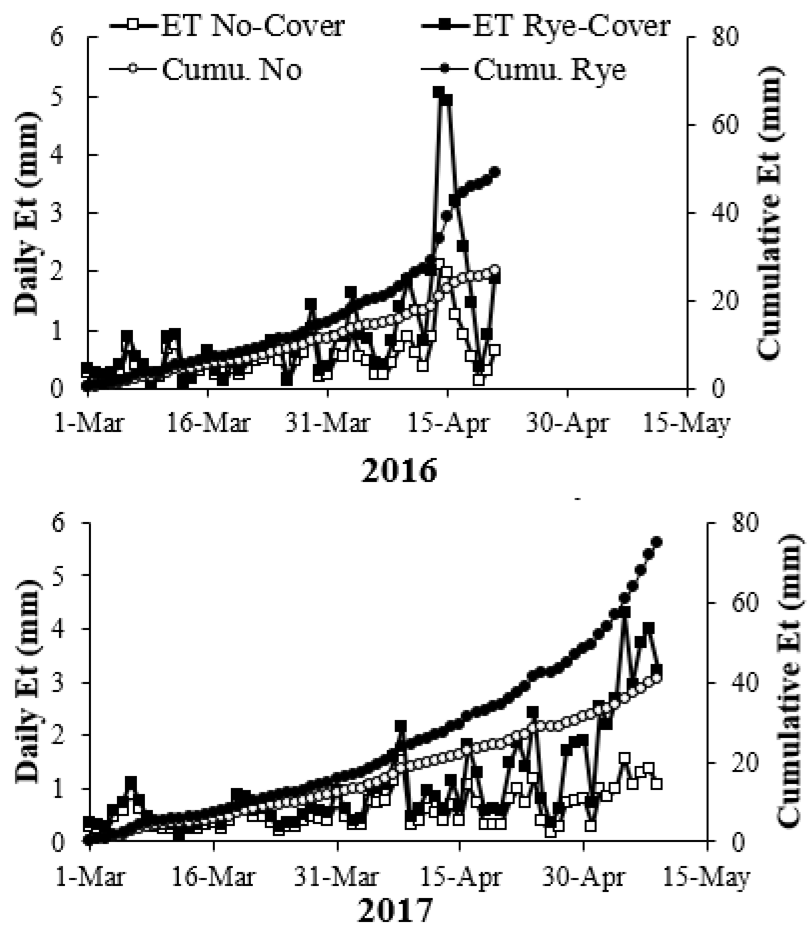

Figure 2. 3. Daily and cumulative ET (mm) for Rye-Cover and No-Cover from spring growth through termination.

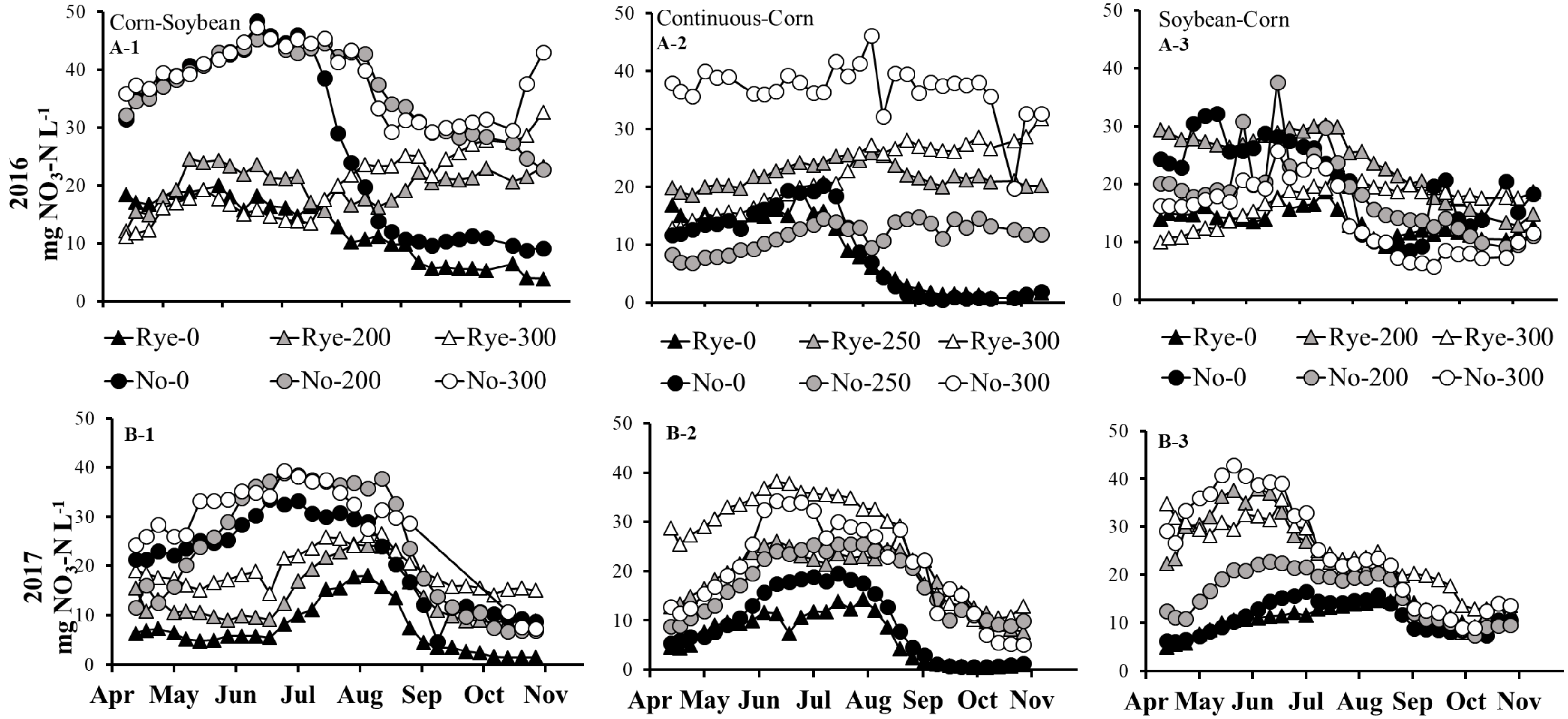

Figure 2. 4. Mean in–season NO_3–N concentrations leached across 31 (2016) and 30 (2017) sampling periods under corn-soybean (CSb), continuous-corn (CC), and soybean-corn (SbC).

