Minnesota Agricultural Water Resource Center

Our comments are provided in the uploaded letter along with reference materials. Please contact Warren Formo if there are follow up questions.

Minnesota Pollution Control Agency
c/o George Schwint
12 Civic Center Plaza, Suite 2165
Mankato, MN 56001

August 29, 2024

Re: NPDES and SDS General Feedlot Permits

Dear Mr. Schwint,

The undersigned farm organizations wish to raise the following concerns with the proposed revisions to the MPCA's NPDES and SDS Feedlot Permits on behalf of Minnesota farmers and related professionals.

Concern #1- Proposed changes violate engagement process

The proposed permit changes for vulnerable groundwater areas have been developed with little engagement with farmers. In addition, the MPCA has initiated the Southeast Minnesota Nitrate Strategies Collaborative Work Group to develop strategies to address nitrate in groundwater in response to the activist petition submitted to the EPA in April 2023. The Work Group is scheduled to meet monthly for the next year, and is charged with developing recommendations for improving, prioritizing, and implementing strategies, including strengthening communication and engagement activities, policy or funding proposals, or collaborative strategies to accelerate prevention and mitigation activities.

The Work Group includes several farmers committed to working with other task force members to identify nitrate mitigation strategies. Allowing the work group to complete its work first will result in greater buy-in and engagement of all sectors, but only if the agencies then implement the strategies they have contributed to and agreed on.

It is extremely disingenuous of the agency to convene this group while proposing such substantive changes to feedlot permits. The proposed permit changes should be withdrawn until the Work Group concludes its process.

Concern #2- Definition of "vulnerable groundwater area"

The agency proposes new prohibitions and/or requirements for manure applications defined by the agency as "vulnerable," but provides no criteria for the vulnerable groundwater designation. It appears that the agency is largely adopting the MDA's vulnerable groundwater map. However, MDA lists the specific data sources that determine the vulnerable groundwater areas subject to the fall fertilizer application restriction. At a minimum, MPCA should list the data sources on the map description page of their website.

The broad singular characterization as “vulnerable” does not recognize degrees of vulnerability, which differ across the designated regions. Soil depth above bedrock and karst differ, suggesting different levels of vulnerability which the proposed rule does not account for.

Utilizing the same map as the MDA’s Groundwater Protection Rule is also problematic because the logistics of manure and fertilizer management are very different. The timeframe for fertilizer application includes a few weeks prior to planting, at planting, and for several weeks during the growing season. Manure applications under the agency proposal would be greatly limited, as applications at planting time and into a growing crop are not feasible with current technology.

Concern #3- Forcing spring manure applications will increase risk

Limiting the number of days available to apply manure presents a significant hardship to livestock producers, crop producers who utilize transferred manure, and commercial manure applicators. Narrowing the window of available days for manure applications could also lead to negative management outcomes due to poor early crop growth due to soil compaction and the inability to avoid runoff-inducing rainfall events, which could all lead to a loss of yield and potentially *increase* nitrate leaching. For example, an unintended consequence of spring application is soil compaction which could create nutrient runoff rather than allowing nutrients to soak into the soil.

Many livestock farmers apply manure both in the spring and fall. For many of them, inadequate manure storage would prevent them from storing 12 months manure production. Further, weather conditions frequently disrupt application plans. The current proposal to limit fall applications would require farmers to increase storage capacity to 14-18 months production to provide a buffer against weather delays. This would require a significant investment and may not be feasible for some farmers.

Current permit requirements, specifically, delaying fall applications until soils are below 50 degrees F, should be a continued option, along with nitrogen stabilizers and split application.

Concern #4- Cover crop requirements in vulnerable groundwater areas

Cover crops hold promise for reducing nitrate leaching loss. We support the incentivizing of cover crops as an option. However, research and farmer experience show that later planted cover crops have much less potential to reduce nitrate leaching due to limited growth in our short growing season.

In a four-year replicated study, conducted at the University of Minnesota Southern Research and Outreach Center drainage facility, it was documented that the weather permitted adequate cover crop growth only during one season that allowed for a significant reduction of nitrates in tile drainage. Vetsch, J. 2020. Vegetative cover crops as a nitrate reduction strategy for tile drainage water. Four-year final report available at mncorn.org.

Research has shown that the lack of precipitation for more than a week after cover crop seeding often results in their poor establishment. The authors argued that "in rainfed agriculture of northern climates weather conditions drive the success of cover crops use in conventional maize production systems". Rusch, H.L., Coulter, J.A., Grossman, J.M., Johnson G.A., Porter, P.M and Garcia y Garcia. A., 2020. Towards sustainable maize production in the U.S. upper Midwest with interseeded cover crops. PLoS ONE 15(4): e0231032. https://doi.org/10.1371/journal.pone.0231032.

The ability of cover crops to reduce nitrate losses without adverse effects on the primary crop greatly depends on season length. Research conducted in Minnesota shows that cover crops work best in late planted, early harvested crops. This is a significant limitation for full season crops intended to be planted in April or early May and harvested in October. "Cover cropping practice provides promising opportunities for reductions in N losses for cropping rotations wherein the primary crops are harvested before mid-September and planted after mid-May." Feyereisen, G.W., Wilson, B.N., Sands, G.R., Strock, J.S., Porter, P.M. 2006. Potential for a rye cover crop to reduce nitrate loss in southwestern Minnesota. Agron. J. 98, 1416-1426.

And finally, Dr. Melissa Wilson's recent and ongoing manure management research is modernizing University of Minnesota manure application recommendations. She reports that "waiting until after soils had cooled to below 50ºF resulted in similar or better corn yields than spring fertilizer. This trend happened regardless of whether cover crops were planted or not." (emphasis added) https://www.mncorn.org/research-item/best-management-practices-to-integrate-cover-crops-and-manure/

Clearly, more research is needed on the effectiveness of cover crops to mitigate nitrate leaching in manured systems.

We ask the agency to provide additional options in addition to cover crops, specifically, continuation of the current permit options to delay application until soil temp is below 50 degrees F, the use of a nitrogen stabilizing agent/product, or split application.

Concern #5- Extending requirements to transferred manure

The MPCA does not have authority through the permit process to extend its reach to recipients of transferred manure. Legally, the permit is issued to the permittee and the permittee only – the permit is not and cannot be issued to a purchaser of manure. The proposed rule places an undue burden on permitholders to collect information from manure recipients that is beyond their purview, and beyond MPCA's authority under the NPDES process. This is unreasonable and will cause some current manure users to switch to fertilizer.

Manure is a proven source of nitrogen that helps to reduce greenhouse gas (GHG) emissions in agriculture. A switch from manure to fertilizer would increase greenhouse gas emissions and work at cross purposes with other MPCA goals and initiatives to reduce GHG emissions in agriculture. Changes to the general feedlot permits should also take into account any unintended consequences of the proposed changes and the increased difficulty in achieving MPCA goals in other areas.

Livestock and crop production working together provide a sustainable cycle, reducing dependence on fertilizer manufactured elsewhere and transported here. Our environment and economy benefit when manure is used efficiently as plant food. Reporting mandates should be streamlined.

Concern #6- Field inspections

The requirement for field inspections during and up to 14 days following application should be clarified. Delays and costs associated with agency inspection would be unworkable. Any reporting required by manure applicators or permittees should be streamlined. Additionally, most manure is incorporated within 24 hours as a best practice recognized by the MPCA.

We encourage the MPCA to consider our recommendations and look forward to working with the agency as the new permits are developed.

Sincerely,

Warren Formo, Executive Director
Minn. Agricultural Water Resource Center

Dana Allen-Tully, President
Minnesota Corn Growers Association

Dan Glessing, President
Minnesota Farm Bureau Federation

Lucas Sjostrom, Executive Director
Minnesota Milk Producers Association

Daryl Timmerman, President
Minnesota Pork Producers Association

Darin Johnson, President
Minnesota Soybean Growers Association

Jake Thompson, President
Minnesota State Cattlemen's Association

Jake Vlaminck, President
Minnesota Turkey Growers Association

Mindy Larsen, CEO
North Central Poultry Association

ver. 3/21/21

Vegetative Cover Crops as a Nitrate Reduction Strategy for Tile Drainage Water
PROJECT NUMBER: MCR&PC / 4121-16SP, (CON000000060901)
2020 Final Report

Jeffrey Vetsch
Univ. of Minnesota
Southern Research and Outreach Center
Waseca, MN 56093-4521

Introduction / Justification

Nitrogen (N) is an essential input for profitable corn production. Previous research (Randall and Mulla, 2001, Dinnes et al., 2002) has shown subsurface tile drainage systems deliver nitrate-N to surface waters and thereby degrade water quality. Row crop agriculture in the Midwest is under scrutiny to reduce NO_3 concentrations and loads in tile drainage. The use of cover crops and applying appropriate rates of N for corn are potential management strategies to reduce NO_3 losses in tile drainage water (Dinnes et al., 2002). The species of cover crop, establishment date and termination date could greatly affect their potential to sequester N. Cereal rye is effective at scavenging N when it's established early and not terminated until spring. Generally, Minnesota farmers who use cover crops either use cereal rye in a no-till system or seed a blend of annuals like annual rye, crimson clover and radish. The annual covers are terminated either by cold temperatures or tillage. The potential of fall/winter terminated covers to scavenge N in a corn - soybean rotation in Minnesota is not well known.

The objective of this study was to measure the effects of vegetative covers (e.g. winter hardy and winter terminating cover crops) at various N rates on the following: 1) tile water flow, NO_3-N concentration and NO_3-N loss in tile drainage water and 2) corn and soybean yields, nitrogen uptake, and nitrogen use efficiency (NUE).

Experimental Procedures

A research experiment was initiated in 2016 at the Univ. of Minnesota Southern Research and Outreach Center drainage research facility on a poorly drained Canisteo-Webster clay loam soil complex. Thirty-six individual tile drainage plots were installed in 1976. Each plot, measures 20 ft. by 30 ft., has a separate drain outlet and is isolated from adjacent plots to minimize lateral flow. A single tile is placed four ft deep perpendicular to the rows. The plot spacing simulates a 50-ft. tile drain spacing. A randomized complete block design with 4 replications was used in this study. A restriction on randomization within blocks, based on previous tile flow history, helped balance variability in tile flow among the 36 plots. This restriction put plots with the greatest historical flow all in the same block.

Nine treatments were comprised from a factorial combination of two management factors, cover crop species (termination date) and N rate each at three levels. The three cover crop treatments include: no cover crop, a late summer seeded cover of cereal rye (rye) with spring termination and a late summer seeded cover as a blend (blend) of annuals (annual rye, crimson clover and radish) with late fall or winter termination due to freezing. Cover crops were broadcast seeded by hand (simulate aerial seeding) at R6 prior to leaf drop in soybean on 2 Sep 2016 and 7 Sep 2018 and at R5 in corn on 13 Sep 2017 and 6 Sep 2019. Seeding rates were 90 lb/ac for cereal rye and 12, 15, and 5 lb/ac for annual rye, crimson clover, and radish, respectively. Nitrogen rates for corn in 2017 and 2019 were 3, 120 and 150 lb N/ac. The 3-lb rate was a control that received 3 lb N/ac from starter fertilizer. These control treatments allow for assessment of N contributions from the soil and cover crops. The 120-lb rate was near the 2016 MRTN for Minnesota for a 0.10 price ratio (N price / corn price). The 150-lb rate, 125% of the MRTN, allows us to test our hypothesis that the cereal rye cover terminated in spring may require a greater N rate to maximize corn production and better defines differences in NO_3 concentrations in tile drainage water. Nitrogen fertilizer was applied at planting as ammonium poly phosphate (APP, 10-34-0 at 2.5 gal/ac). In addition to in-furrow applied APP, the 120 and 150 lb N/ac treatments received urea ammonium nitrate (UAN, 28-0-0 at 9 gal/ac) surface-dribbled 3 inches from the corn row at planting for a total of 30 lb N/ac at planting. Urea with NBPT (Factor 3 qt/ton) was broadcast-applied at 90 and 120 lb N/ac to the 120 and 150 lb N/ac treatments, respectively at V4 on 10 June in both 2017 and 2019.

Soybeans (Asgrow 20-35, 20X9 in 2020) were planted at 135,000 seeds/ac on 9 May 2016, 17 May 2018 and 6 May 2020 (Appendix Pic. 8). Weeds were controlled with broadcast applications of glyphosate (24 oz/ac of PowerMax) in 2016 and 2018 and glyphosate plus ExtendMax (22 oz/ac) in 2020. Soybean seed yield and moisture were measured by combine harvesting four rows on 10 Oct 2016, 21 Oct 2018 and 7 Oct 2020.

Corn (NuTech 5L-503AMX in 2017 and Pioneer brand 0157AMXT in 2019) was planted at 36,000 seeds/ac on 7 May 2017 and 6 May 2019. Weeds were controlled with broadcast applications of Liberty at 24 oz/ac (31 May and 16 Jun 2017 and 7 Jun 2019); glyphosate at 24 oz/ac (4 May and 4 Jul 2019) and Harness at 1.75 pt/ac (13 May 2019). Stand counts were taken from the center six rows (harvest rows) and plots were thinned to a uniform population. Relative leaf chlorophyll content (RLC) was calculated from Minolta SPAD meter measurements from the ear leaf at R1 on 19 Jul 2017 and 29 Jul 2019. During the growing season six whole corn plants were collected at V8 and VT to determine biomass yield, nutrient concentration, and nutrient uptake. At R6 on 28 Sep 2017 and 27 Sep 2019, six random plants were harvested to determine corn stover and cob yield and harvest index. Biomass yield and nutrient uptake were calculated after correcting for moisture and plant density. Grain yield and moisture were measured by combine harvesting on 25 Oct 2017 and 26 Oct 2019.

Corn grain samples were analyzed for nutrient content after microwave acid digestion at a commercial lab. Nitrogen removal in corn grain was calculated from grain and stover yield and N concentration data. Nitrogen use efficiency parameters: partial factor productivity, PFP (the ratio of the grain yield to the applied rate of N) and agronomic efficiency, (the ratio of the increase in grain yield over N-control plots to the applied rate of N) were calculated as described by Snyder and Bruulsema (2007). For these NUE calculations the 3 lb N/ac rate from starter fertilizer was assumed to be the zero N control. Whole plant biomass samples were collected from all soybean plots at R6.5 on 10 Sep 2018. Total dry matter yield was calculated, a biomass sample was analyzed for nutrient content, and N and P uptake were determined. Soybean seed samples were also analyzed for nutrient content (same method as corn grain) to determine crop removal of nutrients in the seed.

Cover crop biomass yields were measured by cutting and collecting all material from 6.25 sq. ft. in the fall and prior to termination in spring [21 Oct 2016, 17 Apr 2017, 1 Nov 2017, 16 May 2018, 4 May 2019, 26 Oct 2019, 6 May 2020 and 21 May 2020 (twice in spring of 2020)]. No biomass harvest was conducted in the fall of 2018 due to very little cover crop growth (Appendix Pic. 9). Since the annual blend cover terminated during the winter, these plots were not sampled in spring. Biomass samples was dried, weighed, ground, and analyzed for nutrient content using the same procedures as grain and whole plant samples. Cereal rye cover was terminated with herbicide on 17 April 2017, 16 May 2018, 4 May 2019 and 21 May 2020.

After soybean harvest, strip tillage was performed and a subsurface band of 0-50-90 (0-46-0 at 50 lb P_2O_5/ac and 0-0-60 at 90 lb K_2O/ac) was placed 7-inches deep on 24 Oct 2016 and 31 Oct 2018. After corn harvest, on 2 Nov 2017 and 2019, P and K fertilizer (0-25-45) was broadcast-applied as 0-46-0 and 0-0-60 prior to strip tillage. Sulfur as Gypsum (120 lb/ac, 20 lb S/ac) was applied for corn each spring after corn planting (11 May 2017 and 17 May 2019).

Tile drainage is measured via an automated collection system. Tile water collects in drainage wells, then is pumped via a sump pump through water meters that measure flow volume. Flow volume is recorded on a datalogger hourly. These hourly flow data are examined for outliers prior to summarizing daily. The previous 24-hours of flow are summed at 8 am each day. Whenever the sump pump turns on and pressurizes the system, a portion (flow-weighted) of flow is collected in containers. Tile water samples are taken from each plot once a week during normal tile flow and two or three times per week during heavy tile flow. Water samples are kept cool prior to collection and then frozen after collection.

Each year, soil samples were taken from all plots in Jun (0- to 6-inch depth) and in the spring and fall (0- to 6-, 7- to 12-, 13- to 24-, and 25- to 36-inch depths). Samples were immediately dried at 105º F, then ground and sieved to pass a 2-mm screen. June samples were analyzed for pH, Olsen P, exchangeable K and soil organic matter using standard soil test methods for the North Central Region. Spring and fall samples were analyzed for nitrate and ammonium-N. All soil samples were analyzed at commercial labs.

All data were statistically analyzed using ANOVA with proc mixed in SAS® (SAS 9.2, SAS Institute Inc., 2008. Cary, North Carolina). A two-factor factorial ANOVA compared the effects and interactions of cover crop species and termination date [none, cereal rye (spring termination), and annual blend (winter termination)] and total N rate (3, 120, and 150 lb/ac). Mean separations were determined using the P Diffs procedure in SAS with alpha=0.10 level of significance. Treatments followed by different letters within a row or column are significantly different. *Tile flow, NO_3-N concentration and loss data in 2018, 2019 and 2020 were log transformed (base 10) to meet normality assumptions; therefore, the means presented in Tables 6b and 6c were back transformed. Tile flow, NO_3-N concentration and loss data in all figures are arithmetic means and not log transformed.*

Results and Discussion

Weather

Weather in 2016 was extraordinary and record breaking (Table 1). These data were taken from the SROC weather station located 0.3 miles from the research site. March and Apr were warmer and drier than normal, which resulted in early spring field work and planting in southern Minnesota. May and Jun had near normal temperature and precipitation, nearly ideal for crop development. Precipitation in Jul, Aug and Sep was 202, 246 and 403 percent of normal, respectively. Each of these months had a 24-hour rainfall event that exceeded three inches. Extensive runoff and tile flow (Figure 1), water ponding, and saturated soil conditions were observed during these months, especially Aug and Sep. Growing season (Apr-Sep) rainfall totaled a record 45.88 inches or 21.21 inches (86%) more than normal. Total annual rainfall totaled 56.24 inches, a statewide record, and 157% of normal at Waseca. Near or slightly warmer than normal temperatures were observed throughout the 2016 growing season. Growing degree units (GDU) from 1 May through 9 Oct (first freeze) totaled 2,938 about 17% more than normal. Despite excessive rainfall in Jul, Aug and Sep, the 2016 growing season was a good one for crop production in south-central Minnesota.