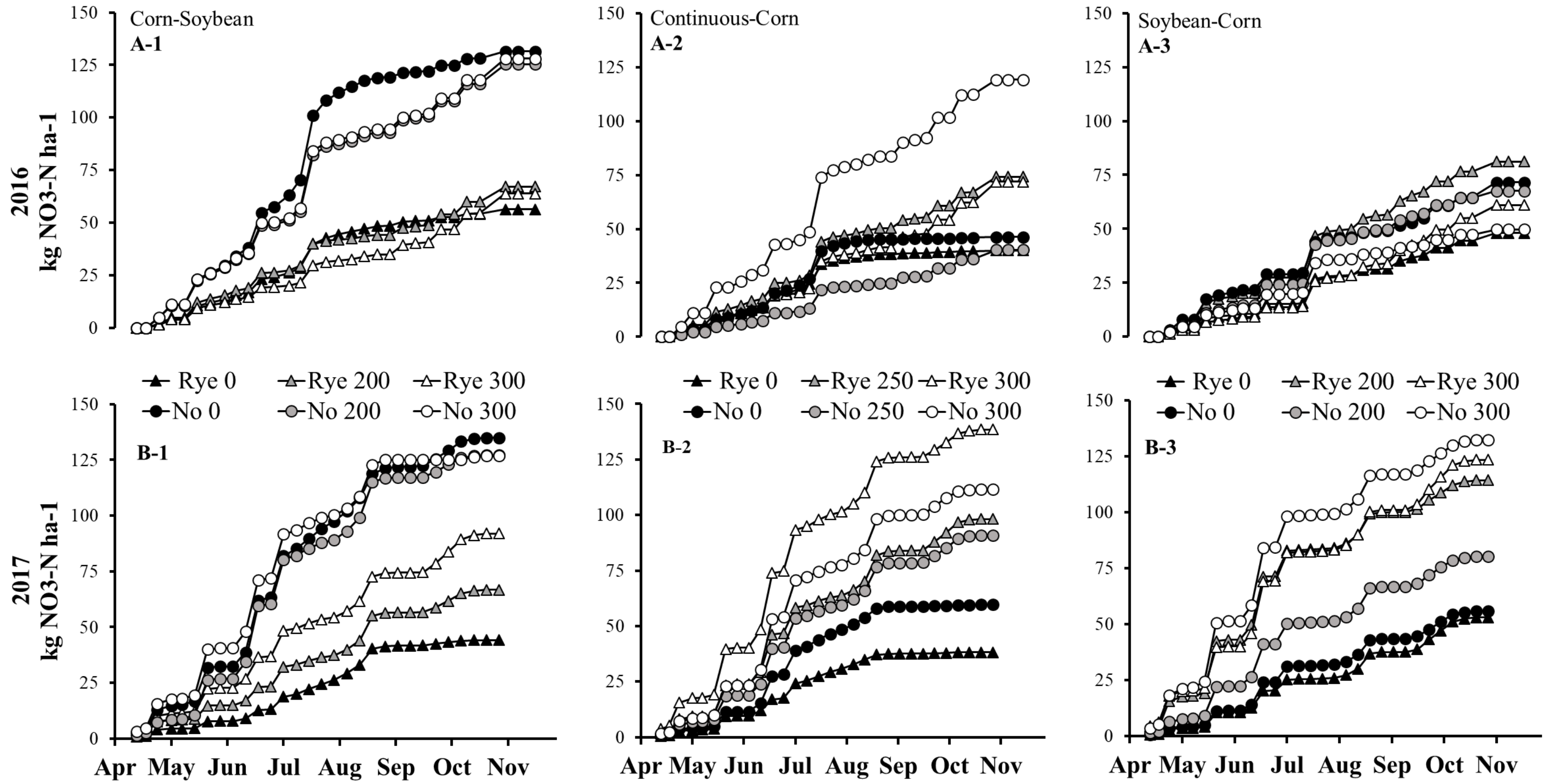

Figure 2. 5. Season–long cumulative NO_3–N load (kg NO_3–N ha^{-1}) leached below the root zone during 2016 and 2017 for various N rates (kg N ha^{-1}) and covers (Rye–Cover and No–Cover) in Corn–Soybean, Continuous–Corn, and Soybean–Corn. Nitrogen rates in Soybean–Corn are residual from the previous year's corn crop.

CHAPTER 3: Nitrate Leaching and Crop Production Under an Establishing Kura Clover Living Mulch on Irrigated Coarse-Textured Soils

3.1. Synopsis

Kura clover (*Trifolium ambiguum* M. Bieb.) as a living mulch may help reduce nitrate–N (NO_3–N) leaching on coarse-textured soils in corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] production. The objective of this study was to determine NO_3–N loss during kura clover (Kura) establishment in a two-stage experiment: Stage 1 the seeding year of Kura and Stage 2 the initial year of corn and soybean cropping into Kura. Kura establishment parameters, corn and Kura N uptake, and corn and soybean yield were also measured. During Stage 1, Kura received a total of 100 kg N ha^{-1} applied in four split applications. Cropping rotations included corn–soybean (CSb), continuous–corn (CC), and soybean–corn (SbC). Corn crops received 0, 200, or 250 kg N ha^{-1}, also split in four applications. Average load of NO_3–N leached under a mono-stand of Kura during Stage 1 was 140 kg NO_3–N ha^{-1}. When Kura was intercropped with corn or soybean during Stage 2, NO_3–N leaching load averaged across N rate was reduced by 92%, 88%, and 84% in CSb, CC, and SbC, respectively. Nitrate–N leaching did not exceed 15 kg NO_3–N ha^{-1} in any rotation with Kura. These results indicated that Kura has high potential to reduce N leaching after the initial year of establishment. Additionally, Kura establishment practices such as supplemental N fertilizer applications need to be adjusted for coarse-textured soil to avoid excess leaching while still supporting establishment. Compared to plots without cover, Kura reduced yield by 38%, 31%, and 22% in CSb, CC, and SbC, respectively. Corn that received 0–N yielded 63% less in CSb

and 68% less in CC compared to treatments that received 200 or 250 kg N ha^{-1}. Residual N rate had no effect on soybean yield. Kura is a promising option for NO_3–N leaching reduction on coarse-textured soils after the establishment year, but management to minimize yield loss for row crop needs further refinement.

3.2. Introduction

Groundwater supplies potable water for most cities and private households in the upper Midwest. Shallow aquifers under highly permeable conditions, such as coarse-textured soils, are susceptible to NO_3–N contamination. In 1988, 215 of 500 wells sampled from Minnesota counties were contaminated with elevated levels of NO_3–N (Klaseus et al., 1988). One of the most important sources of NO_3–N contamination to groundwater is corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] production on coarse-textured soils (Pollution Control Agency, 2013). Nitrogen management practices such as fertilizer rate, timing, source, and placement have been implemented over several decades to reduce N losses (Roberts, 2007). Many of these practices have increased N efficiency but recent studies have also shown that additional management is needed for these soils. For example, after four consecutive years with 0-N applied, corn in a CC cropping system leached 21 kg NO_3–N ha^{-1} (Struffert et al., 2016).

Living mulch systems may allow us to achieve reductions in NO_3–N leaching that cannot be achieved with traditional best management practices. A living mulch is a non-cash crop that is integrated with a cash crop and both are managed simultaneously. Benefits of living mulches are reduced erosion, increased biodiversity, and improved nutrient management (Hall et al., 1984; Prasifka et al., 2006; Siller et al., 2016). One promising living mulch for the upper Midwest is kura clover (Kura). This clover is native to Georgia and was introduced to the United Stage in 1944; it is cold tolerant, disease resistant, and withstands repeated defoliation from cutting or grazing without stand loss (Taylor, 2008). Widespread adoption of Kura is limited by its poor seed production, competition with row crops, and slow establishment (Genrich et al., 1998; Affeldt et al., 2004; Walker and King, 2010). Successful Kura establishment requires proper rhizobia inoculation (Laberge et al., 2005) and may also benefit from supplemental N (Seguin et al., 2001). Kura can be established with a companion crop but is highly sensitive to competition (Seguin et al., 1999).

The effect of Kura on corn production over the last 20 years has produced conflicting results with some studies showing no corn yield reduction (Zemenchik et al., 2000; Affeldt et al., 2004; Pearson et al., 2014) and others showing yield reduction (Qi et al., 2008; Sawyer et al., 2010; Ochsner et al., 2017). Practices that include the use of drought tolerant corn, supplement N, herbicide suppression of Kura, and tillage were all recommended to reduce yield loss (Ziyomo et al., 2013; Pearson et al., 2014). Most studies focused on Kura have been conducted on silt loams or other fine-textured soil. Some of these data suggest that Kura reduces NO_3–N leaching (Qi et al., 2008; Ochsner et al., 2017), but similar studies in coarse-textured soils are lacking. If Kura sufficiently reduces NO_3–N leaching, it may be an ideal alternative N management tool under coarse-textured soils that have high NO_3–N leaching potential.

The objective of this study was to determine NO_3–N loss during Kura establishment in a two-stage experiment: Stage 1 the seeding year of Kura and Stage 2 the initial year of corn and soybean cropping into Kura. Kura establishment parameters, corn and Kura N uptake, and corn and soybean yield were also measured.