Abundant and well distributed rainfall with moderate swings in temperatures describe the weather in 2017 (Table 1). The months of May, Jun, and Oct had significantly greater than normal precipitation; whereas, other months had near normal or less than normal precipitation. Growing season (Apr-Sep) rainfall totaled 24.56 inches only 0.11 inches less than normal. Daily rainfall exceeded 2.00 inches on just one day (10 Jul, Figure 3) in 2017; therefore, leaching and tile drainage was minimal compared to recent growing seasons. January and Feb were considerably warmer than normal all other months were near normal. Growing season GDU's totaled 2656 and were 3% more than normal.

Urea fertilizer with NBPT was broadcast-applied on 10 Jun 2017, only 0.02 inches of rainfall was recorded the next two days and daily maximum air temperatures were in the 90's F. On 13 Jun, 1.73 inches of rainfall was recorded. Leaf burning due to ammonia volatilization from surface-applied unincorporated urea with NBPT was observed a few days after application; therefore, some of this fertilizer N was likely lost due to volatilization.

Weather data characterizing the 2018 growing season are presented in Table 1 and Figure 4. Abundant rainfall and large temperature deviations from normal describe the weather during the first few months of the growing season. April had near normal precipitation but much of it came as snow due to air temperatures which averaged 13° less than normal. Soil remained frozen or partially frozen (varied in field) until mid-April. The months of May and Jun had greater than normal precipitation and were warmer than normal. July and Aug were near normal for both precipitation and temperature. Sep had 287% of normal precipitation and was warmer than normal. On 4 and 5 Sep 6.44 inches of precipitation was recorded, this resulted in field and drainage culvert flooding. Growing season (Apr-Sep) rainfall totaled 34.29 inches or 9.62 inches more than normal. Growing degree units (GDUs) for the season were 111% of normal.

The 2019 weather data are presented in Table 1 and Figure 5. April and May were cooler and wetter than normal. These conditions delayed spring field operations and planting. About 4.5 inches of rainfall were recorded in the last two weeks of May and daily high temperatures only reached the upper 50's and low 60's on many days during this period. These cool and wet conditions slowed crop development. Mean monthly temperatures were near normal for June and July and slightly cooler than normal in August. Precipitation was 1.5 inches less than normal in June and greater than normal for all other months of the growing season. Growing season (Apr-Sep) rainfall totaled 32.36 inches compared with the 24.67 inches normal. Rainfall in Sep and Oct was 199% of normal and resulted in 6.42 inches of tile drainage (42% of annual total). In recent years, excessive precipitation in late summer and early fall months has been common and has resulted in a considerable late season tile flow. Growing degree units (GDUs) for the year totaled 2,528 (102% of normal); however, GDUs lagged below normal throughout most of the growing season.

The 2020 weather data are presented in Table 1 and Figure 6. April and May had below normal temperatures and Apr and the first half of May had considerably less than normal precipitation. These conditions were ideal for field operations and early planting of corn. About 3.8 inches of rainfall were recorded in the last two weeks of May. Air temperatures were greater than normal in Jun, Jul and Aug. Total monthly precipitation was also greater than normal in Jun, Jul and Aug. A 4.41 inch rainfall was recorded on 26 Jul. A 4-inch rainfall usually results in significant N leaching, denitrification and tile flow; however, soils were dry prior to this event and minimal water ponding and tile drainage were observed after the event. Precipitation for the period from Sep through Dec was less than normal and did not produce measureable time flow. Growing season precipitation totaled 26.16 inches compared to the normal of 24.67 inches. Growing degree units (GDUs) for the year totaled 2,602 (112% of normal). The 2020 growing season was ideal for early planting, crop growth and soybean production.

<u>Soybean production in 2016 (setup year)</u>

Soybean yields averaged 75 bu/ac in this extraordinarily wet growing season (Table 2). Yields were slightly greater without a cover crop than with either rye or blend. Due to the early September seeding date and plentiful rainfall, it's unlikely this yield difference was due to plant competition or soil moisture. It likely resulted from foot traffic in plots during cover crop seeding as some plants in this very dense canopy were trampled down during seeding.

Soybean production in 2018

Soybean yields were about 2 to 3 bu/ac greater without a cover crop than with blend and rye covers, respectively (Table 2). Due to minimal cover crop growth, it's unlikely this yield difference was due to plant competition or soil moisture. Foot traffic during cover crop seeding may have contributed to this reduction; however, much of the difference came from the no cover with 3 lb N/ac treatment (66.4 bu/ac). This treatment also had the highest yield in 2016. Prior to this study (2016), some parts of these control plots were used as grassed borders for easier access to the drainage culverts. Therefore, these grassed areas were not cropped to corn and soybean. We will analyze soil samples from these plots to see if they have lower levels of soybean cyst nematode compared to the rest of the field, which could partly explain their greater yield.

Soybean production in 2020

Soybean yields were not affected by the main effect of cover crop when averaged across previous N rates for corn (Table 2). However, soybean yields were greater at 3 lb N/ac compared with 120- and 150-lb. A significant cover crop × N rate interaction showed with no cover soybean yields were greater at 120 lb N/ac than at 150; whereas, with rye cover yields were greater at 150 lb N/ac than at 120. Yields were greatest with the no cover and 3 lb N/ac treatment (80.4 bu/ac). This treatment also had the highest yield in 2016 and 2018. Greater soybean yields in the N rate control plots (3 lb N/ac treatment) could be related to less corn residue cover leading to warmer soils in spring and greater early season soybean growth/development.

Cover crop biomass

Cover crop biomass on 21 Oct 2016 was 120% greater (194 lb/ac) with rye than with blend (88 lb/ac), when averaged across future N treatments (Table 3a). This biomass yield difference resulted in greater N and P uptake with rye (5.9 lb N/ac) than blend (3.0 lb N/ac), despite a greater N concentration in the blend. Significant cover crop × N rate interactions showed biomass yield and N uptake were affected by the future N rate for corn with the blend cover but not with the rye cover. Moreover, the 120 lb N rate and blend cover had considerably greater biomass yield and subsequently greater N uptake. Since these N rates were not applied until spring 2017, it's unclear what these differences mean. They could be random in field variation or a remnant from the previous study on this plot. Whatever the reason, some annual blend plots had considerably greater biomass than others; whereas, the rye cover biomass was more consistent among plots within and across treatments. On 17 Apr 2017, rye biomass and N and P uptake was greater with the 150 lb N/ac rate (not yet applied) than with other N rates. By 17 Apr the blend cover had terminated and decomposed so much so it was difficult to locate which plots had blend without a plot plan (see appendix Pic. 5 and 6). On 17 Apr, N uptake in the rye biomass ranged from 5.7 to 10.9 lb/ac. The amount of sequestered N in this study is less than what is typically reported in the research literature.

Biomass yields were extremely low (≤13 lb/ac) on 1 Nov 2017 and were not affected by the main effects of cover crop and N rate for corn (Table 3b). However, significant cover crop × N rate interactions showed treatment #6 (rye with 150 lb N/ac for corn) had greater biomass yield and nutrient uptake than other treatments. It's unclear why these differences occurred; however, with such minimal growth and uptake the impact of these differences on crop production, water use, and soil health are likely negligible. Nitrogen concentration in cover crop biomass was greater with 120 and 150 lb N/ac for corn than with the control (3 lb N/ac), when averaged across cover crop species. On 16 May 2018, biomass yield of the rye cover averaged 46 lb/ac and was not affected by N rate for corn. Like fall, N concentration in cover crop biomass was greater when 120 and 150 lb N/ac was applied for corn than with the control. At termination, N uptake in cereal rye cover ranged from only 1.1 to 1.7 lb/ac. This small amount would likely have little effect on N leaching or subsequent crop production.

Biomass yields were not taken in the fall of 2018 due to poor growth and patchy stands (Table 3c). On 5 May 2019, cereal rye biomass ranged from 39 to 61 lb/ac among N rates for corn and averaged 48 lb/ac. Nitrogen concentration ranged 3.69 to 3.77% and averaged 3.75%. Nitrogen rates for corn in 2017 had no effect on cereal rye biomass yield, nutrient concentration and nutrient uptake. The lack of significant differences was expected as this N fertilizer was applied for corn in 2017. At termination, N uptake in cereal rye cover ranged from only 1.5 to 2.2 lb/ac, which is similar to spring of 2018.

Biomass yields ranged from 13 to 74 lb/ac among treatments and averaged only 41 lb/ac on 26 Oct 2019 (Table 3d). When averaged across N rates for corn, biomass yields and N uptake were about 2X greater with rye than blend and carbon concentration was slighty greater with rye. Biomass yields, N uptake and C:N ratio were all greater with 3 lb N/ac than with 120- and 150-lb, when averaged across cover crop treatments. Both cover crop treatments had patchy uneven growth and growth was greater in the control (3-lb N) treatments likely due to less corn residue and more bare soil. However, N concentration in biomass was less with 3 lb N/ac which could be due to nutrient dilution, as this treatment had greater growth or could be due to less N remaining in the soil after corn. Carbon:Nitrogen ratio ranged from 12.4 to 15.6% among treatments. Because of patchy and minimal growth we delayed termination of rye cover until 21 May 2020 but we took two yield measurements. Biomass yield of the rye cover averaged 94 and 154 lb/ac on 6 and 21 May 2020, respectively and was not affected by N rate for corn in 2019. Carbon concentration was slightly greater with 150 lb N/ac on 6 May 2020 and greater with 120 and 150 lb N/ac on 21 May 2020. Like the 26 Oct 2019 results, N concentration in rye cover crop on 21 May 2020 was least with 3 lb N/ac and 3-lb N had the highest C:N ratio. Except for the spring of 2017, cover crop biomass yields were <240 lb/ac for all samplings and N uptake in the aboveground biomass was <5 lb/ac.

Corn production in 2017

Corn biomass yield, N concentration, and N uptake at V8 and VT are presented in Table 4a. When averaged across N rate, V8 corn biomass yield and N uptake was greatest with no cover, intermediate with blend, and least with rye. What is unclear is why the rye slowed early growth of corn. It could be due to less N availability and/or the extra residue from spring terminated rye (Pic. 6) kept the soil cooler thus slowing early growth. When averaged across cover crops, V8 biomass yield, N concentration, and N uptake were greater with 120 and 150 lb N/ac than with 3 lb N/ac (control). At the 3 lb N/ac rate, no cover had 82% greater biomass yield at V8 than rye. At VT, interaction between treatment main effects, cover crop and N rate, were found for biomass yield, N concentration, and N uptake. Generally, biomass yields were not different among cover crop treatments at 120 and 150 lb N/ac; whereas, biomass yields with the 3 lb N/ac control were greatest with no cover, intermediate with blend and least with rye. These data showed the cover crop treatments “caught up” to the no cover treatment by VT when fertilized with adequate N. This also suggests the reduction in growth with rye cover, when averaged across N rates, was most likely due to N deficiency. Nitrogen concentration and uptake at VT were not different among covers at 150 lb N/ac, but were less or trended less with no cover and rye at 120 lb N/ac. At 3 lb N/ac, N concentration with no cover was greater than blend and N uptake with no cover was greater than both blend and rye. These data showed in the control (3 lb N/ac) treatments, no cover had 10 and 17 lb/ac more N uptake at VT than the blend and rye, respectively. This suggests some of the N sequestered in the cover crops did not get released back to the corn crop by VT.

The effects of cover crop species and N rates on corn production parameters are presented in Table 5a. Corn grain moisture was wettest with rye at 3 lb N/ac and driest with no cover at 3 lb N/ac. These data showed delayed maturation of corn with rye and accelerated maturation with no cover, but only with 3 lb N/ac control treatment. When averaged across N rates, stover N concentration and uptake were greater with no cover than with rye or blend. When averaged across cover crop treatments, stover and grain N concentration and stover N uptake increased with increasing N rate. No significant differences in final plant population due to treatments were observed in these data.

Significant interaction between treatment main effects was observed for corn grain, cob, stover, and silage yield, grain N uptake, total N uptake, and RLC (Table 5a). At 150 lb N/ac grain yields were not statistically different among the three cover crop treatments; however, at 120 lb N/ac grain yields were reduced compared with 150 lb N/ac for both no cover and rye cover. At 3 lb N/ac grain yields were greatest (150 bu/ac) with no cover, intermediate (120 bu/ac) with blend, and least (108 bu/ac) with rye. This 42 bu/ac spread in grain yield was expected as research (Badger and Kaiser, 2017) has shown corn yields can be reduced at less than optimum N rates when following cereal rye covers; therefore, corn grown following rye requires more N fertilizer to optimize production. Cob yields were not affected by cover crop treatments at 150 lb N/ac; however, at 3 lb N/ac cob yields ranked no cover > blend > rye. Corn stover yields were similar among cover crop treatments at both 120 and 150 lb N/ac. At 3 lb N/ac stover yield was greater with no cover than with rye and blend covers. The silage yield response to treatments was nearly identical to corn grain yield.

Both cover crops reduced grain N uptake compared with no cover at 3 lb N/ac (Table 5a). Rye cover reduced grain N uptake at 120 lb N/ac; however, no significant differences in grain N uptake were found among cover crop treatments at 150 lb N/ac. Total N uptake was greater with no cover than with rye at all N rates. Total N uptake was greater with no cover than with blend at 3 and 150 lb N/ac. Nitrogen uptake was generally less with cereal rye compared with no cover. This suggests some of the N sequestered by cereal rye was either lost, likely through gaseous N compounds, and/or still immobilized in soil organic matter.

At VT/R1, RLC was similar among cover crop treatments at both 120 and 150 lb N/ac; whereas, at 3 lb N/ac RLC was greater with no cover and the blend than with rye (Table 5a). At VT/R1, RLC data predicted no N deficiencies in corn at 120 lb N/ac; however, N deficiency symptoms were evident at R5 and yields were reduced in both no cover and rye cover treatments at the 120 lb N/ac rate (Appendix Pic. 7). These data suggest a considerable amount of N was taken up after VT/R1 and that N deficiency this late can reduce yield.

<u>Corn production in 2019</u>

Corn biomass yield, N concentration, and N uptake at V8 and VT are presented in Table 4b. When averaged across N rates, V8 and VT corn biomass yield, N concentration and N uptake were not affected by the main effect of cover crops in 2019. When averaged across cover crops, V8 and VT biomass yield and N concentration were greater with 120 and 150 lb N/ac than with 3 lb N/ac (control). At V8, N uptake was greater with 120 and 150 lb N/ac than with the 3 lb N/ac control. At VT, the 150 lb N/ac rate had 15 lb/ac greater N uptake than the 120 lb N/ac rate and 56 lb N/ac more than the control. Unlike 2017, there were no significant interactions between treatment main effects (cover crop specie and N rate). These contradictory findings between years are likely explained by differences in rye biomass yield and N uptake, both were considerably less in 2019 compared with 2017.

The effects of cover crops and N rates on corn production parameters are presented in Table 5b. Corn grain moisture was wettest with 3 lb N/ac and driest with 120 lb N/ac, when averaged across cover crops. Corn grain, stover and silage yields were not affected by the main effect of cover crops in 2019 like they were in 2017. However, cob yields were greater with rye than with blend and no cover. When averaged across cover crops, grain, cob and silage yields increased as N rate increased up to 150 lb/ac. The 150 lb N/ac rate increased grain yield 11 bu/ac compared with the 120 lb N/ac rate. This result is not surprising considering the wet growing season and a cooler than normal spring (April and May). Stover yields were statistically similar between the 120 and 150 lb N/ac rates, but greater than the control treatment.

Stover and grain N concentration and stover, grain and silage N uptake and RCL were not affected by the main effect of cover crops (Table 5b). When averaged across cover crops, all the aforementioned corn production parameters increased as N rates increased up to 150 lb N/ac. Total N uptake was 51, 123 and 142 lb/ac with

3, 120 and 150 lb N/ac, respectively. No significant interactions between main effects (cover crops and N rates) were observed in any of the corn production parameters in 2019. However, at 120 lb N/ac NUE parameters were numerically greater with covers crops than without a cover crop. The lack of significant interaction between main effects suggests cover crops had minimal effect on corn production and N uptake, likely due to limited growth of the covers. However, numeric differences in total N uptake and NUE parameters at 120 lb N/ac suggests that cover crops may have increased N availability to corn. Final plant populations were about 900 plants/ac greater with cover crops than with no cover. The authors have no explanation for differences in plant population.

Tile drainage and nitrate concentrations and loss in 2016

Tile drainage and nitrate concentrations in drainage water were measured during the 2016 growing season. The goal during this setup year of the study was to flush out residual NO_3-N from the previous research study and thereby remove any legacy effects in the tile drainage system. Over 17 inches of tile drainage was recorded in this record wet 2016 growing season (Fig. 1). This amount is twice as much as a typical growing season and therefore ideal for flushing out the system. The majority, nearly 13 inches, of drainage was recorded in Aug and Sep, which is very unusual. Nitrate-N concentrations in Jun ranged from 8 to 10 mg/L and modest differences due to legacy effects of previous study were observed (Fig. 2). By Sep 2016, NO_3-N concentrations had declined to about 4.5 mg/L and variability among the newly seeded cover crop treatments was minimal.

Tile drainage and nitrate concentrations and loss in 2017 (corn year)

The effects of cover crop species and N rates for corn on tile flow, flow-weighted (FW) NO_3-N concentrations, NO_3-N loss (load), and flow adjusted loss in 2017 are presented in Table 6a. Tile flow began in Feb and some tile flow occurred in every month except Jan and Dec of 2017 (Fig. 3). Total annual flow averaged across treatments was only 4.2 inches, which is less than normal. Due to the lack of consistent flow in many months the flow data have been pooled into two periods, pre-N application (Pre) and post N application (Post). The first N treatments were applied at planting on 7 May; therefore, Pre was from 15 Feb to 7 May and Post was from 8 May to 16 Nov. Tile flow was not affected by treatment main effects, cover crop species and N rate for corn, or by interaction of these main effects. Some numeric differences were observed, these could be a result of treatment effects, seasonal flow variability (low flow year), and/or random variability.