3.3. Site Description

The experiment was conducted in 2016 and 2017 at the Rosholt Farm (45°42’49.1” N, 95°10’16.2” W) in Westport, Minnesota, on an Arvilla sandy loam (sandy, mixed, frigid Calcic Hapludolls) with a sandy/gravelly outwash parent material. Adjacent CC: continuous-corn, CSb: corn-soybean, and SbC: soybean cropping rotations were established in 2011 and were arranged in a randomized complete block design. Plots (4.5 m by 12 m) in three of four replications had three porous suction-tube lysimeters per plot permanently installed in 2011 at the depth of 1.2-m below soil surface. A weather station and linear irrigation system were also on site. Additional site description was given by Rubin et al. (2016)

3.4. Stage 1

3.4.1. Materials and Methods

In 2016, the field site was prepared with a disk and field cultivator. In two plots per replication, Kura variety ‘Endura’ was drilled at 15–cm spacing on 3 May 2016 (19 kg seed ha^{-1}) along with an oat companion crop (28 kg seed ha^{-1}). Kura seeds were pretreated with an appropriate rhizobial inoculant and coated with a clay shell; seeding rate was adjusted to ensure there were approximately 400–500 seeds m^2. When the oat companion crop reached 10 – 15 cm it was terminated on 2 June with glyphosate, N–(phosphonomethly) glycine at 1.15 kg a.i. ha^{-1}. Weeds were mechanically managed, and plots were mowed on 28 June, 25 July, and 23 August 2016. Kura stand counts were recorded at 44 and 78 days after planting (DAP). Urea (46–0–0) (N–P–K) treated with a urease inhibitor [N– (n–butyl) thiophosphoric triamide (NBPT)] was applied in four equal split applications on 19 May, 16 June, 26 June, and 14 July 2016 for a total of 100 kg N ha^{-1}. Kura was not water limited and the site received 721–mm of precipitation and 100–mm of irrigation; see Chapter 1. Porous suction-tube lysimeters were sampled every 7 – 10 days for NO_3–N concentration. Daily drainage was calculated using a water balance equation where evapotranspiration (ET) was determined using the Standard Reference Evapotranspiration Equation (SREE) and mean crop coefficients (K_c) (Walter et al., 2000). The K_c values for peas were used as a surrogate for Kura; where "0" was seeding and "100" was defoliation. After the initial defoliation of Kura, the K_c values for alfalfa "last cycle" were used where "50" was the day before the next defoliation until the end of the season. General trends for K_c values are summarized in Fig. 3.1. Full details for NO_3–N and drainage methods can be found in Chapter 2. Because all Kura plots had the same management, no treatments imposed during Stage 1, there was no difference in NO_3–N concentration or load for Kura plots within the same replication and the values were averaged during Stage 1. Kura plots within replication were separated for the respective treatments in Stage 2. For comparison the NO_3–N concentrations and loads for treatments receiving no N (0–N) and the recommended N rate (Rec–N) are also reported. The Rec–N rates are based on the University of Minnesota extension publication for fertilizing corn on irrigated sandy soils and are 200 kg N ha^{-1} for CSb and 250 kg N ha^{-1} for CC (Lamb et al., 2015). Kura above-ground biomass samples were collected on 4 November and were analyzed for N content. Data analysis were preformed using SAS software version 9.4 and procedures MIXED and GLIMMX (SAS institute, 2012). Differences between treatment means were considered significant at $P<0.05$.

3.4.2. Kura Establishment

Kura and oat emergence occurred approximately 10 DAP with true leaves developing 20 DAP. Plant development was delayed compared to spring seeded Kura in Genrich et al. (1998) and was likely inhibited by cool conditions in early May (Chapter 1). The average stand counts recorded at 44 and 78 DAP indicated that the number of individual plants decreased over time (Table 3.1). Both stand counts occurred after oat termination and the reduction in stand was likely not related to competition from the companion crop. However, Kura is highly sensitive to inter- and intra-species competition (Steiner and Snelling, 1994). Kura rapidly accumulated biomass from June – July, it is likely that the stand reduction was the result of self-competition. In November, above-ground biomass was similar in all rotations and averaged 917 kg ha^{-1} (Table 3.1) and N uptake averaged 16 kg N ha^{-1}. When compared to other studies that recorded Kura above-ground biomass during its seeding year, biomass results were greater than samples collected in July from Seguin et al. (1999), but lower than samples collected in October by Genrich et al., (1998). Besides differences in the sampling time between studies, variations may be the result of different soil type, the latter studies were conducted on silt loams, and Kura variety, ‘Rhizo’ (Seguin et al., 1999) and ‘Endura’ (Genrich et al., 1998). Similarities included seeding rate, 9–11 kg ha^{-1}, and spring seeding in May. In the aforementioned studies the biomass accumulated during the establishment year was sufficient to survive the winter and re-establish the following spring, as will be described in the discussion of ‘Stage 2’ of this study. Kura establishment during Stage 1 was highly variable even when best management practices such as inoculation, supplemental N, and weed management were implemented. Challenges with reliable establishment have been cited as a limitation for other cover crops and living mulches as well, such as rye (Wilson et al., 2013) and white clover (Chapman et al., 1984).

3.4.3. Drainage

Drainage was greatest in Stage 1 under Kura followed by corn with 0–N, soybean, and corn with Rec–N (Table 3.2). The trends in drainage values were typical and drainage increased with reduced ET. Kura stands were small compared to neighboring corn and soybean crops and therefore had less ET. Corn crops that were N deficient had less biomass and greater drainage.

3.4.4. Nitrate–N Concentration

During Stage 1, the rotation into which Kura was seeded had no effect on NO_3–N concentration ($P<0.9021$) (Table 3.5). The effect of N rate on Kura and crop concentration could not be compared due to a lack of uniformity among treatments. General patterns in Fig. 3.2 suggest that Kura NO_3–N concentrations were greater than for corn and soybean throughout the growing season (Fig. 3.2; A-2 and 3). The only exception was in the first portion of the growing season (until approximately the middle of July) in corn–soybean (Fig. 3.2; A-1). This is likely because the soybean residue from the previous crop resulted in substantial mineralization, whereas in CC and SbC the corn residue from the previous crop likely resulted in N immobilization, which limited leaching compared to Kura. Nitrate leaching concentration under Kura averaged 31 mg

NO_3–N ha^{-1} (±11) across rotations (Table 3.5). Concentrations under Kura were generally stable April – August and then steadily decreased until the end of the season (Fig. 2; A-1,2,3). This is likely an artifact of the supplemental N applications.

3.4.5. Nitrate–N Load

The cumulative NO_3–N load under Kura was the same across rotations ($P<0.8569$) and averaged 140 kg NO_3–N ha^{-1} (Table 3.5). There was a substantial amount of leaching under Kura and suggests that the majority of supplemental N applied during Stage 1 was lost through leaching (Fig. 3.3). The total amount of leaching likely exceeded applied N as N produced through mineralization was also lost. Several previous studies recommend supplying supplemental N while Kura is developing and has minimal nodulation and N fixing capabilities (Seguin et al., 2001; Laberge et al., 2005). While N fertilization may be important for Kura establishment, our study shows that substantial N loss (even when N is applied in small increments) can occur in coarse-textured soils when Kura has limited capacity to take up N during the establishment phase.

When averaged across rotations, 69% of the cumulative load under Kura occurred after 11 July 2016 (Fig. 3.3); this timing corresponds with the final N application. In contrast, under CC 0–N, only 41% of cumulative leaching occurred after 11 July. These results highlight that there is likely substantial amount of mineralization during the summer months, but the fact that less leaching occurs in corn than Kura indicates that corn is taking up substantially more N than Kura at that time of the year. During the summer Kura had minimal N uptake in above-ground biomass (16 kg N ha^{-1}) unlike CC where N uptake in above-ground biomass was much greater (88 kg N ha^{-1}, Chapter 1).