When averaged across N rates, FW NO_3-N concentrations were greatest with no cover, intermediate with blend, and least with rye (Table 6a). These concentration differences were consistent for Pre and Post periods and the annual average. When compared to cereal rye, annual average NO_3-N concentrations were 3.4 times greater with no cover and 2.6 times greater with blend. When averaged across cover crops, NO_3-N concentrations were not significantly affected by N rates for corn although some small numeric differences were observed. NO_3-N loss or load to surface waters during the Post period was greatest with no cover, intermediate with blend, and least with rye, when averaged across N rates for corn. There were no significant differences for NO_3-N load during Pre period or for the annual total. Flow-adjusted NO_3-N loss (Eq. 1) was greatest with no cover (1.9 lb/inch), intermediate with the blend (1.5 lb/inch), and least with cereal rye (0.6 lb/inch), when averaged across N rates for corn.

$$\text{Equation 1} \qquad total\ nitrate\ lost \div total\ flow\ = flow\ adjusted\ loss$$

Tile drainage and nitrate concentrations and loss in 2018 (soybean)

The effects of cover crop species and N rates (applied to 2017 corn) on tile flow, FW NO_3-N concentrations, NO_3-N loss and flow adjusted loss in 2018 are presented in Table 6b. Due to cold spring temperatures and frozen soils, significant tile flow did not begin until mid-April in 2018 (Fig. 4). Averaged across treatments, annual flow totaled 13.2 inches with 46% during the period from Apr–Jun and 45% in Sep. Due to the lack of consistent flow in some months, flow data were pooled into quarterly periods: M-M (Mar-May), J-A (Jun-Aug), S-N (Sep-Nov), and D-F (Dec-Feb). During this research period (crop and drainage season), no flow was measured in Nov and Dec of 2018 and Jan of 2019. Tile flow was greater with rye cover than with no cover and blend in M-M, S-N, and the annual total, when averaged across the main effect of N rate for corn in 2017. At this time, we cannot determine if flow differences observed in 2018 are treatment effects, unexpected flow trends (different from previous years flow trends), or random flow variation. Hopefully more years of data will aid in explaining these results.

When averaged across N rates, FW NO_3-N concentrations were greater with no cover and blend than with rye in M-M and annual avg. (25% greater) and were greater with blend than rye in J-A (Table 6b). Nitrate-N concentrations increased with increasing N rate in J-A and annual avg. and were greater with 120 and 150 lb N/ac than control in other 3-month periods, when averaged across the main effect of cover crop. Significant cover crop specie × N rate interactions for NO_3-N concentration showed NO_3-N concentrations were not significantly different between the 120 and 150 lb N/ac rates with blend and no cover; whereas, NO_3-N concentrations were greater with 150 lb N/ac than 120 with rye cover. In 2018, NO_3-N concentrations were quite low ranging from 1.7 to 6.5 mg/L in fertilized plots (120 and 150 lb N/ac rates). Usually NO_3-N concentrations in tile drainage water exceed the EPA drinking water standard of 10 mg/L. The record wet year of 2016 dramatically reduced NO_3-N concentrations during the setup year of this study and concentrations have generally remained relatively low since. Keeping NO_3-N concentrations <10 mg/L during the last two years of this study is partly due to cover crop treatments, cool wet falls, and appropriate N rates for corn. Nitrate loss from tile drainage was not affected by the main effect of cover crop in 2018, when averaged across the N rates for corn. Nitrate loss was greater with 120 and 150 lb N/ac than with the control (3 lb N/ac) for all 3-month periods and the annual total. Total NO_3-N loss ranged from 4.7 lb/ac in the control to 10.3 lb/ac in the 150 lb N/ac treatment, when averaged across the main effect of cover crop. Significant cover crop specie × N rate interactions for NO_3-N loss showed NO_3-N losses were similar between the 120 and 150 lb N/ac with blend and no cover; whereas, NO_3-N losses were greatest with 150 lb N/ac with rye cover. These significant interactions are like those observed for FW NO_3-N concentration. In 2018, flow-adjusted NO_3-N loss was greater with no cover (0.68 lb/inch) and blend (0.67 lb/inch) than with rye cover (0.55 lb/inch), when averaged across the main effect of N rate for corn. When averaged across cover crops, flow-adjusted NO_3-N loss in tile drainage increased with increasing N rate. The significant cover crop × N rate interaction for flow-adjusted NO_3-N loss showed flow-adjusted NO_3-N losses with a cereal rye cover crop were not significantly different between the control and 120 lb N/ac treatments (0.43 vs 0.48 lb/inch, respectively); however, with blend and no cover the 120 lb N/ac rate increased flow-adjusted losses compared with the control.

Some similarities were found between the 2018 and 2017 tile water data. Generally, these data showed a cereal rye cover crop terminated in the spring reduced NO_3-N concentration and flow-adjusted loss in tile drainage water, especially when N fertilizer was applied near the recommended (MRTN) rate of 120 lb N/ac for corn after soybean. A blend of annual covers terminated in late fall reduced NO_3-N concentration and load compared to no cover during the corn year, but not nearly as much as cereal rye.

<u>Tile drainage and nitrate concentrations and loss in 2019 (corn)</u>

The effects of cover crop species and N rates (applied to 2019 corn) on tile flow, FW NO_3-N concentrations, NO_3-N loss and flow adjusted loss in 2019 are presented in Table 6c. Due to cold spring temperatures and frozen soils, tile flow did not begin until mid-April (Fig. 5). This late start to flow was like 2018, but unusual compared to historical data at this site. Averaged across treatments, annual flow totaled 15.2 inches (32% of annual precipitation) with 45% during the period from Apr–Jun and 42% from Sep–Oct. Equipment for measuring tile flow was winterized (drained to prevent freezing of pipes and damage to flow meters) in late Nov; therefore, flow was not measured from Dec of 2019 through Feb of 2020. Soils were frozen in November but thawed in Dec due to a significant rainfall event. As we prepared for the 2020 drainage season in early March, we confirmed some tile flow had occurred in Dec, about 2/3 of the 36 plots had flowed. Tile flow was greater with rye cover than with no cover and blend for the S-N period and annual total, when averaged across N rates. Increased tile flow with cereal rye has been observed in some periods and/or the annual total for each of the three years of this study. These data and past history at this drainage site suggests these differences are related to variability of flow among the 36 plots and not a result of treatment differences.

When averaged across N rates, FW NO_3-N concentrations were not significantly different among cover crops during any 3-month period or the annual average (Table 6c). However, NO_3-N concentrations were numerically less with cereal rye for all periods and the annual average. When averaged across the main effect of cover crops, NO_3-N concentrations were almost always greater with 120 and 150 lb N/ac than with the control (3 lb N/ac) for all 3-month periods and the annual average. A significant cover crop × N rate interaction for NO_3-N concentration for the J-A period was a result of NO_3-N concentration in treatment # 9 (blend with 150 lb N/ac) being less than treatment # 8 (blend with 120 lb N/ac). This small difference is of little consequence as no other significant interactions were observed and it's not highly significant ($p > F = 0.097$). Nitrate-N concentrations were quite low during the M-M and S-N periods and for the annual average ranging from 3.0 to 6.1 mg/L in fertilized plots (120 and 150 lb N/ac rates). Usually NO_3-N concentrations in tile drainage water exceed the EPA drinking water standard of 10 mg/L, especially in years when corn is grown. Nitrate-N concentrations did exceed 10 mg/L during the J-A period in 2019. However, concentrations quickly declined to very low levels (<3.4 mg/L) during the S-N period. Likely due to N uptake in corn, a cool (October and November) and very wet fall and nominal N rates for corn.

Nitrate-N loss in tile drainage was not affected by the main effect of cover crop during any 3-month period or the annual total (Table 6c). When averaged across the main effect of cover crops, NO_3-N loss during the S-N period was significantly greater with 120 and 150 lb N/ac than with the control (3 lb N/ac); whereas, losses were only numerically greater with 120 and 150 lb N/ac than with 3 lb N/ac for the M-M and J-A periods and the annual total. Total loss ranged from 10.4 lb/ac in the control to 16.4 lb/ac with 120 lb N/ac. When averaged across cover crops, flow-adjusted NO_3-N loss was greater with 120 and 150 lb N/ac than with 3 lb N/ac. During this very wet year with greater than 15 inches of tile drainage, flow adjusted NO_3-N loss averaged 1.18 lb/inch of drainage in the 120 and 150 lb N/ac plots. In 2019, cover crops, including cereal rye that was terminated in the spring, did not reduce NO_3-N concentration, loss or flow-adjusted loss in tile drainage water, which is contrary to 2017 and 2018 results.

<u>Tile drainage and nitrate concentrations and loss in 2020 (soybean)</u>

The effects of cover crops and N rates (applied to 2019 corn) on tile flow, FW NO_3-N concentrations, NO_3-N loss and flow adjusted loss in 2020 are presented in Table 6d. Tile flow began on 8 March 2020 (Fig. 6). Averaged across treatments, annual flow totaled 6.74 inches (18% of annual precipitation) with 86% during the period from Mar–Jun and 13% in Jul. Total annual flow ranged from 3.9 to 7.2 inches among treatments (Table 6d, data were log transformed, then back transformed after ANOVA). Due to minimal flow, the S-N period (Sep-Nov) has been left blank in Table 6d and no flow was measured from Dec of 2019 through Feb of 2020. Tile flow was not affected by treatments in 2020.

When averaged across N rates applied for corn in 2019, FW NO_3-N concentrations were about 30% greater with no cover than with rye in M-M and annual avg.; however, concentrations were extraordinarily low and averaged only 2.3 mg/L (Table 6d). Nitrate-N concentrations increased with increasing N rate for the J-A period and were greater with 120 and 150 lb N/ac than with 3 lb for the M-M period and annual avg., when averaged across the main effect of cover crop. A significant cover crop × N rate interaction for FW NO_3-N concentration showed NO_3-N concentrations at 120 lb N/ac were less than at 150 lb N/ac and similar to 3 lb N/ac with rye cover; whereas, with no cover and blend, NO_3-N concentrations were greater with 120 lb N/ac than with 3 lb. Similar to 2018, NO_3-N concentrations in 2020 were quite low in fertilized plots (120 and 150 lb N/ac rates).

Total annual NO_3-N loss from tile drainage ranged from 1.5 to 5.2 lb/ac among treatments in 2020 and was not affected by the main effect of cover crop, when averaged across the N rates for corn (Table 6d). Nitrate-N loss was greater with 120 and 150 lb N/ac than with the control (3 lb N/ac) for the J-A period and the annual total. Significant cover crop × N rate interactions for NO_3-N loss showed NO_3-N losses were greater with 120 than with 150 lb N/ac with blend and no cover; whereas, NO_3-N losses were greatest with 150 lb N/ac with rye cover. These significant interactions are like those observed for FW NO_3-N concentration except for greater tile flow in treatment #2 (no cover with 120 lb N/ac for corn) probably magnified these differences. Flow-adjusted NO_3-N loss was greater with no cover (0.57 lb/inch) than with rye cover (0.44 lb/inch), when averaged across the main effect of N rate for corn. When averaged across cover crops, flow-adjusted NO_3-N loss in tile drainage were greater with 120 and 150 lb N/ac than with 3-lb.

The effects of cover crop treatments, averaged across N rates for corn, and crop rotation on 3-month (seasonal) FW NO_3-N concentrations during the 4-year research study (Sep 2016 through Nov 2020) are presented in Figure 6. Due to the historically wet 2016 (record precipitation and tile flow) FW NO_3-N concentrations were quite low (<4 mg/L) in the S-N 2016 period (S-N16). Cover crops especially cereal rye maintained NO_3-N concentrations at low levels in spring of 2017 (M-M17); whereas, with no cover NO_3-N concentrations increased to nearly 10 mg/L during this corn year. Tile drainage was minimal during the summer and fall of 2017, thus no data. Cereal rye had lower NO_3-N concentrations in M-M18 and J-A18 than with no cover and blend; furthermore, rye had slightly lower NO_3-N concentrations in M-M19, J-A19 and M-M20 than with no cover. Averaged across N rates for corn, FW NO_3-N concentrations peaked near 10 mg/L in J-A19 (corn year) and then declined to about 3 mg/L in S-N19, concentrations remained around 3 mg/L throughout 2020 (soybean year). In summary, these data showed 1) NO_3-N concentrations were < 10 mg/L and often < 5 mg/L throughout this 4-year research study; 2) cover crops, especially cereal rye, can reduce NO_3-N concentrations in tile drainage when well established and not terminated until spring; and 3) NO_3-N concentrations were greater during the corn years than during soybean years.

The influences of treatment main effects (cover crops and N rates) on cumulative NO_3-N loss or load to surface waters are presented in Figure 7. Nearly half of the four-year total NO_3-N loss in this study occurred in 2019, a corn year with considerable tile flow (nearly 14 inches) and moderate NO_3-N concentrations. Nitrate-N loss was minimal in 2017, 2018 and 2020 due to minimal tile flow in 2017, very low NO_3-N concentrations in 2018 and both in 2020. Nitrate-N loss was 1) reduced by cereal rye in 2017; 2) not affected by cover crops in 2018 and 2020; and numerically greater with cereal rye in 2019. This resulted in 4-year cumulative NO_3-N losses totaling 39, 35 and 34 lb/ac for no cover, cereal rye and blend, respectively (Figure 7 top). Nitrogen rates for corn had the greatest effect on NO_3-N losses in the fall of 2018 (soybean year) and summer and fall of 2019 (Figure 7 bottom). Four-year cumulative NO_3-N losses totaled 30, 42 and 36 lb/ac for the 3, 120 and 150 lb/ac N rates, respectively (Figure 7 bottom). These data show the complexity of how treatment and residual effects interact with tile flow and precipitation over time.

Soil inorganic nitrogen

The effects of cover crops and N rates on soil NO_3-N at four soil depths are presented in Tables 7a and 7b. For the fall 2016 sampling, soil NO_3-N was not significantly affected by treatment main effects at any depth. At the 0- to 6-inch depth NO_3-N ranged from 10.6 to 16.3 lb/ac among treatments and was numerically less with cereal rye (11.2 lb/ac) and blend (12.0 lb/ac) compared with no cover (14.5 lb/ac). For the spring 2017 sampling, soil NO_3-N was affected by cover crops at all depths. At 0- to 6-inch depth, soil NO_3-N was greatest with no cover, intermediate with blend and least with rye, when averaged across N rates for corn in 2017 (fertilizer N applied in May and Jun). At the 7- to 12-, 13- to 24-, and 25- to 36-inch depths, cereal rye had significantly less soil NO_3-N than no cover and blend. The 0- to 36-inch total soil NO_3-N was 51.2, 26.2, and 42.5 lb/ac for the no, rye, and blend cover crop treatments, respectively (data not shown). These data showed cereal rye, which was terminated on 17 Apr in 2017, effectively sequestered soil N and thereby reduced the amount of NO_3-N that could be leached via tile drainage in the spring. Only one depth (7- to 12-inch) had significant differences among treatments for the fall 2017 sampling. Soil NO_3-N was less with no cover at 3 lb N/ac compared with rye and blend covers at 3 lb N/ac. Soil NO_3-N was greater in the fall of 2017 than in fall of 2016 and spring of 2017. In spring of 2018, cover crops did not affect soil NO_3-N at any depth, when averaged across N rates applied to corn in 2017 and soil NO_3-N was greater with 120 and 150 lb N/ac than with 3 lb N/ac (control) at all depths except the 0- to 6-inch depth, when averaged across the main effect of cover crop. There were no significant interactions between cover crops and N rates for corn in spring of 2018. Soil NO_3-N in the spring of 2018 was considerably less (about half) than what was measured in the fall of 2017. This suggests residual soil N was lost from fall to spring or had leached below the soil sampling depth. It's unlikely this reduction was due to cover crop treatments because cover crops had no effect on spring 2018 soil NO_3-N.

Cover crops and N rates did not affect soil NO_3-N at any depth in the fall of 2018 (Figure 7b). The lack of treatment effects is reasonable when following soybean and considering the poor cover crop establishment and growth observed in the fall of 2018. Main effects (cover crops and N rates) did not affect soil NO_3-N at any depth in the spring of 2019. However, a significant interaction between main effects at the 25- to 36-inch depth showed soil NO_3-N at 120 lb N/ac was less than the control with no cover and blend but equal with cereal rye. Soil NO_3-N was considerably less in the spring of 2019 than in the fall of 2018, especially in the 0- to 6- and 7- to 12-inch depths. For the fall 2019 sampling, soil NO_3-N influenced treatment main effects and interactions at 3 of the 4 sampling depths. At the 0- to 6- and 7- to 12-inch depths, soil NO_3-N was generally greatest at 120 lb N/ac with no cover, greatest at 150 lb N/ac with cereal rye, and not affected by N rate with blend. At the 25- to - 36-inch depth, soil NO_3-N was greater with 150 lb N/ac than with 3 or 120 lb N/ac, when averaged across the main effect of cover crop. Soil NO_3-N in the spring of 2020 was considerably less than what was measured in the fall of 2019. This suggests residual soil N was lost from fall to spring or had leached below the soil sampling depth during the wet fall of 2019. In the spring of 2020, soil NO_3-N at 0- to 6-inch depth was greater with blend than with no cover or rye, when averaged across N rates for corn in 2019. A significant interaction between main effects at 0- to 6-inch depth showed the blend had greater soil NO_3-N at 3 lb N/ac but similar at other N rates. At the 12- to 24-inch depth, soil NO_3-N was least at 3 lb N/ac, intermediate at 120 lb and greatest at 150 lb. A significant interaction between main effects at the 25- to 36-inch depth showed with each cover crop treatment soil NO_3-N was slightly greatest at a different N rate for corn.

In summary, soil NO_3-N was rarely and inconsistently affected by cover crops. A cereal rye cover reduced soil NO_3-N, in spring of 2017 (at two depths) and spring of 2019 (only deepest depth); however, rye cover increased soil NO_3-N in fall of 2019 (two surface soil depths). Nitrogen rate for corn occasionally and inconsistently affected soil NO_3-N. In the spring of 2018 and fall of 2019, soil NO_3-N generally increased with increasing N rate at most depths.

The effects of cover crops and N rates on total inorganic N (TIN) in soil at four soil depths are presented in Tables 8a and 8b. For fall 2016 sampling, TIN was not significantly affected by treatment main effects at any depth and only small numeric differences were observed among cover crop treatments, when averaged across N rates. For spring 2017 sampling, soil TIN was affected by cover crops at the 0- to 6- and 7- to 12-inch depths. At 0- to 6-inch depth, TIN was greater with no cover than with blend and rye, when averaged across N rates. At the 7- to 12-inch depths, cereal rye had significantly less TIN than no cover and the blend. The 0- to 36-inch total for soil TIN was 78.3, 62.4, and 73.1 lb/ac for the no cover, rye, and blend treatments, respectively. Soil TIN was not affected by treatments at any depth for the fall 2017 sampling. In spring of 2018, treatments did not affect TIN at the 0- to 6- and 7- to 12-inch depths. At the 13- to 24-inch depth, TIN was greater with 120 and 150 lb N/ac for 2017 corn than with the control (3 lb N/ac), when averaged across the main effect of cover crops. Similarly, at the 25- to 36-inch depth TIN was greater with 150 lb N/ac than with 3 and 120 lb N/ac.

In the fall of 2018, TIN was generally not affected by treatment main effects (Table 8b). However, a significant ($P > F = 0.094$) interaction between main effects at the 13- to 24-inch depth showed TIN was greatest with rye cover at 3 lb N/ac and less with rye cover at 120 lb N/ac. No other significant differences were observed; therefore, this barely significant interaction is of little consequence. A significant interaction between main effects at the 25- to 36-inch depth resulted from TIN at 120 lb N/ac being less than the control; whereas, TIN at 120 lb N/ac was equal to the control with cereal rye and blend. Treatment effects and interactions among main effects for soil TIN from the fall of 2019 sampling were nearly identical to those observed for soil NO_3-N which are explained above. Generally, soil TIN was greater in the fall than in spring. Soil TIN was considerably less in the spring of 2020 than fall of 2019 or any other sampling time in this four year study. No significant differences among treatment main effects were found for soil TIN in spring of 2020. A significant interaction between main effects at the 0- to 6-inch depth resulted from TIN at 120 lb N/ac being less than the control with no cover; whereas, TIN at 120 lb N/ac was greatest with cereal rye.

The general lack of consistent treatment effects on soil NO_3-N and TIN can be partly explained by poor cover crop growth, especially in fall of 2017 and spring and fall of 2018. Poor growth was partly due to poor germination of the cover crop in the fall of 2018, but primarily due to cool and wet weather in the fall of 2017, 2018, and 2019 and spring of 2018 and 2019.

Results Summary

Over the last 30+ years, the use of nitrogen BMP's has been the primary strategy for reducing nitrate loss in tile drainage water. A research study was initiated in 2016 to evaluate the potential of cover crops and university recommended N rates for corn as management practices to reduce nitrate loss in tile drainage water. The objective of this research was to measure the effects of two vegetative covers [winter hardy (cereal rye) and winter terminating (blend of annuals)] at various N rates on the following: 1) tile water flow, NO_3-N concentration, and NO_3-N loss in tile drainage water and 2) corn and soybean yields, nitrogen uptake and NUE. Cover crops were overseeded (broadcast) in early Sep (R6 in soybean and R5 in corn) each year beginning in 2016. These research data were greatly influenced by weather during each growing / drainage season. Warm Sep and Oct in 2016 and Apr in 2017 were ideal for cover crop germination and growth, especially cereal rye that was terminated on 17 Apr. In 2017, FW NO_3-N concentrations and flow-adjusted losses were 70 and 20% less with cereal rye and annual blend than no cover, respectively. At the greatest N rate (150 lb N/ac) corn grain yields in 2017 were statistically similar among the three cover crop treatments; however, at the 2016 MRTN rate for corn following soybean (120 lb N/ac) grain yields were reduced compared with 150 lb N/ac in both the no cover and cereal rye treatments. Even though a cold Apr in 2018 (13° F below normal) hindered rye growth, FW NO_3-N concentrations and flow-adjusted losses were about 20% less with cereal rye than no cover. In 2018 (soybean), NO_3-N concentrations and losses increased as N rate for corn in 2017 increased; however, NO_3-N concentrations were quite low (<4 mg/L) and annual losses averaged only 10 lb/ac across the 120 and 150 lb N/ac treatments in this wet year with 12 inches of tile drainage. A wet and cold fall in 2018 and spring in 2019 resulted in very little cover crop growth. Cover crops did not affect FW NO_3-N concentrations, NO_3-N losses or corn grain yields in 2019. Nitrate-N concentrations and losses were greater with fertilized treatments (120 and 150 lb N/ac) than the control. Corn grain yields and N uptake increased with increasing N rates in this very wet year with 48.5 inches of annual precipitation and 14 inches of tile drainage. A warm 2020 with near normal growing season precipitation resulted in 6.7 inches of tile drainage and very low (< 4 mg/L) FW NO_3-N concentrations and minimal loss. A rye cover reduced annual mean FW NO_3-N concentrations about 30% (only 0.6 mg/L) and flow-adjusted NO_3-N loss in 2020. Generally, soybean yields were not or minimally affected by treatments in this study. However, legacy effects from past studies affected yields in one treatment. This study has shown a cereal rye cover crop can reduce NO_3-N in tile drainage water if weather permits adequate cover crop growth. However, rye may interact with corn production requiring a greater N rate to optimize yield. These data suggest annual blend covers that are terminated by cold temperatures in late fall in Minnesota have little value for mitigating nitrate in tile drainage water.

Outreach and Extension Activities

This research information has been presented at several meetings: Ag Expo on 25 Jan 2017, the SROC Agronomy tour on 20 Jun 2017, MCR&PC research update in Shakopee on 7 Sep 2017, Ag Expo on 24 Jan 2018, Stearns Co. Farmers Fair on 7 Mar 2019, North American Farm and Power Show on 14 Mar 2019, the SROC Agronomy tour on 18 Jun 2019, ACS International Annual Meeting on 13 Nov 2019 in San Antonio, Texas, Ag Expo on 23 Jan 2020, Cover Crop podcast on 29 Sep 2020, North Central Soil Fertility Conference (Poster) 19 Nov 2020, MCR&PC Project Update on 9 Dec 2020, and the Drainage Podcast on 10 Feb 2021. Recorded a video update about project and had several media (radio, TV, newspapers, and ag press) interviews. Video can be found here: https://www.youtube.com/watch?v=hqUFNLdiM44
https://blog-crop-news.extension.umn.edu/2021/02/video-can-cover-crops-reduce-nitrate.html

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Table 1a. Monthly total precipitation, mean air temperature, and growing degree units (GDU, base 50/86) as compared to 30-year normal values at Waseca.

		Precipitation		Mean Air Temp.		GDUs	
Month	Year	Observed	Normal†	Observed	Normal†	Observed	Normal†
		----- inches -----		------ ºF ------			
Jan	2016	0.45	1.25	14.8	13.2	-	-
Feb	2016	0.85	1.00	23.5	18.5	-	-
Mar	2016	2.20	2.49	39.3	31.2	-	-
Apr	2016	1.97	3.21	48.4	46.1	-	-
May	2016	3.73	3.93	59.2	58.7	367	332
Jun	2016	4.75	4.69	70.6	68.5	600	538
Jul	2016	8.93	4.42	72.8	72.0	696	655
Aug	2016	11.70	4.75	71.9	69.8	674	597
Sep	2016	14.80	3.67	66.6	61.3	509	348
Oct	2016	3.12	2.67	53.0	48.2	94	20
Nov	2016	1.63	2.16	44.1	32.7	-	-
Dec	2016	2.11	1.48	17.9	17.8	-	-
Apr-Sep	Total	45.87	24.67	64.9	62.7	2845	2470
Annual	Total	56.24	35.72	48.5	45.0	2845	2490
Jan	2017	1.43	1.25	19.4	13.2	-	-
Feb	2017	1.56	1.00	29.4	18.5	-	-
Mar	2017	1.50	2.49	31.6	31.2	-	-
Apr	2017	2.84	3.21	49.1	46.1	-	-
May	2017	5.10	3.93	57.8	58.7	310	332
Jun	2017	4.14	4.69	70.1	68.5	578	538
Jul	2017	6.56	4.42	73.6	72.0	716	655
Aug	2017	3.90	4.75	66.3	69.8	505	597
Sep	2017	2.02	3.67	63.9	61.3	446	348
Oct	2017	4.14	2.67	49.6	48.2	100	20
Nov	2017	0.17	2.16	31.4	32.7	-	-
Dec	2017	0.90	1.48	16.9	17.8	-	-
Apr-Sep	Total	24.58	24.67	63.5	62.7	2556	2470
Annual	Total	34.28	35.72	46.6	45.0	2656	2490
Jan	2018	1.84	1.25	10.9	13.2	-	-
Feb	2018	1.16	1.00	11.0	18.5	-	-
Mar	2018	1.16	2.49	29.1	31.2	-	-
Apr	2018	3.52	3.21	33.1	46.1	-	-
May	2018	5.28	3.93	65.2	58.7	468	332
Jun	2018	5.78	4.69	70.8	68.5	608	538
Jul	2018	4.38	4.42	71.1	72.0	647	655
Aug	2018	4.79	4.75	69.3	69.8	599	597
Sep	2018	10.54	3.67	64.0	61.3	454	348
Oct	2018	3.16	2.67	43.5	48.2	0	20
Nov	2018	1.34	2.16	24.5	32.7	-	-
Dec	2018	2.10	1.48	22.8	17.8	-	-
Apr-Sep	Total	34.29	24.67	62.3	62.7	2775	2470
Annual	Total	45.05	35.72	42.9	45.0	2775	2490

† 30-Yr normal, 1981-2010.

Table 1b. Monthly total precipitation, mean air temperature, and growing degree units (GDU, base 50/86) as compared to 30-year normal values at Waseca.

		Precipitation		Mean Air Temp.		GDUs	
Month	Year	Observed	Normal†	Observed	Normal†	Observed	Normal†
		----- inches -----		------ ºF ------			
Jan	2019	1.28	1.25	11.9	13.2	-	-
Feb	2019	3.03	1.00	6.7	18.5	-	-
Mar	2019	2.01	2.49	24.5	31.2	-	-
Apr	2019	4.25	3.21	44.4	46.1	-	-
May	2019	6.33	3.93	53.6	58.7	217	332
Jun	2019	3.32	4.69	68.4	68.5	550	538
Jul	2019	6.43	4.42	72.6	72.0	692	655
Aug	2019	5.34	4.75	67.4	69.8	540	597
Sep	2019	6.69	3.67	64.8	61.3	457	348
Oct	2019	5.94	2.67	44.0	48.2	72	20
Nov	2019	2.29	2.16	27.9	32.7	-	-
Dec	2019	1.58	1.48	21.0	17.8	-	-
Apr-Sep	Total	32.36	24.67	61.9	62.7	2456	2470
Annual	Total	48.49	35.72	42.3	45.0	2528	2490
Jan	2020	1.62	1.25	18.0	13.2	-	-
Feb	2020	1.14	1.00	15.1	18.5	-	-
Mar	2020	3.34	2.49	34.4	31.2	-	-
Apr	2020	1.53	3.21	42.2	46.1	-	-
May	2020	4.27	3.93	56.7	58.7	296	332
Jun	2020	5.83	4.69	72.2	68.5	641	538
Jul	2020	5.43	4.42	73.2	72.0	706	655
Aug	2020	7.03	4.75	70.3	69.8	626	597
Sep	2020	2.17	3.67	59.5	61.3	327	348
Oct	2020	2.53	2.67	41.0	48.2	6	20
Nov	2020	0.86	2.16	37.3	32.7	-	-
Dec	2020	0.69	1.48	23.4	17.8	-	-
Apr-Sep	Total	26.26	24.67	62.4	62.7	2,596	2470
Annual	Total	36.44	35.72	45.3	45.0	2,602	2490

Table 2. Soybean seed yield in 2016 (setup year), 2018 and 2020 as affected by cover crops and N rates applied for corn.

Cover crop	Nitrogen rates for corn 3	120	150	Mean†
	-------------- 2016 yield, bu/ac --------------			
None	78.4	75.9	76.3	76.9A
Cereal rye	73.7	73.0	75.4	74.1B
Annual blend	72.9	74.2	74.7	73.9B
Mean:	75.0	74.4	75.5	
	-------------- 2018 yield, bu/ac --------------			
None	66.4	63.9	62.3	64.2A
Cereal rye	60.3	59.8	63.1	61.0B
Annual blend	62.8	61.7	61.7	62.1B
Mean:	63.2	61.8	62.4	
	-------------- 2020 yield, bu/ac --------------			
None	80.4a	74.1cd	71.2ef	75.2
Cereal rye	77.2bc	70.5f	73.0de	73.5
Annual blend	78.0ab	73.1def	73.6def	74.9
Mean:	78.5A	72.6B	72.6B	

† Within each row or column uppercase letters indicate significant differences in main effects. Lowercase letters indicate significant interaction of main effects at $P \leq 0.10$.

Table 3a. Cover croop biomass yield, nutrient concentration, and uptake as affected by treatments.

	Treatments		Cover Crop Biomass on 21 Oct. 2016					Cover Crop Biomass on 17 Apr. 2017				
Trt	Cover crop	N rate	Yield	N conc.	P conc.	N uptake	P uptake	Yield	N conc.	P conc.	N uptake	P uptake
#		lb/ac	lb/ac	------------ %	------------	--------- lb/ac	---------	lb/ac	----------- %	-----------	--------- lb/ac	---------
4	Cereal rye	3	173 ab	3.11 bc	0.37	5.4 a	0.63	195	3.64	0.33	6.9	0.66
5	Cereal rye	120	185 ab	3.18 bc	0.38	5.9 a	0.70	170	3.34	0.39	5.7	0.69
6	Cereal rye	150	224 a	2.94 c	0.41	6.5 a	0.96	337	3.30	0.42	10.9	1.42
7	Annual blend	3	77 c	3.40 b	0.38	2.6 b	0.29					
8	Annual blend	120	140 b	3.40 b	0.45	4.8 a	0.68					
9	Annual blend	150	46 c	3.83 a	0.40	1.7 b	0.19					
Stats for RCB Design with a two-factor factorial arrangement												
Cover crop												
Cereal rye			194 A	3.08 B	0.39	5.9 A	0.77 A	234	3.43	0.38	7.8	0.93
Annual blend			88 B	3.54 A	0.41	3.0 B	0.39 B					
P > F:			<0.001	0.001	0.565	<0.001	0.015					
N rate for corn in 2017												
3			125	3.25	0.37	4.0	0.46	195 B	3.64	0.33	6.9 B	0.66 B
120			163	3.29	0.41	5.3	0.69	170 B	3.34	0.39	5.7 B	0.69 B
150			135	3.38	0.41	4.1	0.58	337 A	3.30	0.42	10.9 A	1.42 A
P > F:			0.300	0.617	0.690	0.210	0.421	0.048	0.155	0.351	0.022	0.078
Interaction (cover crop × N rate)												
P > F:			0.046	0.043	0.659	0.091	0.116					

Table 3b. Cover crop dry matter yield, nutrient concentration, and uptake as affected by treatments.

	Treatments		Cover Crop Biomass on 1 Nov 2017					Cover Crop Biomass on 16 May 2018				
Trt	Cover crop	N rate	Yield	N conc.	P conc.	N uptake	P uptake	Yield	N conc.	P conc.	N uptake	P uptake
#		lb/ac	lb/ac	------------ %	------------	--------- lb/ac	---------	lb/ac	----------- %	-----------	--------- lb/ac	---------
4	Cereal rye	3	5.4 bc	3.87	0.51	0.21 bc	0.026 ab	43	2.67	0.50	1.1	0.19
5	Cereal rye	120	4.3 bc	4.37	0.39	0.18 bc	0.016 b	38	3.18	0.54	1.2	0.18
6	Cereal rye	150	13.0 a	4.60	0.40	0.59 a	0.047 a	56	3.23	0.53	1.7	0.30
7	Annual blend	3	9.5 ab	4.17	0.46	0.40 ab	0.044 a					
8	Annual blend	120	3.9 bc	4.76	0.42	0.18 bc	0.018 b					
9	Annual blend	150	2.8 c	4.49	0.37	0.12 c	0.010 b					
Stats for RCB Design with a two-factor factorial arrangement												
Cover crop												
Cereal rye			7.6	4.28	0.43	0.33	0.030	46	3.03	0.52	1.3	0.22
Annual blend			5.4	4.47	0.42	0.23	0.024					
P > F:			0.302	0.301	0.813	0.319	0.519					
N rate for corn in 2017												
3			7.5	4.02 B	0.48	0.30	0.035	43	2.67 B	0.50	1.1	0.19
120			4.1	4.56 A	0.41	0.18	0.017	38	3.18 A	0.54	1.2	0.18
150			7.9	4.54 A	0.39	0.36	0.028	56	3.23 A	0.53	1.7	0.30
P > F:			0.241	0.051	0.297	0.249	0.186	0.689	0.024	0.819	0.586	0.587
Interaction (cover crop × N rate)												
P > F:			0.043	0.427	0.702	0.033	0.054					

Table 3c. Cover crop dry matter yield, nutrient concentration, and uptake as affected by treatments.

Treatments			Cover Crop Biomass, fall 2018					Cover Crop Biomass on 5 May 2019				
Trt	Cover crop	N rate	Yield	N conc.	P conc.	N uptake	P uptake	Yield	N conc.	P conc.	N uptake	P uptake
#		lb/ac	lb/ac	----------- % -----------		--------- lb/ac ---------		lb/ac	---------- % ----------		--------- lb/ac ---------	
4	Cereal rye	3	no data, too small to harvest					39	3.77	0.28	1.5	0.13
5	Cereal rye	120						43	3.77	0.32	1.6	0.14
6	Cereal rye	150						61	3.69	0.31	2.2	0.20
7	Annual blend	3										
8	Annual blend	120										
9	Annual blend	150										
Stats for RCB Design with a two-factor factorial arrangement												
Cover crop												
Cereal rye								48	3.75	0.30	1.8	0.16
Annual blend												
P > F:												
N rate for corn in 2017												
3								39	3.77	0.28	1.5	0.13
120								43	3.77	0.32	1.6	0.14
150								61	3.69	0.31	2.2	0.20
P > F:								0.368	0.927	0.857	0.399	0.687
Interaction (cover crop × N rate)												
P > F:												

† Numbers followed by different letters are significantly different at α = 0.10 level. Capital letters signify differences in main effects and small letters are differences due to interaction between main effects.

Table 3d. Cover crop dry matter yield, nutrient concentration, nitrogen uptake and C:N ratio as affected by treatments.