The majority of Kura biomass has been recorded to accumulate below the soil, up to 60% (Genrich et al., 1998), but it is unlikely that the biomass below the soil would account for a significant amount of N uptake compared to corn. In Seguin et al., (2000), it was estimated that 2 to 3-year-old Kura stands were capable of producing 155 kg N ha^{-1} yr^{-1} from atmospheric fixed N. An establishing stand likely has less capability but still has the potential to fix substantial amounts of N. The N generated from biological fixation in Kura may have also contributed to greater N losses relative to corn.

3.4.6. Stage 1 Summary

Kura seeded into irrigated coarse-textured soil has the potential to establish and produce adequate amounts of above-ground biomass to survive the winter. One potential concern of Kura establishment on coarse-textured soils is the increased risk of NO_3–N leaching. Kura produced 917 kg ha^{-1} of biomass but had minimal above-ground biomass N uptake. This resulted in 140 kg NO_3–N ha^{-1} leaching below the root zone which was greater than the total amount of N supplied to the system. Approximately 69% of the cumulative NO_3–N load occurred after N was applied, indicating that Kura may fix adequate amounts of N to sustain itself during the establishment year. Our data highlights that applying supplemental N only during the first part of the growing season may be sufficient to aid Kura establishment, but N loss is a risk because the crop has limited capacity to use all the available N during the establishment phase.

3.5. Stage 2

3.5.1. Materials and Methods

Kura initiated new growth in early April 2017 and rapidly accumulated biomass. Above-ground biomass samples were collected on 24 May 2017 and stands were 20 – 25 cm tall. On 24 May 2017, an Orthman 1tRIPr (Orthman Manufacturing Inc., Lexington, NE) was used to prepare equal width strips of undisturbed Kura and tilled soil. Glyphosate resistant corn hybrids and soybean varieties were planted on 25 May 2017 at 87,700 and 345,800 seeds ha^{-1}, respectively. To suppress Kura, plots were mowed on 8 June 2017 when corn was at approximately V2 development stage; at this point, Kura growth had encroached into the tilled strip. All plots were treated with glyphosate, N–(phosphonomethly) glycine at 1.25 kg a.i. ha^{-1} on 18 Jun. 2017 and this application sufficiently suppressed Kura growth. Corn growing with No–Cover and Kura received either 0–N or Rec–N. Nitrogen fertilizer was applied as urea with a urease inhibitor, as in 2016. The four split applications occurred on 15 June, 7 July, 12 July, and 26 July 2017 and N was broadcast applied in No–Cover treatments but applied at the base of corn plants in Kura treatments to try to increase N availability to the corn crop. No N was applied to soybean. Full details of corn and soybean management are in Chapter 1. In 2017 715–mm of precipitation and 114–mm irrigation was applied. Drainage for Kura and integrated row crop were determined using the K_c values for alfalfa “intermediate cycles” from spring growth to defoliation (Walter et al., 2000). After defoliation and herbicide suppression, Kura was assigned a set K_c and the values for corn and soybean were added to the K_c for Kura (Fig. 3.1).

3.5.2. Kura Above-Ground Biomass

Spring above-ground biomass samples averaged 1631 kg ha^{-1} (Table 3.1) with a mean N uptake of 35 kg N ha^{-1} (±14) (data not shown). Due to promising stand vigor, the plots were strip-tilled and seeded with corn and soybean, this was atypical management as Kura is usually not managed with a row crop until two years after planting (Walker and King, 2010). The Kura remained established after mechanical and chemical suppression, but above-ground growth slowed around mid-August likely due to high temperatures, canopy shading, and weed competition. Kura resumed growth after harvest, but frost and snow cover inhibited fall above-ground biomass sampling.

Stand counts recorded at V4 corn development stage indicated that Kura had no impact on stand count in CSb, but reduced stand counts in CC by 14% ($P<0.0283$) compared to No–Cover (data not shown). The stand count reduction in CC was likely caused by plant competition as the Kura filled in rows. The typical critical period of weed control in corn ranges from development stage V2 to V8 (Bedmar et al., 1999) and Kura was encroaching into the corn rows as early as V2. One likely factor that reduced stands was that occasionally the planter was not centered in the strip and would deposit the corn seeds close to or into the undisturbed Kura. This would have caused increased competition between the species. Continuous-corn was the first rotation seeded and the planting issue was corrected before the CSb rotation was seeded; however, there is no clear explanation as to why plant population differences were only seen in the CC rotation; abundant residue in CC may have impacted uniform planting contributing to greater variability in the rotation. Corn stand counts in Kura were also inconsistently reduced across sites in (Sawyer et al., 2010) and they attributed this observation to competition with Kura.

3.5.3. Crop Yield and N Uptake

Full details of corn and soybean yield are summarized in Chapter 1. The comparison of 0–N and Rec–N with Kura or No–Cover are in Table 3.3. In CSb and CC N rate and cover were independently significant. Kura reduced yield by 38% in CSb and 31% in CC. Treatments receiving 0–N yielded 63% less in CSb and 68% less in CC. Corn yield results were similar to those reported by Ochsner et al., (2010), where Kura reduced yield by 30%. In contrast, others have found no corn yield reduction with Kura (Pearson et al., 2014; Affeldt et al., 2004; Zemenchik et al., 2000). Two of the primary factors of successful corn management in Kura appear to be Kura stand age and aggressive row management. The age of Kura stand (at least three years) seems to be important not only for the longevity of the Kura but also for the survivability of corn. A mature Kura stand is likely able to fix a substantial amount of N and likely have less competition for N with the row crop (Seguin et al., 2000). Additionally, studies that recorded successful corn yields all implemented extensive row management including row preparation with tillage and chemical suppression. In our study, the Kura stand was likely still developing below-ground biomass and was an efficient competitor for nutrients. Also, while strip-tillage provided an adequate corn seedbed, Kura likely needed to be better suppressed to inhibit regrowth into the rows until past the critical period of weed control. Several studies (Ochsner et al., 2010; Pedersen., 2009) attribute water stress to the reduction in yield, but that is unlikely in our study due to ample water supplied through irrigation.

In SbC, soybean yield without Kura ranged 3.6–4.4 Mg ha^{-1} and soybean yield with Kura ranged 2.5–3.7 Mg ha^{-1}. On averaged Kura reduced soybean yield by 0.85 Mg ha^{-1} and residual N rate had no effect on yield (Table 3.3). There are limited results describing soybean yield when managed with a Kura living mulch. Pedersen et al. (2009) found that soybean managed in established 2 and 5-year-old Kura stands yielded similarly to soybean without Kura if the living mulch was suppressed with glyphosate, tilled, and chemically suppressed two additional times early in the season. Pedersen et al. (2009) reported soybean yield decreased by 0.77–2.88 Mg ha^{-1} when Kura was suppressed with fewer herbicide applications. During Stage 2 of the study conducted at the Rosholt Farm, the Kura was strip-tilled, mowed, and chemically suppressed once. The minimal suppression may have allowed row encroachment from insufficiently suppressed Kura and contributed to the 22% decrease in soybean yield. Additionally, establishing Kura stands, like at the Rosholt Farm, may provide greater competition with soybean than fully established stands such as those reported in Pedersen et al. (2009).

Mean total N uptake was significantly less with Kura than without Kura in both CSb and CC suggesting that Kura was competing for N and limiting corn N uptake (Table 3.4). These results differ from Zemenchik et al. (2000), where N uptake values suggested that the established Kura stands were contributing N opposed to competing for N. Plant N concentrations were greater with Kura, likely because corn plants had less N dilution due to reduced dry biomass compared to corn grown without Kura. Also, as expected plant N uptake and concentrations were greater due to N fertilizer in the Rec–N compared to 0–N.