Treatments			Cover Crop Biomass on 26 Oct 2019					Cover Crop Biomass on 6 May 2020					Cover Crop Biomass on 21 May 2020				
Trt	Cover crop	N rate	Yield	N conc.	C conc.	N uptake	C:N ratio	Yield	N conc.	C conc.	N uptake	C:N ratio	Yield	N conc.	C conc.	N uptake	C:N ratio
#		lb/ac	lb/ac	----------- % -----------		lb/ac		lb/ac	---------- % ----------		lb/ac		lb/ac	------------ % ------------		lb/ac	
4	Cereal rye	3	74	2.56	39.6	1.91	15.6	122	2.39	40.5	2.66	17.7	216	2.08	40.2	4.15	20.0
5	Cereal rye	120	47	3.02	39.8	1.40	13.3	63	2.79	40.7	1.67	14.9	103	3.08	41.3	2.82	13.8
6	Cereal rye	150	47	3.01	39.2	1.42	13.1	96	2.91	41.4	2.75	14.3	143	2.70	41.2	3.61	15.7
7	Annual blend	3	42	2.48	37.0	1.01	15.1										
8	Annual blend	120	23	3.07	37.6	0.68	12.5										
9	Annual blend	150	13	3.07	37.8	0.41	12.4										
Stats for RCB Design with a two-factor factorial arrangement																	
Cover crop																	
Cereal rye			56 A†	2.86	39.5 A	1.58 A	14.0	94	2.70	40.9	2.36	15.6	154	2.62	40.9	3.53	16.5
Annual blend			26 B	2.87	37.5 B	0.70 B	13.3										
P > F:			0.010	0.923	0.031	0.008	0.335										
N rate for corn in 2017																	
3			58 A	2.52 B	38.3	1.46 A	15.3 A	122	2.39	40.5 B	2.66	17.7	216	2.08 B	40.2 B	4.15	20.0 A
120			35 B	3.04 A	38.7	1.04 B	12.9 B	63	2.79	40.7 B	1.67	14.9	103	3.08 A	41.3 A	2.82	13.8 B
150			30 B	3.04 A	38.5	0.91 B	12.8 B	96	2.91	41.4 A	2.75	14.3	143	2.70 AB	41.2 A	3.61	15.7 AB
P > F:			0.009	0.024	0.832	0.042	0.038	0.298	0.333	0.089	0.279	0.231	0.306	0.096	0.052	0.586	0.080
Interaction (cover crop × N rate)																	
P > F:			0.711	0.876	0.729	0.713	0.984										

† Numbers followed by different letters are significantly different at α = 0.10 level. Capital letters signify differences in main effects and small letters are differences due to interaction between main effects.

Table 4a. Corn dry matter yield and N uptake as affected by cover crops and N rates in 2017.

Treatments			V8 Corn Dry Matter Yield			VT-R1 Corn Dry Matter Yield		
Trt	Cover crop	N rate	Yield	N conc.	N uptake	Yield	N conc.	N uptake
#		lb/ac	lb/ac	%	lb/ac	lb/ac	%	lb/ac
1	None	3	1105	2.28	25.3	5715 c^	1.11 d	63.3 d
2	None	120	1296	3.71	47.9	6720 ab	1.40 c	93.8 c
3	None	150	1252	3.75	46.9	7056 ab	1.58 ab	111.6 ab
4	Cereal rye	3	607	2.20	13.4	3653 e	0.98 de	35.9 e
5	Cereal rye	120	933	3.77	35.1	6405 bc	1.51 bc	95.8 bc
6	Cereal rye	150	923	3.86	35.6	7254 ab	1.57 ab	115.7 a
7	Annual blend	3	820	2.17	18.2	4502 d	0.95 e	42.9 e
8	Annual blend	120	1230	3.69	45.2	7357 a	1.55 ab	114.7 a
9	Annual blend	150	1077	3.68	39.6	6990 ab	1.67 a	116.8 a
Statistical significance of treatment main effects for a two-factor factorial arrangement								
Cover crop								
No cover			1217 A	3.25	40.0 A	6497 A	1.36	89.6
Cereal rye			821 C	3.27	28.0 C	5771 B	1.35	82.5
Annual blend			1042 B	3.18	34.4 B	6283 AB	1.39	91.5
P > F:			0.005	0.259	0.007	0.089	0.785	0.341
N rate for corn								
3			844 B	2.22 B	19.0 B	4623 B	1.01 C	47.4 C
120			1153 A	3.72 A	42.7 A	6827 A	1.49 B	101.4 B
150			1084 A	3.76 A	40.7 A	7100 A	1.61 A	114.7 A
P > F:			0.012	<0.001	<0.001	<0.001	<0.001	<0.001
Interaction (cover crop × N rate)								
P > F:			0.709	0.500	0.838	0.026	0.100	0.004

^ Numbers followed by different letters are significantly different at α = 0.10 level. Capital letters signify differences in main effects and small letters are differences due to interaction between main effects.

Table 4b. Corn dry matter yield and N uptake as affected by cover crops and N rates in 2019.

Treatments			V8 Corn Dry Matter Yield			VT-R1 Corn Dry Matter Yield		
Trt	Cover crop	N rate	Yield	N conc.	N uptake	Yield	N conc.	N uptake
#		lb/ac	lb/ac	%	lb/ac	lb/ac	%	lb/ac
1	None	3	804	2.15	17.5	5408	0.88	56.6
2	None	120	1360	3.45	46.9	8204	1.14	94.9
3	None	150	1484	3.48	51.9	8833	1.19	105.0
4	Cereal rye	3	721	2.18	15.7	5408	0.80	42.5
5	Cereal rye	120	1290	3.51	45.2	8204	1.05	85.8
6	Cereal rye	150	1327	3.61	48.0	9041	1.16	105.5
7	Annual blend	3						
8	Annual blend	120						
9	Annual blend	150						
Statistical significance of treatment main effects for a two-factor factorial arrangement								
Cover crop								
No cover			1216	3.02	38.8	7482	1.07	85.5
Cereal rye			1113	3.10	36.3	7551	1.00	77.9
Annual blend								
P > F:			0.437	0.382	0.588	0.448	0.455	0.402
N rate for corn								
3			762 B^	2.16 B	16.6 B	5408 B	0.84 B	49.6 C
120			1325 A	3.48 A	46.1 A	8204 A	1.09 A	90.3 B
150			1405 A	3.54 A	49.9 A	8937 A	1.17 A	105.3 A
P > F:			0.008	<0.001	0.001	<0.001	0.003	<0.001
Interaction (cover crop × N rate)								
P > F:			0.813	0.858	0.949	0.375	0.831	0.449

^ Numbers followed by different letters are significantly different at α = 0.10 level. Capital letters signify differences in main effects and small letters are differences due to interaction between main effects.

Table 5a. Corn production and nitrogen use efficiency parameters as affected by cover crops and N rates in 2017.

Trt	Treatments: Cover crop	Treatments: N rate	Grain H_2O	Grain Yield	Relative Grain Yield	Cob Yield	Stover Yield	Silage Yield	Stover [N]	Grain [N]	Nitrogen uptake: Stover	Nitrogen uptake: Grain	Nitrogen uptake: Total	Relative Leaf Chlor.	Final Plant Pop.	NUE PFP	NUE AE
#		lb/ac	%	bu/ac	%	-----------	tdm/a	-----------	%	%	---------	lb N/ac	---------	%	pl*10^3/ac	bushel/lb N	
1	None	3	17.5 d^	154 d	60.5 d	0.48 c	2.80 b	6.92 d	0.30	0.97	16.8	70 d	87 e	72.7 c	33.8		
2	None	120	18.0 cd	240 b	94.6 b	0.61 b	3.41 a	9.70 bc	0.45	1.16	30.9	132 b	163 bc	99.0 ab	34.1	2.00	0.72
3	None	150	18.4 bc	254 a	100.0 a	0.66 a	3.50 a	10.17 a	0.51	1.20	35.4	144 a	179 a	99.0 ab	33.8	1.69	0.67
4	Cereal rye	3	19.3 a	108 f	42.5 f	0.36 e	2.08 c	5.00 f	0.27	0.95	11.1	49 e	60 f	67.1 d	33.9		
5	Cereal rye	120	18.8 ab	226 c	89.1 c	0.62 b	3.45 a	9.43 c	0.40	1.12	27.5	120 c	147 d	97.6 b	33.9	1.89	0.99
6	Cereal rye	150	18.5 bc	247 ab	97.2 ab	0.64 ab	3.35 a	9.84 ab	0.45	1.19	30.3	139 ab	169 bc	98.7 ab	33.5	1.65	0.93
7	Annual blend	3	18.6 bc	120 e	47.1 e	0.41 d	2.16 c	5.40 e	0.30	0.98	13.1	55 e	69 f	71.9 c	34.0		
8	Annual blend	120	18.5 bc	244 b	95.9 b	0.64 ab	3.41 a	9.81 abc	0.39	1.16	26.2	133 b	159 c	98.7 ab	33.9	2.03	1.03
9	Annual blend	150	18.4 bc	247 ab	97.3 ab	0.62 ab	3.35 a	9.83 ab	0.46	1.17	30.8	137 ab	168 b	100.0 a	33.9	1.65	0.85
Statistical significance of treatment main effects for a two-factor factorial arrangement																	
Cover crop																	
No cover			18.0 B	216 A	85.0 A	0.58 A	3.24 A	8.93 A	0.42 A	1.11	27.7 A	115 A	143 A	90.2 A	33.9	1.85	0.69
Cereal rye			18.9 A	194 C	76.3 C	0.54 B	2.96 B	8.09 B	0.37 B	1.08	23.0 B	102 B	125 B	87.8 B	33.8	1.77	0.96
Annual blend			18.5 A	203 B	80.1 B	0.56 AB	2.98 B	8.35 B	0.38 B	1.10	23.4 B	109 AB	132 B	90.2 A	34.0	1.84	0.94
P > F:			0.008	0.008	0.008	0.070	0.007	0.007	0.059	0.491	0.014	0.047	0.030	0.011	0.563		
N rate for corn																	
3			18.5	127 C	50.1 C	0.42 B	2.35 B	5.77 C	0.29 C	0.97 C	13.7 C	58 C	72 C	70.6 B	33.9		
120			18.4	237 B	93.2 B	0.62 A	3.42 A	9.64 B	0.41 B	1.14 B	28.2 B	128 B	156 B	98.4 A	33.9	1.97	0.91
150			18.4	249 A	98.2 A	0.64 A	3.40 A	9.94 A	0.47 A	1.19 A	32.1 A	140 A	172 A	99.2 A	33.7	1.66	0.81
P > F:			0.964	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.492		
Interaction (cover crop × N rate)																	
P > F:			0.017	<0.001	<0.001	0.002	<0.001	<0.001	0.500	0.193	0.840	0.003	0.023	0.003	0.612		

^ Numbers followed by different letters are significantly different at α = 0.10 level. Capital letters signify differences in main effects and small letters are differences due to interaction between main effects.

Table 5b. Corn production and nitrogen use efficiency parameters as affected by cover crops and N rates in 2019.

	Treatments		Grain	Grain	Relative Grain	Cob	Stover	Silage	Stover	Grain	Nitrogen uptake			Relative Leaf	Final Plant	NUE	NUE
Trt	Cover crop	N rate	H_2O	Yield	Yield	Yield	Yield	Yield	[N]	[N]	Stover	Grain	Total	Chlor.	Pop.	PFP	AE
#		lb/ac	%	bu/ac	%	----------- tdm/a -----------			%	%	--------- lb N/ac ---------			%	pl*10^3/ac	bushel/lb N	
1	None	3	22.3	84	45.4	0.25	1.56	3.78	0.47	0.87	14.5	34	49	66.7	30.8		
2	None	120	18.3	167	89.8	0.49	3.01	7.43	0.54	1.07	32.7	85	117	93.7	32.3	1.39	0.64
3	None	150	18.3	182	98.0	0.54	3.22	8.07	0.57	1.17	36.6	101	137	99.5	32.7	1.22	0.65
4	Cereal rye	3	22.5	90	48.6	0.30	1.77	4.20	0.40	0.87	14.1	37	51	66.0	32.9		
5	Cereal rye	120	18.2	177	94.9	0.55	3.17	7.89	0.48	1.17	30.6	97	128	94.8	33.1	1.47	0.72
6	Cereal rye	150	19.3	186	100.0	0.57	3.22	8.19	0.63	1.12	40.8	99	139	98.1	32.9	1.24	0.64
7	Annual blend	3	22.3	87	46.5	0.27	1.74	4.06	0.45	0.96	15.5	39	55	65.2	32.8		
8	Annual blend	120	18.6	177	94.9	0.51	3.17	7.85	0.55	1.08	34.6	90	125	94.1	33.0	1.47	0.75
9	Annual blend	150	19.6	185	99.3	0.53	3.19	8.09	0.59	1.28	37.6	112	149	97.7	32.9	1.23	0.65
Statistical significance of treatment main effects for a two-factor factorial arrangement																	
Cover crop																	
No cover			19.6	145	77.7	0.42 B	2.59	6.43	0.53	1.04	27.9	73	101	86.6	32.0 B	1.30	0.64
Cereal rye			20.0	151	81.2	0.47 A	2.72	6.76	0.50	1.05	28.5	78	106	86.3	32.9 A	1.36	0.68
Annual blend			20.1	149	80.3	0.44 B	2.70	6.67	0.53	1.10	29.2	80	110	85.6	32.9 A	1.35	0.70
P > F:			0.496	0.417	0.415	0.047	0.346	0.170	0.567	0.286	0.837	0.273	0.328	0.702	0.076		
N rate for corn																	
3			22.4 A	87 C	46.8 C	0.27 C	1.69 B	4.01 C	0.44 C	0.90 C	14.7 C	37 C	51 C	65.9 C	32.2		
120			18.4 C	173 B	93.2 B	0.52 B	3.11 A	7.73 B	0.52 B	1.11 B	32.6 B	91 B	123 B	94.2 B	32.8	1.44	0.70
150			19.1 B	184 A	99.1 A	0.55 A	3.21 A	8.11 A	0.60 A	1.19 A	38.4 A	104 A	142 A	98.4 A	32.8	1.23	0.65
P > F:			<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.002	<0.001	<0.001	<0.001	<0.001	<0.001	0.310		
Interaction (cover crop × N rate)																	
P > F:			0.243	0.875	0.876	0.878	0.752	0.835	0.152	0.196	0.489	0.334	0.843	0.817	0.323		

^ Numbers followed by different letters are significantly different at α = 0.10 level. Capital letters signify differences in main effects and small letters are differences due to interaction between main effects.

Table 6a. Tile flow, flow-wieghted NO_3-N concentration, NO_3-N loss, and flow-adjusted loss as affected by treatments in 2017.

	Cover	N application		Tile flow			Flow-weighted NO_3-N			NO_3-N lost			Flow adj.
Trt	Crop	Planting	V4	Pre†	Post	Total	Pre	Post	Average	Pre	Post	Total	NO_3 loss
#		---- lb/ac ----		------ inch ------			------ mg/L ------			------ lb/ac ------			lb/inch
1	None	3	0	1.0	2.8	3.8	6.4	8.8	8.4	1.4	5.5	6.9	1.8
2	None	30	90	1.3	3.5	4.8	8.3	9.5	9.3	2.4	7.2	9.5	2.0
3	None	30	120	0.5	1.8	2.3	7.3	9.1	8.8	0.8	3.7	4.4	1.9
4	Rye	3	0	1.6	3.9	5.5	2.8	2.7	2.8	1.0	2.7	3.7	0.7
5	Rye	30	90	1.0	3.1	4.1	2.7	2.5	2.5	0.5	1.7	2.2	0.5
6	Rye	30	120	1.6	3.5	5.1	3.0	2.3	2.4	0.8	1.8	2.6	0.5
7	Blend	3	0	1.0	3.0	4.1	5.8	5.8	5.8	1.2	3.7	4.8	1.2
8	Blend	30	90	1.4	3.2	4.6	6.4	8.3	7.8	2.2	5.7	7.9	1.7
9	Blend	30	120	0.8	2.4	3.2	5.8	7.2	6.9	1.0	3.9	4.9	1.5
Stats for RCB Design with a two-factor factorial arrangement													
Cover crop													
No cover				0.9	2.7	3.6	7.3 A‡	9.1 A	8.8 A	1.5	5.4 A	6.9	1.9 A
Cereal rye				1.4	3.5	4.9	2.8 C	2.5 C	2.6 C	0.8	2.1 B	2.8	0.6 C
Annual blend				1.1	2.9	4.0	6.0 B	7.1 B	6.8 B	1.5	4.4 AB	5.9	1.5 B
P > F:				0.352	0.405	0.378	0.001	<0.001	<0.001	0.343	0.093	0.130	<0.001
N rate for corn													
3				1.2	3.3	4.4	5.0	5.8	5.7	1.2	4.0	5.1	1.2
120				1.2	3.2	4.5	5.8	6.8	6.5	1.7	4.9	6.6	1.4
150				1.0	2.6	3.6	5.4	6.2	6.0	0.9	3.1	4.0	1.3
P > F:				0.786	0.615	0.666	0.318	0.115	0.198	0.507	0.451	0.463	0.194
Interaction (cover crop × N rate)													
P > F:				0.365	0.704	0.586	0.591	0.147	0.292	0.379	0.534	0.476	0.291

† Pre N applicatoin period (Feb - 7 May), Post (8 May - Nov).

‡ Numbers followed by different letters are significantly different at α = 0.10 level. Capital letters signify differences in main effects and small letters are differences due to interaction between main effects.

Table 6b. Tile flow, flow-wieghted NO_3-N concentration, NO_3-N loss, and flow-adjusted loss during 3-month periods as affected by treatments in 2018.