3.5.4. Drainage

During Stage 2 drainage was reduced when corn and soybean were integrated with Kura (Table 3.2). Early corn development was delayed compared to soybean and may explain why drainage was slightly greater in corn than soybean. Precipitation and irrigation from April – October totaled 829–mm and drainage accounted for 61% of the total water. This was a greater portion of drainage compared to other studies on fine-textured soils where drainage represented 18–31% of precipitation (Brye et al., 2000; Randall and Vetsch, 2005; Ochsner et al., 2010). The low water holding capacity of coarse-textured compared to fine-textured soils likely contributed to the high drainage values seen in our study.

3.5.5. Nitrate–N Concentration

Kura reduced mean NO_3–N concentration in all rotations (Table 3.5 and Fig. 3.2). Averaged across N rate mean concentrations with Kura were 2.2, 1.8, and 2.5 mg NO_3–N ha^{-1} for CSb, CC, and SbC, respectively (Table 3.5). In contrast, No–Cover mean concentrations were 23.0, 13.3, and 13.6 mg NO_3–N ha^{-1} for CSb, CC, and SbC, respectively. A reduction in NO_3–N concentration in tile drainage from corn systems with Kura was also noted by Qi et al., (2008), where the mean annual flow-weighted NO_3–N concentration was 7 mg NO_3–N ha^{-1} with Kura compared to 19 mg NO_3–N ha^{-1} in a corn system without Kura. Our study showed that under Kura, NO_3–N concentration remained relatively low and constant throughout the growing season with weekly concentrations not exceeding 7.0 mg NO_3–N ha^{-1}. This contrasts with the typical pattern of low concentrations in the spring and fall and high concentrations June – August observed for the No–Cover treatments (Fig. 3.2) and as observed in a previous study (Struffert et al., 2016). The fact that NO_3–N concentrations with Kura under the Rec–N were lower than the unfertilized crops without Kura highlights the capacity of Kura to lower NO_3–N concentrations. Unfortunately, this also shows that Kura was actively taking up N, which resulted in reduced grain yield for corn and soybean (Table 3.3). Nitrogen rate was only significant in CC where mean concentrations were greater (mean difference of 4.7 mg NO_3–N ha^{-1}) with Rec–N than 0–N (Table 3.5), but in the CSb and SbC rotations a similar trend was observed. These results support those found in Ochsner et al., (2010) where Kura with 0 or 90 kg N ha^{-1} reduced monthly mean NO_3–N concentration compared to the control. Unlike Ochsner et al., (2010) the same gradual increase in NO_3–N concentration across the season was not observed, instead concentrations stayed consistently low. This was likely due to Kura competing for N while still in its establishment phase. In mid-August, Kura above-ground biomass was relatively stable in size. However, based on the low leaching concentrations in August, it is likely that the Kura stand was redirecting energy and biomass to the root system and continuing to compete for N (Fig. 3.2).

3.5.6. Nitrate–N Load

Averaged across N rate, Kura reduced cumulative NO_3–N load by 92%, 88%, and 84% in CSb, CC, and SbC, respectively (Table 3.5). Nitrogen rate had no effect on cumulative load. On average, No–Cover treatments leached 131, 75, and 68 kg NO_3–N ha^{-1}; CSb, CC, and SbC respectively. On coarse-textured soils, CSb is highly vulnerable to NO_3–N leaching, the lack of crop residue to immobilize residual N from the previous soybean crop is likely a main contributor. In CC and SbC, corn residue from the previous growing season likely immobilized N and reduced leaching losses. The immobilization that occurs with residue from the previous corn crop likely results in the need for additional N for CC than CSb to obtain similar yields observed in a related study by Rubin et al. (2016) as well as in other studies in fine-textured soils (Brye et al., 2000; Basso and Ritchie, 2005). As with concentration, Kura was very effective at scavenging N from the soil throughout the growing season, even after canopy closure. The substantial NO_3–N load reductions across all rotations show promise of Kura as a management practice on high leaching systems. However, the yield reduction we observed (Table 3.3) will be a major stumbling block for the adoption of this living mulch, unless a well-established Kura stand can prove to be less of a competitor for N. Based on an established Kura stand's potential to fix 155 kg N ha^{-1} (Seguin et al., 2000), it is conceivable that Kura may not only result in less competition, but actually supply N to the grain crops. Conversely, ample N supply from a mature Kura stand could become a major contributor to NO_3–N load on permeable soils if the grain crop is not able to use that N. These are questions that were beyond the scope of this study, but that we hope to answer in the future with the continuation of this project.

3.5.7. Stage 2 Summary

Most studies typically allow Kura to grow for two years before incorporating a grain crop in the cropping system. Having two years of establishment can be a major deterrent for farmers to adopt Kura. Partly to investigate the possibility of shortening the establishment phase and because Kura seemed to be sufficiently established where spring above-ground biomass averaged 1631 kg ha^{-1} with a mean N uptake of 35 kg N ha^{-1} (±14) we planted corn and soybean after one year. Corn and soybean yield were reduced in Kura plots suggesting that Kura was not sufficiently suppressed in the strip-tilled rows. Average NO_3–N concentrations were reduced to <3 mg NO_3–N ha^{-1} in all rotations and cumulative NO_3–N load was reduced by 92%, 88%, and 84% in CSb, CC, and SbC, respectively. Crop N uptake was lower in treatments managed with Kura than without, this was likely caused by Kura competing for N as it likely continued to develop below-ground biomass. Kura has great potential to reduce NO_3–N leaching when managed with a corn or soybean crop; however, crop yields were significantly decreased by the living mulch. Mature Kura stands along with aggressive row management are likely required to reduce the negative impact on crop yield.

3.6. Conclusions

Kura shows promise as an alternative management practice to reduce NO_3–N leaching when managed with corn or soybean crops. However, cumulative NO_3–N leaching during the initial seeding year of mono-cropped Kura was elevated. Supplemental N is recommended for establishing Kura stands but due to the high permeability of the soil and slow root development of Kura specific N recommendations are needed to support Kura establishment and limit N loss on coarse-textured soils. After one year of establishment, the Kura stand was strip-tilled and seeded with corn and soybean. When compared to rotations without Kura, Kura treatments reduced the cumulative load of NO_3–N in corn or soybean by 92%, 88%, and 84% in CSb, CC, and SbC, respectively. Compared to rotations without Kura, Kura reduced corn and soybean yield in all rotations. Yield reduction was likely a result of competition from establishing Kura. Compared to fully established Kura stands with full N fixing capabilities, establishing Kura stands appear to actively compete for nutrients and likely require additional management such as increased N rates to counteract competition. Regardless of Kura stand age, intensive Kura suppression in the corn and soybean row needed to reduce yield loss. With adequate management a Kura system can be integrated into corn and soybean rotations on an accelerated timeline. Additional research is needed to refine nutrient recommendations and herbicide management for integrated Kura and cropping systems on varying soil types.

Table 3. 1. Kura stand counts collected at 44 and 78 days after planting (DAP) during Stage 1 and dry biomass production for three crop rotations: continuous corn (CC), soybean-corn (SbC), and corn-soybean (CSb) during Stage 1 and 2.

	Stand Count		Biomass	
	44 DAP	78 DAP	Fall 2016	Spring 2017
Rotation	plants m^2		kg ha^{-1}	
CC	234	60	822	1620
SbC	224	76	920	1642
CSb	171	74	1009	1630

Table 3. 2. In-season drainage calculated for corn with either No-Cover or Kura and fertilized with the recommended amount of N (Rec-N) or no N (0-N). Soybean received no N. Drainage for corn or soybean with Kura was averaged across N rate.

Year	System	Drainage (mm)
2016	Corn Rec-N†	331
	Corn 0-N	419
	Soybean	351
	Kura	431
2017	Corn Rec-N	504
	Corn 0-N	576
	Soybean	493
	Kura+Corn	465
	Kura+Soybean	470

†0-N: 0 kg N ha^{-1}, Recommended-N: 200 (CSb) and 250 (CC) kg N ha^{-1}.

Table 3. 3. Corn and soybean grain yield under various cover and N rate treatments during Stage 2 of Kura establishment.

	Corn-Soybean			Continuous-Corn			Soybean-Corn†		
	Kura	No-Cover	**Mean**	Kura	No-Cover	**Mean**	Kura	No-Cover	**Mean**
N Rate					Mg ha^{-1}				
0-N‡	2.50	5.43	3.97B	2.17	3.98	3.08B	2.93	3.99	3.46A
Recommended-N	8.71	12.59	10.65A	8.10	10.92	9.51A	3.22	3.87	3.55A
Mean	5.61b	9.01a		5.14b	7.45a		3.08b	3.93a	

† N rates represent residual N from previous crop.

‡ 0-N: 0 kg N ha^{-1}, Recommended-N: 200 (CSb) and 250 (CC) kg N ha^{-1}.

§ Means within rotation followed by the same lowercase letter or the same uppercase letter are not significantly different (*P*>0.05).

Table 3. 4. Corn whole plant N uptake and %N under various cover and N rate treatments.

	Corn-Soybean			Continuous-Corn		
	Kura	No-Cover	**Mean**	Kura	No-Cover	**Mean**
N Rate			N Uptake kg N ha^{-1}			
No-N‡	51	69	60B	39	56	48B
Recommended-N	166	211	189A	185	222	204A
Mean	109b‡	140a		112b	139a	
			%N			
No-N†	0.92	0.64	0.78B	0.77	0.65	0.71B
Recommended-N	1.03	1.00	1.02A	1.20	1.12	1.16A
Mean	0.98a	0.82b		0.99a	0.89b	

† 0-N: 0 kg N ha^{-1}, Recommended-N: 200 (CSb) and 250 (CC) kg N ha^{-1}.

‡ Means within rotation followed by the same lowercase letter or the same uppercase letter are not significantly different (*P*>0.05).

Table 3. 5. Mean NO_3-N concentration and cumulative NO_3-N load for No-Cover and Kura treatments.

	Stage 1			Stage 2						
	No-Cover		Kura	No-Cover		Kura				
	0-N†	Rec-N	Est-N	0-N	Rec-N	0-N	Rec-N	Stage 2 Concentration ANOVA *P*>F‡		
	kg NO_3-N ha^{-1}							Cover	Rate	Cover x Rate
CSb	28	37	32	21	24	2	2	<.0001	0.5508	0.4351
CC	9	12	29	9	17	1	3	0.0009	0.0450	0.1274
SbC	21	18	33	11	16	2	2	0.0002	0.1242	0.1287
	mg NO_3-N L^{-1}							Stage 2 Load ANOVA *P*>F		
CSb	131	125	145	135	127	10	10	<.0001	0.9882	0.9501
CC	46	40	130	60	91	5	14	0.0004	0.1109	0.2267
SbC	72	68	146	56	80	11	11	0.0001	0.1060	0.1123

† 0-N: 0 kg N ha^{-1}, Est-N: 100 kg N ha^{-1}, Recommended-N: 200 (CSb), and 250 (CC) kg N ha^{-1}.

‡ ANOVA tables only depict values for Stage 2. Cover and N rate treatments could not be compared in Stage 1.

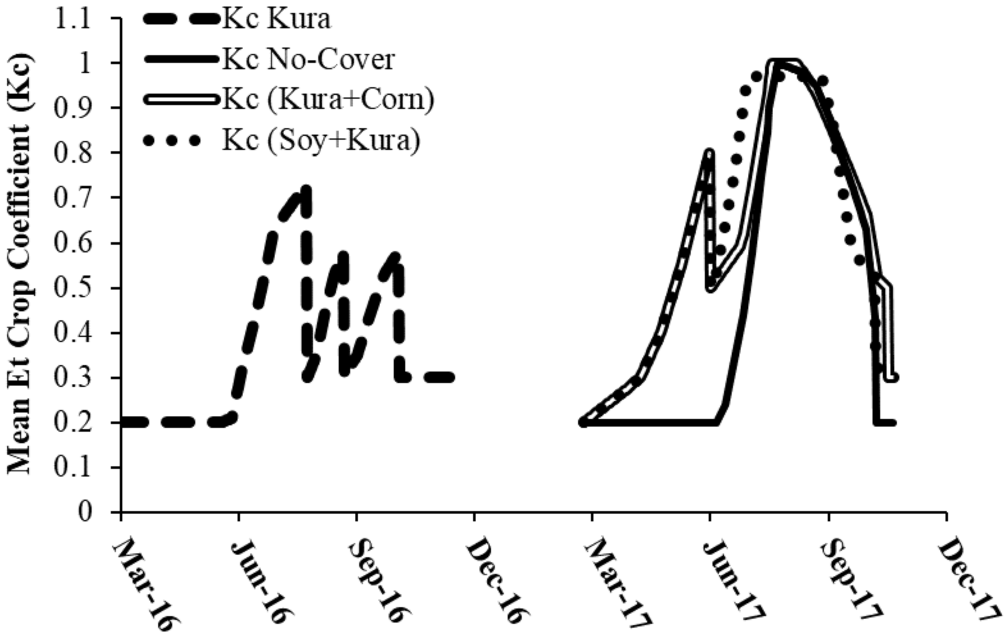

Figure 3. 1. Mean ET Crop Coefficients for Kura No-Cover, corn with Kura, and soybean with Kura.