	Cover	N application		Tile flow				Flow-weighted NO_3-N				NO_3-N lost				Flow adj.
Trt	Crop	Planting	V4	M-M†	J-A	S-N	Total	M-M	J-A	S-N	Avg.	M-M	J-A	S-N	Total	NO_3 loss
#		---- lb/ac ----		------------- inch -------------				------------- mg/L -------------				------------- lb/ac -------------				lb/inch
1	None	3	0	2.3	1.0	5.3	8.9	1.9 e‡	1.2 d	1.4 b	1.6 d	1.0 c	0.3 d	1.7 d	3.1 d	0.35 d
2	None	30	90	2.8	1.9	7.3	12.6	4.6 ab	5.4 a	3.1 a	3.9 ab	3.0 a	2.3 ab	5.1 a	11.1 a	0.88 ab
3	None	30	120	2.9	1.6	6.4	11.1	5.3 a	6.5 a	3.4 a	4.4 a	3.4 a	2.3 ab	4.9 a	11.1 a	1.00 a
4	Rye	3	0	4.3	2.5	8.0	15.1	2.6 d	1.7 c	1.5 b	1.9 cd	2.6 a	1.0 bc	2.8 bc	6.5 bc	0.43 cd
5	Rye	30	90	3.9	2.1	7.7	14.0	2.5 de	2.8 b	1.7 b	2.1 c	2.2 ab	1.3 abc	3.0 bc	6.8 bc	0.48 c
6	Rye	30	120	4.4	2.4	7.7	14.7	3.8 bc	4.8 a	2.8 a	3.4 b	3.7 a	2.6 a	4.9 a	11.4 a	0.78 b
7	Blend	3	0	2.3	1.5	6.5	10.7	2.9 cd	2.3 bc	1.8 b	2.1 c	1.5 bc	0.8 c	2.6 c	5.2 c	0.48 c
8	Blend	30	90	3.2	1.9	6.6	12.0	4.4 ab	4.8 a	2.7 a	3.6 ab	3.2 a	2.1 ab	4.1 ab	9.7 ab	0.81 ab
9	Blend	30	120	2.9	1.6	6.3	11.0	4.3 ab	5.2 a	2.5 a	3.4 b	2.8 a	1.9 ab	3.6 abc	8.5 ab	0.77 b
Stats for RCB Design with a two-factor factorial arrangement																
Cover crop																
No cover				2.7 B	1.4	6.3 B	10.8 B	3.6 A	3.4 AB	2.4	3.0 A	2.2	1.1	3.5	7.3	0.68 A
Cereal rye				4.2 A	2.3	7.8 A	14.6 A	2.9 B	2.9 B	2.0	2.4 B	2.8	1.5	3.5	8.0	0.55 B
Annual blend				2.8 B	1.7	6.4 B	11.2 B	3.8 A	3.9 A	2.3	3.0 A	2.4	1.5	3.4	7.5	0.67 A
P > F:				0.022	0.134	0.025	0.037	0.048	0.082	0.121	0.046	0.434	0.478	0.965	0.810	0.046
N rate for corn																
3				2.8	1.5	6.5	11.3	2.5 B	1.7 C	1.6 B	1.9 C	1.6 B	0.6 B	2.3 B	4.7 B	0.42 C
120				3.3	2.0	7.2	12.9	3.7 A	4.2 B	2.4 A	3.1 B	2.8 A	1.9 A	4.0 A	9.0 A	0.70 B
150				3.3	1.8	6.8	12.2	4.4 A	5.4 A	2.9 A	3.7 A	3.3 A	2.2 A	4.4 A	10.3 A	0.84 A
P > F:				0.500	0.655	0.431	0.556	0.004	<0.001	0.002	0.001	0.021	0.010	0.009	0.010	0.001
Interaction (cover crop × N rate)																
P > F:				0.729	0.564	0.216	0.518	0.001	0.007	0.048	0.005	0.053	0.086	0.028	0.026	0.005

† Three-month preiods M-M (Mar - May), J-A (Jun - Aug), S-N (Sep - Nov), no measured flow during winter period (Dec - Feb).

‡ Numbers followed by different letters are significantly different at α = 0.10 level. Capital letters signify differences in main effects and small letters are differences due to interaction between main effects.

Table 6c. Tile flow, flow-wieghted NO_3-N concentration, NO_3-N loss, and flow-adjusted loss during 3-month periods as affected by treatments in 2019.

Trt	Cover Crop	N application Planting	N application V4	Tile flow M-M†	Tile flow J-A	Tile flow S-N	Tile flow Total	Flow-weighted NO_3-N M-M	Flow-weighted NO_3-N J-A	Flow-weighted NO_3-N S-N	Flow-weighted NO_3-N Avg.	NO_3-N lost M-M	NO_3-N lost J-A	NO_3-N lost S-N	NO_3-N lost Total	Flow adj. NO_3 loss
#		---- lb/ac ----		------------- inch -------------				------------- mg/L -------------				------------- lb/ac -------------				lb/inch
1	None	3	0	2.9	1.1	4.1	14.4	5.2	7.2 d	2.0	3.9	3.4	1.9	1.8	7.2	0.87
2	None	30	90	5.7	2.0	6.5	16.8	6.5	10.1 abc	3.7	5.7	8.5	4.5	5.5	18.7	1.30
3	None	30	120	4.0	1.1	4.9	8.3	7.2	11.3 a	3.6	5.9	6.6	2.9	3.9	13.6	1.34
4	Rye	3	0	6.8	2.6	7.2	14.8	4.7	7.2 d	1.9	3.9	7.2	4.1	3.0	14.7	0.87
5	Rye	30	90	6.0	1.7	6.8	15.0	4.9	9.5 abc	2.4	4.3	6.7	3.7	3.7	14.3	0.96
6	Rye	30	120	6.3	2.1	6.4	10.1	5.4	9.3 bc	3.9	5.4	7.7	4.5	5.7	18.3	1.22
7	Blend	3	0	4.2	1.6	5.2	11.2	5.3	7.4 d	2.2	4.1	5.1	2.7	2.6	10.6	0.94
8	Blend	30	90	5.7	1.8	5.5	13.2	6.2	10.7 ab	3.1	5.5	8.0	4.3	3.8	16.4	1.25
9	Blend	30	120	5.4	1.5	5.5	12.7	5.9	8.9 c	2.8	4.9	7.2	3.0	3.5	14.1	1.11
Stats for RCB Design with a two-factor factorial arrangement																
Cover crop																
No cover				4.1	1.4	5.1 B	10.6 B	6.3	9.3	3.0	5.1	5.7	2.9	3.4	12.3	1.15
Cereal rye				6.4	2.1	6.8 A	15.5 A	5.0	8.6	2.6	4.5	7.2	4.1	4.0	15.7	1.01
Annual blend				5.1	1.6	5.4 B	12.3 AB	5.8	8.9	2.7	4.8	6.6	3.2	3.3	13.5	1.09
P > F:				0.105	0.166	0.091	0.091	0.116	0.437	0.416	0.246	0.514	0.291	0.466	0.385	0.246
N rate for corn																
3				4.4	1.7	5.4	11.6	5.1 B	7.2 B	2.0 B	4.0 B	5.0	2.8	2.4 B	10.4	0.89 B
120				5.8	1.8	6.2	14.1	5.8 AB	10.1 A	3.0 A	5.1 A	7.7	4.1	4.2 A	16.4	1.16 A
150				5.2	1.5	5.6	12.4	6.1 A	9.8 A	3.4 A	5.4 A	7.2	3.4	4.3 A	15.2	1.22 A
P > F:				0.432	0.791	0.542	0.555	0.096	0.004	0.004	0.016	0.213	0.369	0.083	0.199	0.016
Interaction (cover crop × N rate)																
P > F:				0.474	0.409	0.435	0.435	0.536	0.097	0.107	0.236	0.369	0.397	0.139	0.260	0.236

† Three-month preiods M-M (Mar - May), J-A (Jun - Aug), S-N (Sep - Nov), no measured flow during winter period (Dec - Feb).

‡ Numbers followed by different letters are significantly different at α = 0.10 level. Capital letters signify differences in main effects and small letters are differences due to interaction between main effects.

Table 6d. Tile flow, flow-wieghted NO_3-N concentration, NO_3-N loss, and flow-adjusted loss during 3-month periods as affected by treatments in 2020.

	Cover	N application		Tile flow				Flow-weighted NO_3-N				NO_3-N lost				Flow adj.
Trt	Crop	Planting	V4	M-M†	J-A	S-N	Total	M-M	J-A	S-N	Avg.	M-M	J-A	S-N	Total	NO_3 loss
#		---- lb/ac ----		------------- inch -------------				------------- mg/L -------------				------------- lb/ac -------------				lb/inch
1	None	3	0	2.6	1.2	ID	3.9	1.9 bc‡	1.2	ID	1.7	1.1	0.3 e	ID	1.5 d	0.38
2	None	30	90	4.4	2.6		7.2	3.1 a	3.2		3.2	3.2	1.9 a		5.2 a	0.72
3	None	30	120	2.4	1.9		4.3	2.9 a	3.2		3.1	1.6	1.4 abc		3.0 abcd	0.69
4	Rye	3	0	4.2	2.7		7.0	1.5 c	1.3		1.5	1.5	0.8 bcd		2.3 bcd	0.33
5	Rye	30	90	3.4	2.0		5.4	1.6 c	1.8		1.7	1.2	0.8 bcd		2.1 cd	0.38
6	Rye	30	120	4.4	2.4		6.8	2.8 a	3.1		3.0	2.8	1.7 abc		4.5 ab	0.67
7	Blend	3	0	2.9	1.6		4.6	1.7 c	1.5		1.6	1.1	0.5 de		1.7 d	0.37
8	Blend	30	90	4.3	2.2		6.6	2.5 a	2.5		2.5	2.5	1.3 abc		3.7 abc	0.57
9	Blend	30	120	2.8	1.2		4.1	2.4 ab	2.8		2.5	1.5	0.8 cd		2.3 bcd	0.57
Stats for RCB Design with a two-factor factorial arrangement																
Cover crop																
No cover				3.0	1.8		4.9	2.6 A	2.3		2.5 A	1.8	1.0		2.8	0.57 A
Cereal rye				4.0	2.3		6.4	1.9 B	2.0		1.9 B	1.7	1.0		2.8	0.44 B
Annual blend				3.3	1.7		5.0	2.2 AB	2.2		2.2 AB	1.6	0.8		2.4	0.49 AB
P > F:				0.432	0.203		0.372	0.044	0.362		0.081	0.922	0.581		0.763	0.081
N rate for corn																
3				3.2	1.8		5.0	1.7 B	1.3 C		1.6 B	1.2	0.5 B		1.8 B	0.36 B
120				4.1	2.3		6.4	2.3 A	2.4 B		2.4 A	2.1	1.2 A		3.4 A	0.54 A
150				3.1	1.8		4.9	2.7 A	3.1 A		2.8 A	1.9	1.2 A		3.2 A	0.64 A
P > F:				0.442	0.415		0.432	0.006	0.001		0.002	0.222	0.044		0.117	0.002
Interaction (cover crop × N rate)																
P > F:				0.439	0.123		0.347	0.066	0.183		0.117	0.100	0.052		0.093	0.118

† Three-month preiods M-M (Mar - May), J-A (Jun - Aug), S-N (Sep - Nov), no measured flow during winter period (Dec - Feb).

‡ Numbers followed by different letters are significantly different at α = 0.10 level. Capital letters signify differences in main effects and small letters are differences due to interaction between main effects.

ID Insufficient data (tile flow and nitrate samples) for statistical analysis.

Table 7a. Soil nitrate-N by depth as affected by cover crop species, nitrogen rate for corn, and sampling date.

	Fall 2016				Spring 2017				Fall 2017				Spring 2018			
	3†	120	150	Mean	3	120	150	Mean	3	120	150	Mean	3	120	150	Mean
	---------- NO_3-N, lb/ac ----------															
	0- to 6-inch depth															
Cover crop																
None	14.1	16.3	13.2	14.5	13.8	10.7	11.7	12.0A†	14.6	17.4	20.4	17.5	7.0	7.1	6.8	6.9
Cereal rye	11.8	10.6	11.0	11.2	7.1	5.6	5.2	6.0C	13.9	19.6	16.8	16.8	6.3	7.8	7.2	7.1
Blend	13.0	12.0	10.8	12.0	9.0	9.7	9.6	9.5B	14.9	16.5	21.8	17.7	6.6	6.5	6.4	6.5
Mean:	13.0	13.0	11.7		10.0	8.6	8.9		14.5	17.8	19.7		6.6	7.1	6.8	
	7- to 12-inch depth															
None	12.0	13.5	14.8	13.4	12.2	10.6	12.5	11.8A	10.0b	16.0a	19.0a	15.0	5.0	8.7	7.7	7.1
Cereal rye	11.6	10.9	11.3	11.3	5.9	6.0	5.1	5.7B	16.9a	17.9a	13.9ab	16.2	6.2	7.1	7.3	6.9
Blend	13.4	12.3	12.7	12.8	10.5	10.7	10.8	10.6A	15.6a	16.8a	14.9ab	15.7	6.3	7.5	7.7	7.1
Mean:	12.3	12.2	12.9		9.5	9.1	9.5		14.2	16.9	16.0		5.8B	7.8A	7.6A	
	13- to 24-inch depth															
None	14.8	16.9	16.7	16.1	16.3	14.7	15.8	15.6A	24.2	28.1	36.4	29.6	6.5	15.3	15.4	12.4
Cereal rye	16.2	17.6	15.8	16.5	11.6	6.9	5.6	8.0B	27.5	27.3	26.5	27.1	8.0	10.8	11.2	10.0
Blend	16.0	14.8	15.2	15.4	13.4	11.7	12.5	12.6A	27.5	26.3	30.6	28.1	9.3	11.8	15.7	12.3
Mean:	15.7	16.5	15.9		13.8	11.1	11.3		26.4	27.2	31.2		7.9B	12.6A	14.1A	
	25- to 36-inch depth															
None	13.9	14.9	15.8	14.9	12.0	11.5	11.8	11.8A	20.8	24.2	24.0	23.0	4.9	8.6	10.8	8.1
Cereal rye	16.2	12.7	14.1	14.4	6.9	5.9	6.7	6.5B	26.0	27.5	24.3	25.9	4.1	7.3	10.0	7.1
Blend	14.1	13.7	14.4	14.1	11.1	10.4	7.8	9.8A	26.5	16.0	19.8	20.8	5.4	6.4	11.8	7.9
Mean:	14.8	13.8	14.8		10.0	9.3	8.7		24.4	22.5	22.7		4.8C	7.4B	10.9A	

† Nitrogen fertilizer rate for corn in 2017, lb N/ac.

‡ Numbers followed by different letters are significantly different at α=0.10 level. Capital letters signify differences in main effects and small letters are differences due to interaction between main effects.

Table 7b. Soil nitrate-N by depth as affected by cover crop species, nitrogen rate for corn, and sampling date.

	Fall 2018				Spring 2019				Fall 2019				Spring 2020			
	3†	120	150	Mean	3	120	150	Mean	3	120	150	Mean	3	120	150	Mean
	------------------------- NO_3-N, lb/ac -------------------------															
	0- to 6-inch depth															
Cover crop																
None	20.4	19.9	19.5	19.9	8.1	6.8	8.9	7.9	14.0c	22.7a	15.1bc	17.2	6.4b	6.6b	6.6ab	6.2B
Cereal rye	20.7	20.3	22.8	21.3	10.6	9.6	8.3	9.5	14.7bc	17.6b	22.9a	18.4	6.4b	6.3b	6.9ab	6.2B
Blend	22.4	20.1	18.0	20.2	9.8	9.0	9.2	9.3	16.1bc	14.8bc	17.4b	16.1	7.0a	6.7ab	6.8ab	7.2A
Mean:	21.2	20.1	20.1		9.5	8.4	8.8		14.9B	18.3A	18.4A		6.6	6.2	6.8	
	7- to 12-inch depth															
None	14.2	17.2	14.5	15.3	8.6	7.3	8.5	8.1	10.3c	15.9b	13.8bc	13.4	4.5	5.8	6.6	5.6
Cereal rye	15.2	15.4	16.8	15.8	8.5	8.3	8.0	8.2	13.5bc	17.3b	25.2a	18.7	6.4	5.7	6.4	6.2
Blend	16.9	15.0	17.6	16.5	9.0	8.7	9.8	9.2	17.8b	14.4bc	16.1b	16.1	7.4	6.4	6.1	6.7
Mean:	15.4	15.9	16.3		8.7	8.1	8.8		13.9B	15.8AB	18.4A		6.1	6.0	6.4	
	13- to 24-inch depth															
None	23.1	26.4	22.2	23.9	20.3	17.2	18.7	18.7	19.4	29.0	25.0	24.5	7.1	6.9	9.5	7.8
Cereal rye	22.9	17.4	27.0	22.4	18.4	17.9	18.3	18.2	20.6	21.9	31.2	24.5	5.5	9.0	8.2	7.6
Blend	23.4	22.8	22.5	22.9	19.3	18.4	20.4	19.4	21.5	25.3	20.1	22.3	5.4	6.2	7.9	6.5
Mean:	23.1	22.2	23.9		19.4	17.8	19.1		20.5	25.4	25.4		6.0B	7.4AB	8.5A	
	25- to 36-inch depth															
None	16.2	16.5	14.5	15.7	17.8ab	11.8d	18.4a	16.0	19.7	17.9	26.7	21.4	5.6ab	3.0b	4.0b	4.2
Cereal rye	17.0	13.8	19.6	16.8	16.7abc	16.0abc	14.6bcd	15.8	18.7	15.8	27.2	20.6	3.6b	7.5a	4.2b	5.1
Blend	17.3	15.1	17.6	16.6	17.8ab	13.3cd	19.9a	17.0	18.8	19.3	21.7	19.9	4.1b	3.2b	4.8ab	4.0
Mean:	16.8	15.1	17.3		17.5	13.7	17.6		19.1B	17.7B	25.2A		4.4	4.5	4.3	

† Nitrogen fertilizer rate for corn in 2017 and 2019, lb N/ac.

‡ Numbers followed by different letters are significantly different at α=0.10 level. Capital letters signify differences in main effects and small letters are differences due to interaction between main effects.

Table 8a. Soil total inorganic-N by depth as affected by cover crop species, nitrogen rate for corn, and sampling date.

	Fall 2016				Spring 2017				Fall 2017				Spring 2018			
	3†	120	150	Mean	3	120	150	Mean	3	120	150	Mean	3	120	150	Mean
	---------- Total inorganic-N, lb/ac ----------															
	0- to 6-inch depth															
Cover crop																
None	21.3	27.2	21.9	23.5	20.8	19.4	20.4	20.2A‡	21.2	26.2	26.6	24.7	19.2	18.5	16.7	18.1
Cereal rye	24.0	20.8	20.8	21.8	17.4	16.0	13.2	15.5B	21.2	30.7	25.8	25.9	16.9	18.8	18.6	18.1
Blend	23.1	21.0	19.8	21.3	17.4	17.1	17.9	17.4AB	23.6	23.7	30.0	25.7	17.8	16.4	17.2	17.1
Mean:	22.8	23.0	20.8		18.5	17.5	17.2		22.0	26.9	27.4		18.0	17.9	17.5	
	7- to 12-inch depth															
None	18.4	20.9	23.7	21.0	17.1	15.9	17.2	16.8A	13.8	21.4	24.0	19.7	12.9	16.7	15.0	14.8
Cereal rye	19.5	18.1	15.7	17.8	11.8	14.7	9.9	12.1B	21.4	22.8	17.3	20.5	13.2	14.2	12.9	13.5
Blend	20.8	19.2	18.8	19.6	17.0	18.4	15.2	16.9A	19.9	20.2	18.7	19.6	12.8	13.0	16.2	14.0
Mean:	19.6	19.4	19.4		15.3	16.4	14.1		18.4	21.4	20.0		13.0	14.6	14.7	
	13- to 24-inch depth															
None	23.3	30.0	26.9	26.7	20.4	22.7	21.8	21.6	28.3	33.4	41.6	34.4	20.2	27.4	28.1	25.2
Cereal rye	27.6	28.5	26.3	27.5	24.3	16.4	13.5	18.1	35.9	35.4	31.9	34.4	20.1	22.7	22.7	21.8
Blend	27.1	26.2	26.1	26.5	22.0	18.6	17.4	19.4	33.2	32.2	35.9	33.8	21.4	21.7	25.7	22.9
Mean:	26.0	28.2	26.4		22.3	19.2	17.6		32.5	33.7	36.5		20.5B	23.9A	25.5A	
	25- to 36-inch depth															
None	26.6	26.1	27.0	26.6	16.8	22.8	17.6	19.7	26.3	28.6	30.4	28.4	18.1	20.7	23.5	20.7
Cereal rye	29.0	27.3	23.7	26.7	18.2	19.4	12.6	16.7	34.4	35.0	29.5	33.0	18.1	19.2	22.8	20.0
Blend	26.9	25.1	27.3	26.4	19.2	21.0	18.1	19.4	33.4	22.0	25.2	26.8	17.8	18.3	25.0	20.4
Mean:	27.5	26.2	26.0		18.7	21.1	16.1		31.4	28.5	28.4		18.0B	19.4B	23.8A	

† Nitrogen fertilizer rate for corn in 2017, lb N/ac.