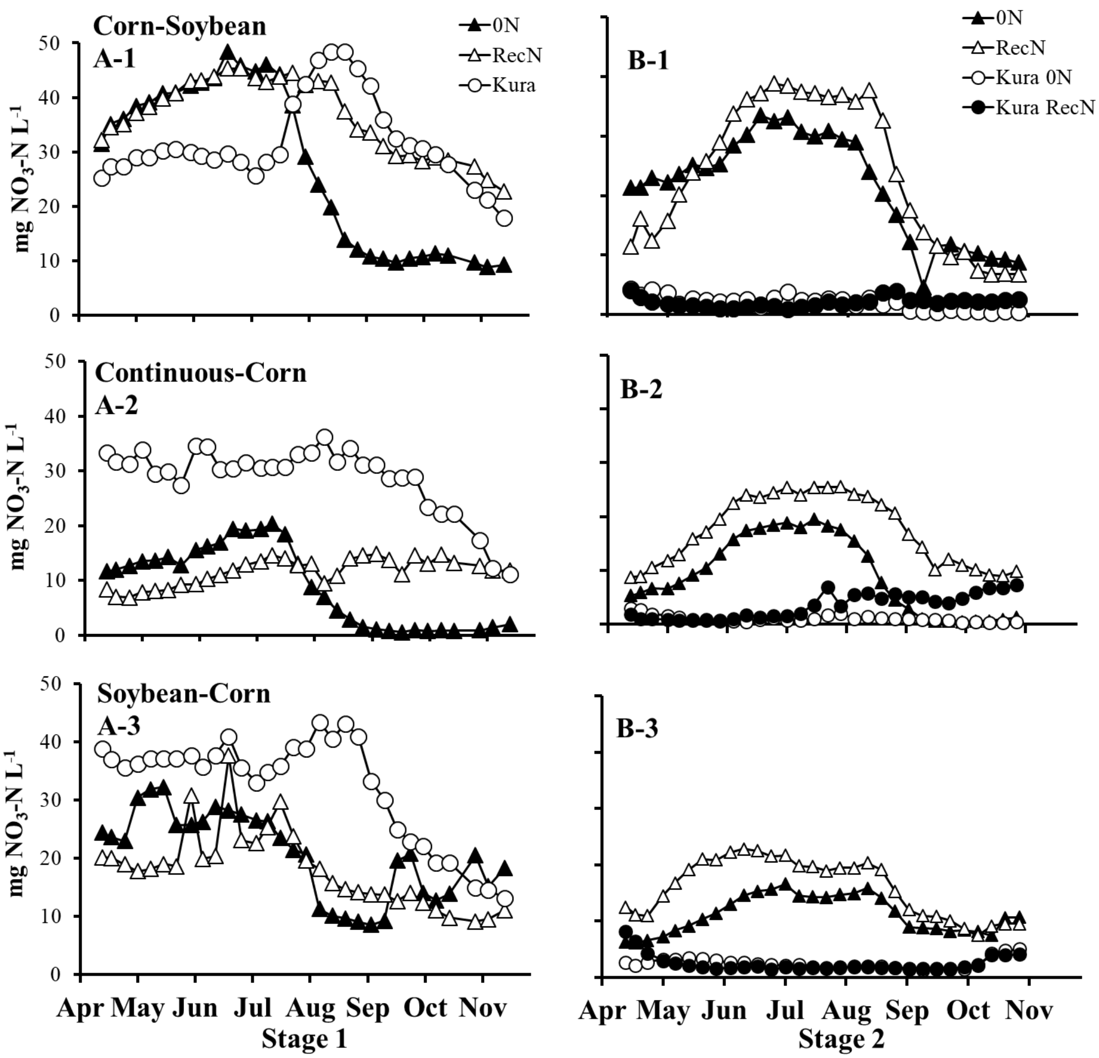

Figure 3. 2. Mean in–season NO_3–N concentrations across 31 (Stage 1, 2016) and 30 (Stage 2, 2017) sampling periods under corn-soybean (CSb), continuous-corn (CC), and soybean-corn (SbC).

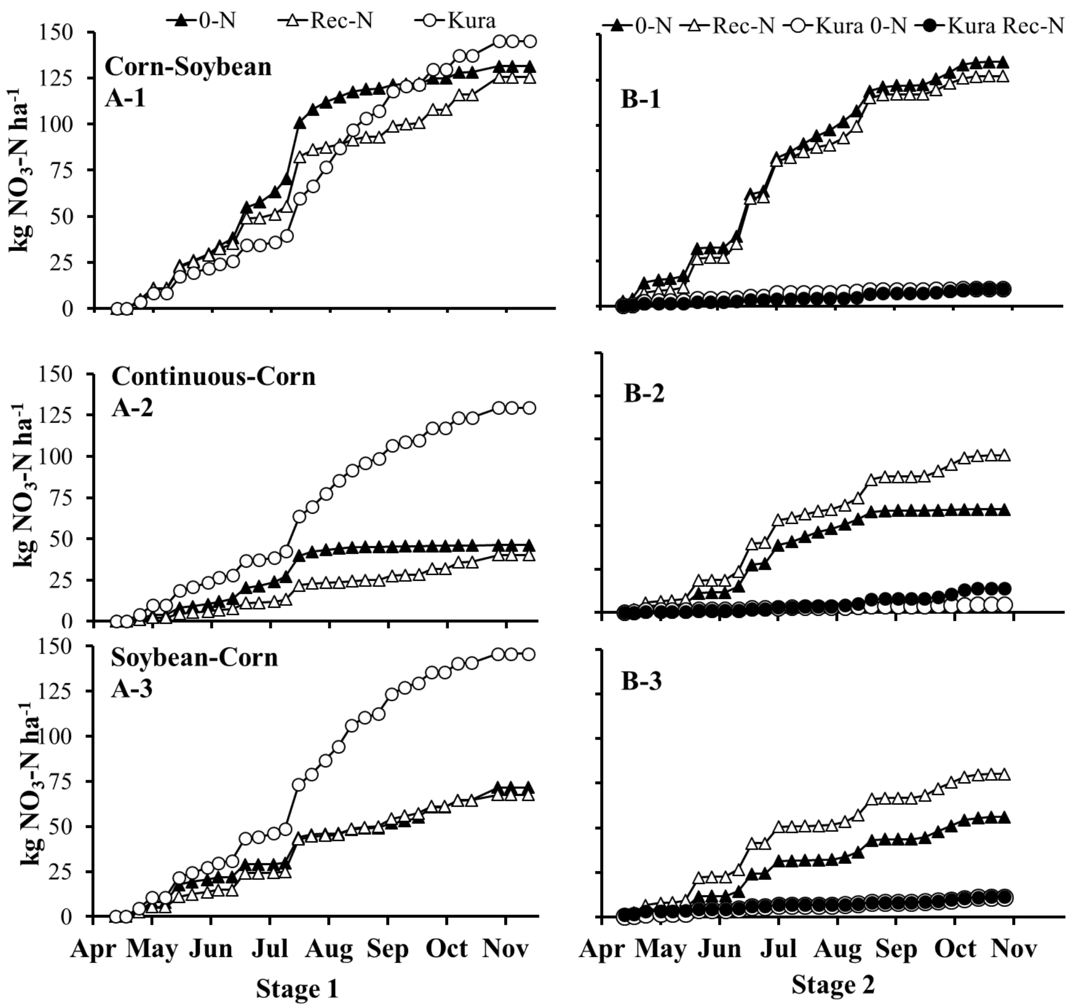

Figure 3. 3. Annual cumulative NO_3–N load leached across 31 (Stage 1, 2016) and 30 (Stage 2, 2017) sampling periods under corn-soybean (CSb), continuous-corn (CC), and soybean-corn (SbC).

CHAPTER 4: CONCLUSIONS

Coarse-textured soils require additional N management to mitigated N loss through leaching. Nitrate leaching is primarily driven by drainage and is highly dependent on precipitation, which is typically outside of management control. However, both Rye–Cover and Kura proved advantageous at reducing total NO_3–N load leaching under select conditions.

Rye–Cover reduced NO_3–N leaching and had no impact on corn grain yield when integrated into standing soybean the fall prior to corn production. Corn N requirements varied between years and were likely dependent on annual precipitation as well as the timing of immobilization and mineralization of rye residue with crop N uptake. Rye–Cover seeded into standing corn had poor establishment in the following CC and SbC rotations and had no impact on NO_3–N leaching reduction. Additionally, Rye–Cover always increased N requirements in CC likely due to increased immobilization. Under all rotations, NO_3–N leaching was still present when no N was applied. Indicating that solely reducing N rate is not sufficient to reduce NO_3–N leaching in coarse-textured soils. The results of this study suggest that rye can be integrated into the soybean phase of a corn–soybean rotation to reduce NO_3–N leaching on coarse-textured soils but that seeding into standing corn is likely not beneficial.

Nitrate–N leaching between the two stages of initial Kura establishment were very different. Leaching under a mono-stand of Kura was very high and exceeded the total amount of N supplied for establishment. When managed with corn or soybean Kura reduced NO_3–N leaching to <15 kg NO_3–N ha^{-1}; however, yield in all rotations was reduced. Yield reduction was tied to competition for nutrients and row encroachment due to insufficient Kura suppression early in the growing season. Kura reduces NO_3–N in all corn and soybean rotations but further refinement is needed for N requirements and stand suppression.

One of the strengths of this study was that the porous suction-tube lysimeters had been in place for multiple years allowing the surrounding soil to settle to best represent field conditions. Additionally, multiple methods were used to measure or calculate drainage. By comparing the methods, we were able to most accurately account for drainage and cumulative NO_3–N leaching.

One shortcoming was that in order to establish Kura the entire field required conventional tillage, but the following season the field was strip-tilled. The differences in tillage likely affected the immobilization and mineralization of rye residue due to the differences in residue incorporation. The differences in tillage made it difficult to determine if variations in N requirements in CSb were from precipitation, tillage, or other source-based effects. An additional shortcoming was that all Kura plots received the same amount of N during Stage 1. This made it difficult to determine if NO_3–N leaching was from the supplemental N, mineralization, or fixation from the Kura.

Several additional studies could improve these management practices. First, a study comparing rye seeding techniques and timing could determine if seeding method impacts rye establishment into standing corn. Potential methods include “Y” drop modified for seeding and drill seeding at varying timings including early season, late season, and post-harvest. Second, measuring NO_3–N leaching under established and establishing Kura stands with a range of N rates to better determine N requirements for varying stages of Kura development. This study would allow us to determine N requirements for Kura establishment on coarse-textured soils. Additionally, the study could produce guidelines for produces on managing Kura at different establishment stages. These studies would further refine the implementation of Rye–Cover and Kura on coarse-textured soils.

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APPENDIX

Appendix 1. Soil nitrate and ammonium N in response to sampling time [V8, R1, and post-harvest (PH)], nitrogen rate, cover crop, and soil depth for the continuous corn cropping system in 2016.

		No		Rye		No		Rye	
Sampling time	N rate	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm
	kg ha^{-1}	——kg NO_3-N ha^{-1}——				——kg NH_4-N ha^{-1}——			
V8	0	19	12	17	15	15	11	15	11
	100	46	31	55	32	22	22	18	16
	200	64	37	74	41	23	22	23	23
	250	71	56	113	85	25	21	26	36
	300	148	68	120	71	49	37	26	26
R1	0	9	2	12	2	9	12	12	15
	100	23	18	33	10	21	21	20	12
	200	44	10	56	11	21	15	32	17
	250	79	28	93	63	23	17	46	36
	300	65	15	106	57	41	16	44	30
PH	0	14	6	12	6	23	21	22	18
	100	14	6	12	4	19	13	16	15
	200	21	9	12	6	18	16	15	16
	250	20	11	32	10	23	21	22	21
	300	23	12	42	16	16	15	15	17

Analysis of Variance

	——kg NO_3-N ha^{-1}——	——kg NH_4-N ha^{-1}——
Source	*P*> F	*P*> F
Cover (C)	0.0447	0.2756
Time (T)	<.0001	0.0187
CxT	0.3313	0.0017
Rate (R)	<.0001	<.0001
CxR	0.3149	0.0016
RxT	0.0003	<.0001
CxRxT	0.4369	0.0151
Depth (D)	<.0001	0.0238
CxD	0.7088	0.5201
TxD	0.0049	0.1706
CxTxD	0.8518	0.4362
RxD	<.0001	0.2398
CxRxD	0.8520	0.5071
RxTxD	0.0647	0.1122
CxRxTxD	0.3566	0.9143

Appendix 2. Soil nitrate and ammonium N in response to sampling time [V8, R1, and post-harvest (PH)], nitrogen rate, and cover crop for the continuous corn cropping system in 2017.

Time	N rate	No 0-30 cm	No 30-60 cm	Rye 0-30 cm	Rye 30-60 cm	No 0-30 cm	No 30-60 cm	Rye 0-30 cm	Rye 30-60 cm
	kg ha^{-1}	——kg NO_3-N ha^{-1}——				——kg NH_4-N ha^{-1}——			
V8	0	7	7	11	7	15	13	18	10
	100	18	14	14	14	20	18	18	16
	200	25	17	17	15	22	17	28	26
	250	29	22	47	38	32	28	37	40
	300	29	27	24	21	30	39	31	32
R1	0	4	.	4	.	11	.	13	.
	100	12	.	14	.	14	.	15	.
	200	39	.	36	.	22	.	34	.
	250	92	.	116	.	52	.	56	.
	300	90	.	117	.	33	.	36	.
PH	0	7	2	6	2	8	6	7	7
	100	10	3	10	3	8	7	8	6
	200	15	4	21	6	9	7	9	9
	250	64	24	78	12	10	6	8	6
	300	36	12	52	14	8	6	9	5

Analysis of Variance

	——kg NO_3-N ha^{-1}—— 0-30 cm	30-60 cm	——kg NH_4-N ha^{-1}—— 0-30 cm	30-60 cm
Source	*P*> F		*P*> F	
Cover (C)	0.0825	0.3145	0.4755	0.6896
Time (T)	<.0001	0.7825	0.0417	0.0013
C x T	0.1065	0.9253	0.9492	0.3505
Rate (R)	0.0026	<.0001	0.0021	<.0001
C x R	0.6771	0.1758	0.7961	0.6951
R x T	0.0342	0.1854	0.4127	0.0004
CxRxT	0.9738	0.4729	0.9963	0.4644

Appendix 3. Soil nitrate and ammonium N in response to sampling time [V8, R1, and post-harvest (PH)], nitrogen rate, cover crop, and soil depth for the corn-soybean cropping system in 2016.

		No		Rye		No		Rye	
Time	N rate	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm
	kg ha^{-1}	——kg NO_3-N ha^{-1}——				——kg NH_4-N ha^{-1}——			
V8	0	32	28	32	25	18	15	20	16
	100	71	65	82	59	18	21	21	28
	200	108	63	147	94	23	23	23	43
	250	181	119	191	111	57	62	41	34
	300	173	142	215	166	33	49	31	52
R1	0	7	2	10	3	10	10	12	15
	100	44	14	39	17	20	15	22	16
	200	97	33	115	71	25	16	32	26
	250	188	41	130	48	66	20	28	17
	300	259	98	270	74	47	26	41	33
PH	0	13	6	10	4	27	24	26	23
	100	18	6	17	6	15	13	16	16
	200	18	9	31	12	24	22	28	22
	250	32	15	46	23	15	17	17	15
	300	43	20	38	31	23	20	22	18

Analysis of Variance

	——kg NO_3-N ha^{-1}——	——kg NH_4-N ha^{-1}——
Source	*P*> F	*P*> F
Cover (C)	0.3401	0.7765
Time (T)	<.0001	0.0117
C x T	0.6647	0.9364
Rate (R)	<.0001	0.0003
C x R	0.3435	0.0123
R x T	<.0001	<.0001
C x R x T	0.8797	0.1683
Depth (D)	<.0001	0.1885
C x D	0.9335	0.1716
T x D	<.0001	<.0001
C x T x D	0.6412	0.2614
R x D	0.0001	0.1933
C x R x D	0.9582	0.9603
R x T x D	0.0010	0.0175
CxRxTxD	0.9308	0.2663

Appendix 4. Soil nitrate and ammonium N in response to sampling time [V8, R1, and post-harvest (PH)], nitrogen rate, and cover crop for the corn-soybean cropping system in 2017.

		No		Rye		No		Rye	
Time	N rate	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm
	kg ha^{-1}	——kg NO_3-N ha^{-1}——				——kg NH_4-N ha^{-1}——			
V8	0	9	12	13	14	17	12	13	14
	100	22	22	22	23	43	32	22	27
	200	20	30	44	50	40	37	34	52
	250	28	57	30	41	48	71	38	74
	300	35	50	31	55	49	58	32	99
R1	0	9	.	10	.	11	.	9	.
	100	12	.	21	.	19	.	22	.
	200	49	.	44	.	17	.	16	.
	250	97	.	75	.	21	.	35	.
	300	151	.	162	.	51	.	80	.
PH	0	12	4	14	4	11	10	8	7
	100	17	5	17	12	12	7	8	6
	200	27	10	23	16	10	10	11	6
	250	49	14	53	36	10	7	11	8
	300	105	25	76	56	9	8	9	8

Analysis of Variance

	——kg NO_3-N ha^{-1}——		——kg NH_4-N ha^{-1}——	
	0-30 cm	30-60 cm	0-30 cm	30-60 cm
Source	*P*> F		*P*> F	
Cover (C)	0.9528	0.3915	0.6656	0.3006
Time (T)	<.0001	0.0001	<.0001	0.0033
C x T	0.8636	0.7852	0.7081	0.5300
Rate (R)	<.0001	<.0001	<.0001	<.0001
C x R	0.7000	0.7829	0.0034	0.1934
R x T	<.0001	0.3166	<.0001	0.0035
C x R x T	0.8469	0.5872	0.4367	0.5928