‡ Numbers followed by different letters are significantly different at α=0.10 level. Capital letters signify differences in main effects and small letters are differences due to interaction between main effects.

Table 8b. Soil total inorganic-N by depth as affected by cover crop species, nitrogen rate for corn, and sampling date.

	Fall 2018				Spring 2019				Fall 2019				Spring 2020			
	3†	120	150	Mean	3	120	150	Mean	3	120	150	Mean	3	120	150	Mean
	------ Total inorganic-N, lb/ac ------															
	0- to 6-inch depth															
Cover crop																
None	34.3	35.7	35.4	35.1	18.1	15.4	20.9	18.2	20.1c	28.4a	21.8bc	23.0	11.4abc	9.4c	12.1ab	10.9
Cereal rye	37.2	34.6	38.8	36.9	25.1	21.4	19.4	22.0	19.9c	25.7ab	29.5a	23.4	10.1bc	12.7a	12.3ab	11.7
Blend	37.4	34.7	32.6	34.9	19.9	22.0	20.8	20.9	23.1bc	20.1c	25.8ab	25.0	13.2a	11.6abc	11.6abc	12.1
Mean:	36.3	35.0	35.6		21.0	19.6	20.4		21.0B	24.8A	25.7A		11.6	11.2	12.0	
	7- to 12-inch depth															
None	29.4	30.6	26.0	28.7	15.1	14.4	14.5	14.6	12.6c	18.6b	17.8b	16.3B	8.1	8.5	10.4	9.0
Cereal rye	30.5	27.5	30.2	29.4	14.1	15.7	14.7	14.8	16.3bc	21.0b	29.1a	22.1A	10.3	8.4	8.9	9.2
Blend	30.8	26.2	28.8	28.6	15.9	14.2	17.4	15.8	19.9b	16.3bc	19.4b	18.5B	10.6	9.0	8.2	9.3
Mean:	30.2	28.1	28.3		15.0	14.8	15.6		16.2B	18.6B	22.1A		9.7	8.6	9.2	
	13- to 24-inch depth															
None	43.6abc	45.3ab	41.2bc	43.4	30.4	28.0	30.2	29.5	23.0	31.7	29.8	28.2	9.7	9.8	13.7	11.1
Cereal rye	51.5a	35.6c	46.0ab	44.4	27.6	30.7	31.6	29.9	23.4	27.0	35.0	28.5	9.0	13.2	10.8	11.0
Blend	40.6bc	43.2abc	46.2ab	43.3	29.7	29.1	32.7	30.5	26.1	27.9	25.5	26.5	8.3	9.1	10.5	9.3
Mean:	45.2	41.4	44.5		29.2	29.3	31.5		24.2	28.9	30.1		9.0	10.7	11.7	
	25- to 36-inch depth															
None	38.8	39.7	36.6	38.4	29.8ab	23.4c	29.3ab	27.5	22.9	20.6	32.5	25.3	8.7	7.0	7.8	7.8
Cereal rye	41.8	32.4	41.3	38.5	28.6abc	28.4ab	26.1bc	27.7	24.5	21.3	32.0	25.9	7.8	12.0	6.8	8.9
Blend	37.9	33.2	38.6	36.6	27.1bc	27.1bc	33.5a	29.3	23.3	21.9	28.4	24.5	7.3	8.7	8.5	8.2
Mean:	39.5	35.1	38.8		28.5	26.3	29.6		23.6B	21.3B	31.0A		7.9	9.3	7.7	

† Nitrogen fertilizer rate for corn in 2017 and 2019, lb N/ac.

‡ Numbers followed by different letters are significantly different at α=0.10 level. Capital letters signify differences in main effects and small letters are differences due to interaction between main effects.

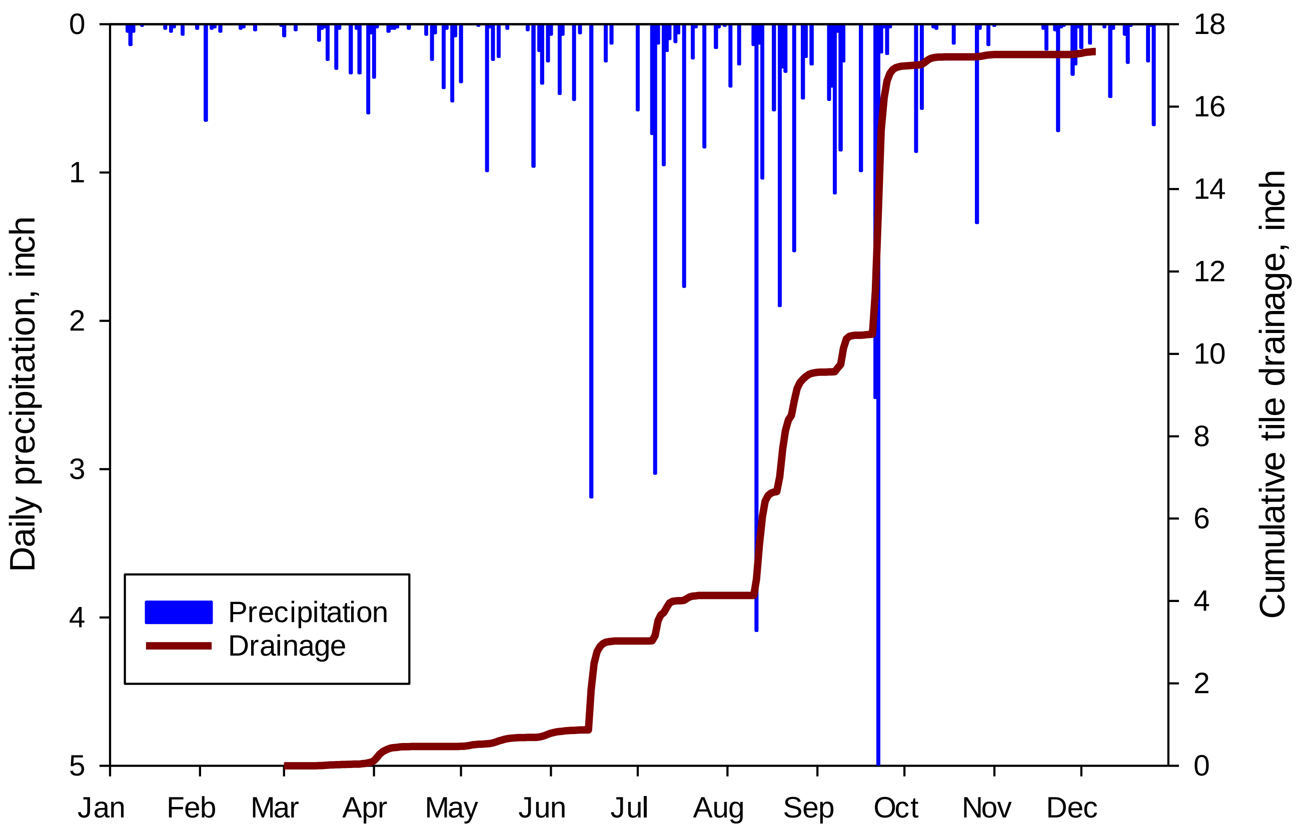


Figure 1. Daily precipitation and cumulative tile drainage in 2016.

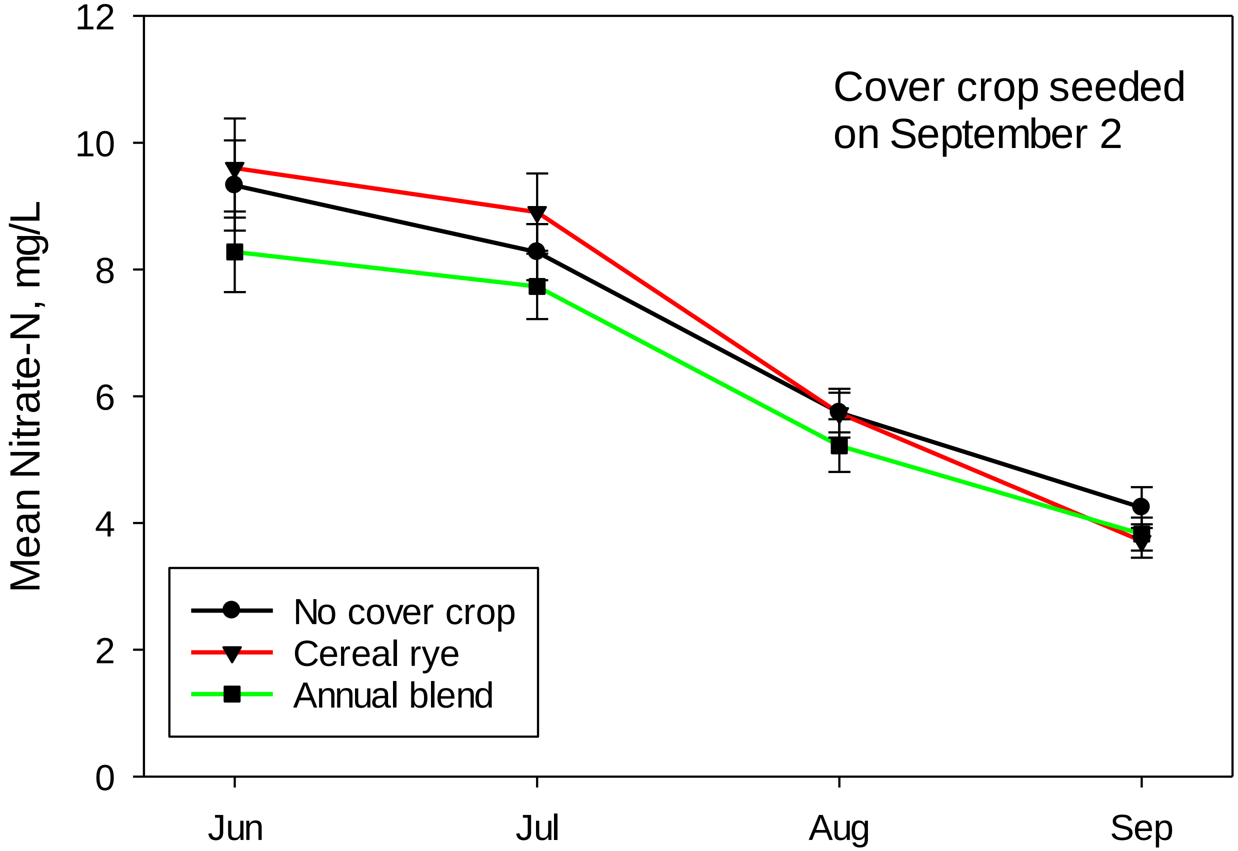


Figure 2. Nitrate-N concentration in tile drainage as affected by cover crop treatments in 2016 (setup year).

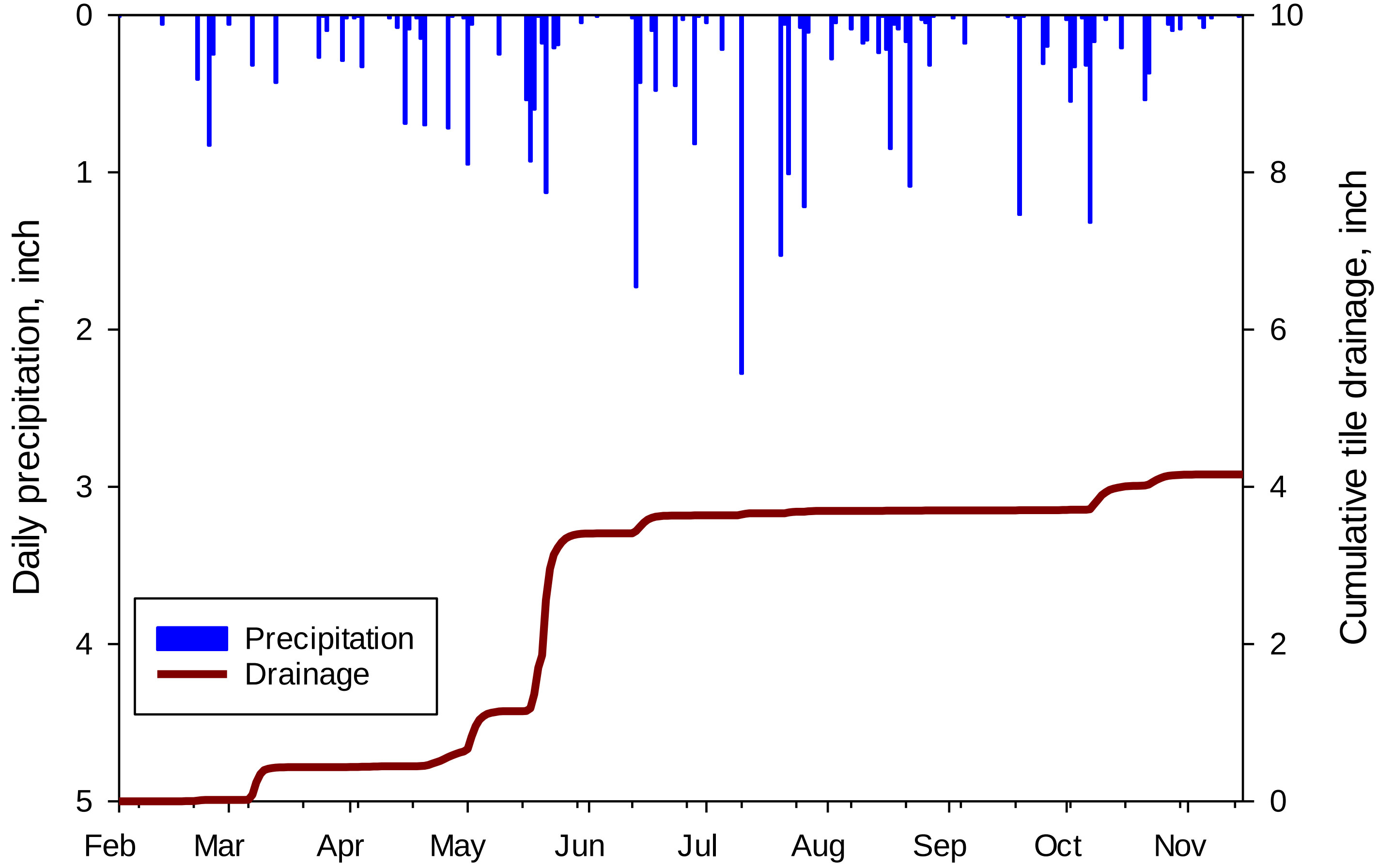


Figure 3. Daily precipitation and cumulative tile drainage in 2017.

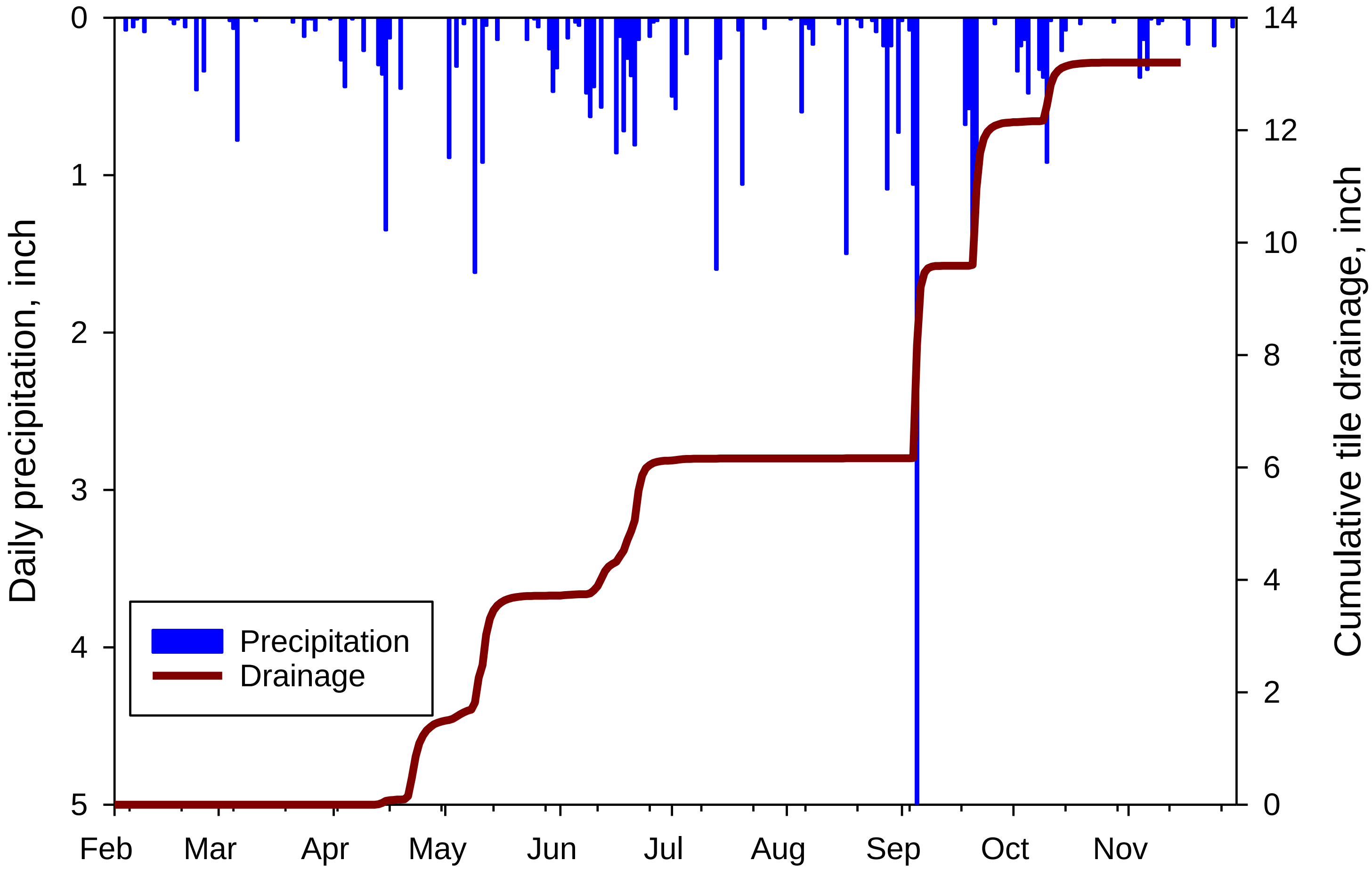


Figure 4. Daily precipitation and cumulative tile drainage in 2018.

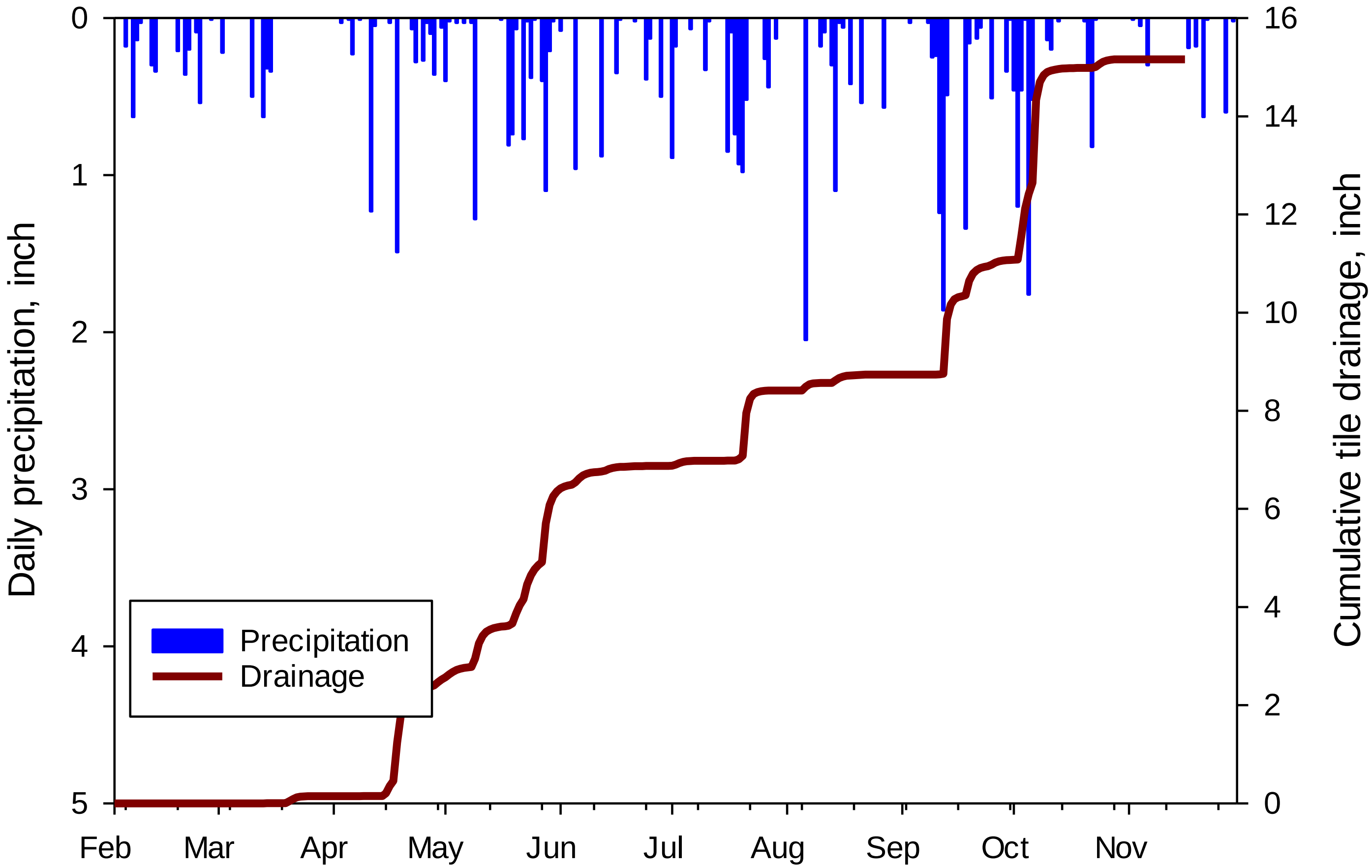


Figure 5. Daily precipitation and cumulative tile drainage in 2019.

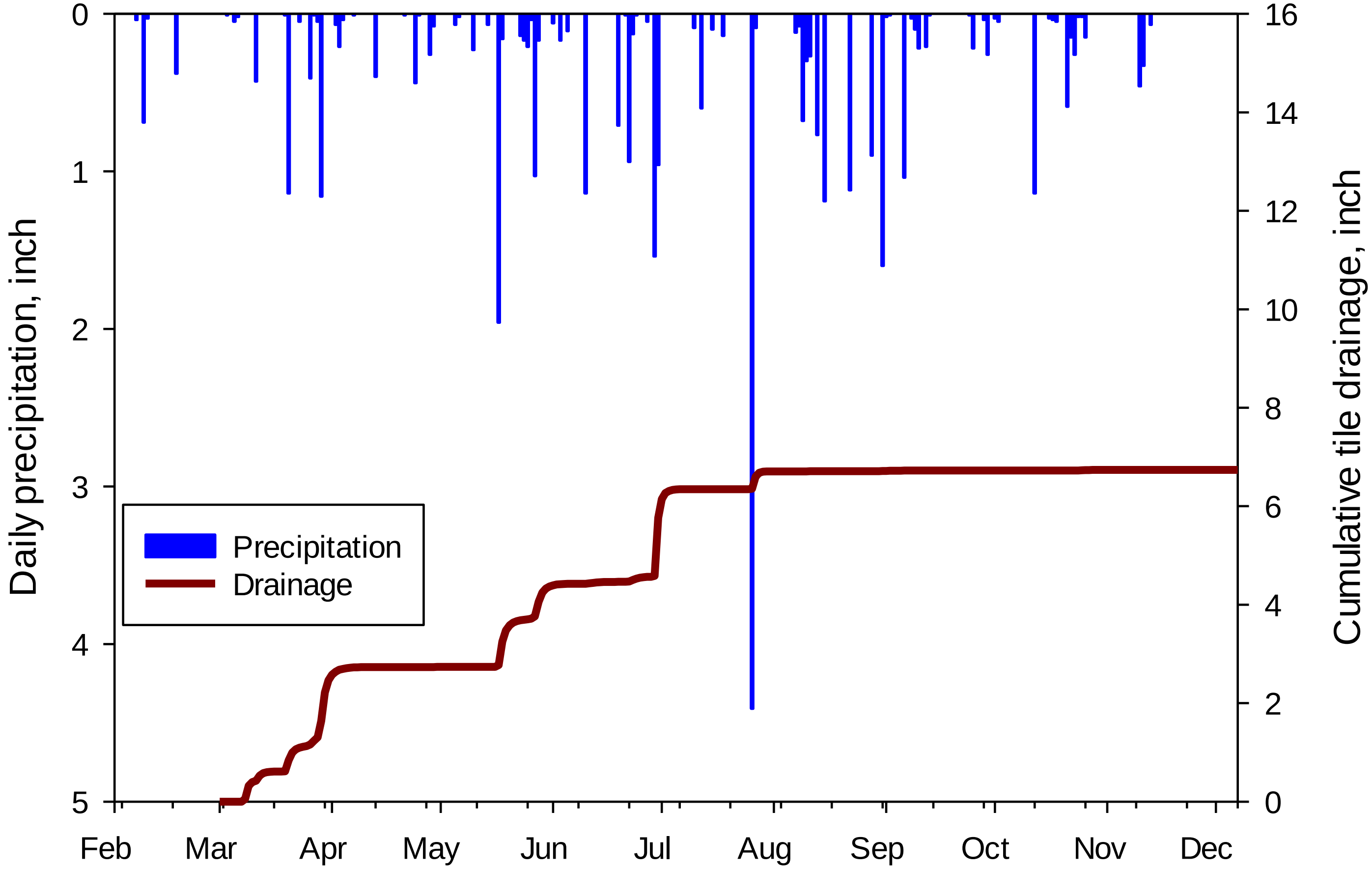


Figure 6. Daily precipitation and cumulative tile drainage in 2020.

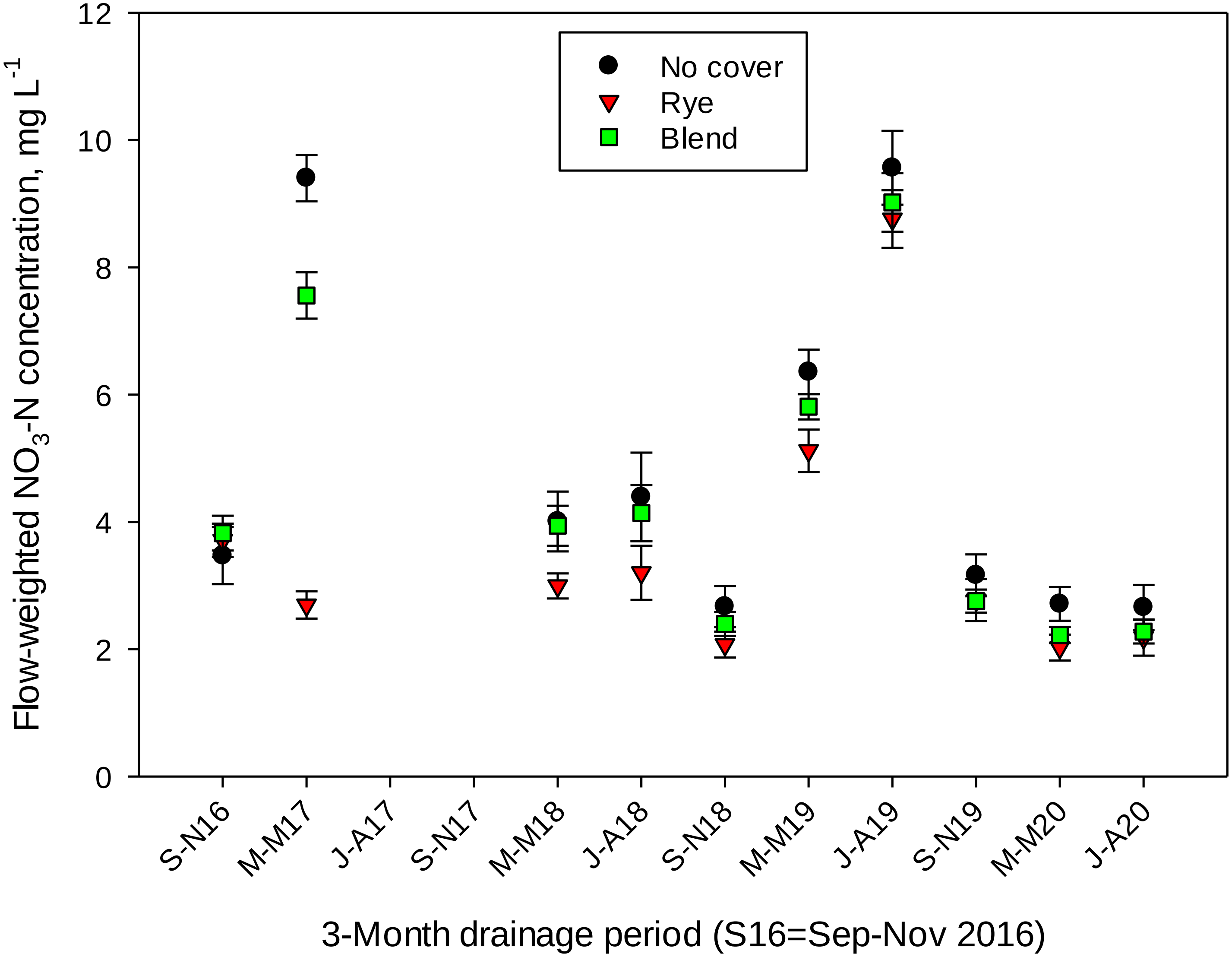


Figure 6. Flow-weighted nitrate-N concentration in tile drainage as affected by the main effect of cover crop specie (3-month periods "drainage seasons" S-N16=Sep-Nov 2016, no data during winter D-F, minimal flow therefore no data during J-A17 and S-N17 seasons, corn in odd years and soybean in even years, error bars indicate standard error of mean).

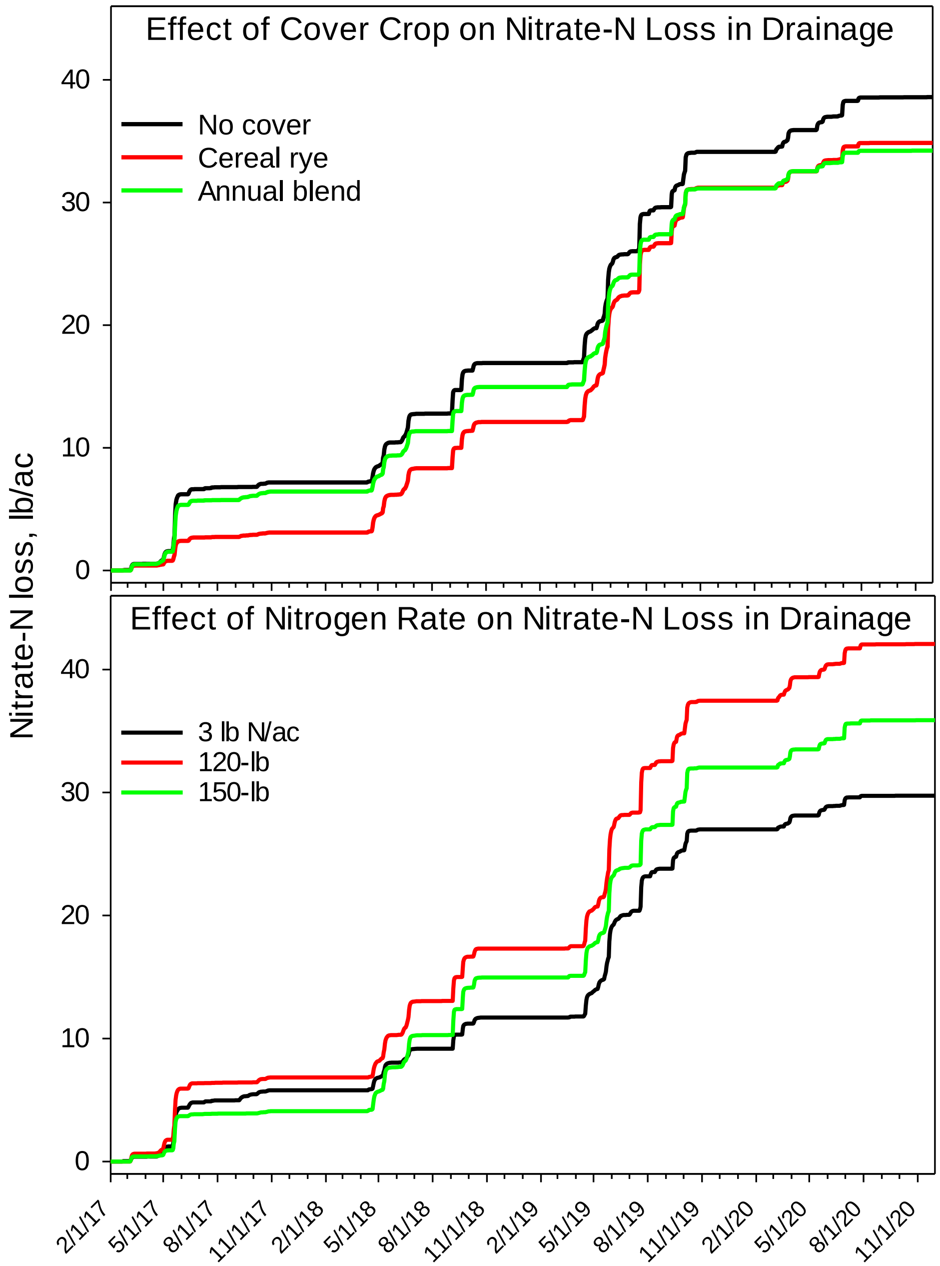


Figure 7. Cumulative nitrate-N loss (load) as affected by the main effects of cover crop specie (top) and N rate (bottom).

Appendix Tables

Appendix Table 1. Yield, nutrient concentration, and nurtrient removal in soybean seed in 2018 as affected by cover crops and nitrogen rates for corn.

Treatments			Soybean seed							
					Seed Concentration			Nutrient removal		
Trt	Cover crop	N rate (corn)	H_2O	Yield	N	P	K	N	P	K
#			%	bu/ac	------------------	%	------------------	---------------	lb/ac	---------------
1	None	3	11.0 a	66.4	5.93	0.608	1.84	205 a	21.1	63.8
2	None	120	10.7 ab	63.9	5.98	0.535	1.77	199 ab	17.9	59.1
3	None	150	10.5 bcd	62.3	6.05	0.566	1.78	197 abc	18.7	58.8
4	Cereal rye	3	10.3 d	60.3	5.86	0.487	1.75	184 d	15.3	54.9
5	Cereal rye	120	10.4 bcd	59.8	5.99	0.506	1.82	187 cd	15.9	56.7
6	Cereal rye	150	10.5 bcd	63.1	6.25	0.549	1.81	206 a	18.1	59.5
7	Annual blend	3	10.6 bc	62.8	6.07	0.555	1.78	199 abc	18.2	58.4
8	Annual blend	120	10.5 bcd	61.7	6.00	0.560	1.78	193 bcd	17.9	57.3
9	Annual blend	150	10.3 cd	61.7	6.08	0.523	1.74	196 abcd	16.9	56.1
Stats for RCB Design with a two-factor factorial arrangement										
Cover crop										
None			10.8 A	64.2 A	5.99	0.570 A	1.80	201	19.2 A	60.6 A
Cereal rye			10.4 B	61.0 B	6.03	0.514 B	1.79	192	16.4 B	57.0 B
Annual blend			10.5 B	62.1 B	6.05	0.546 AB	1.77	196	17.7 B	57.3 B
P > F:			0.0106	0.0353	0.6354	0.0737	0.5632	0.1611	0.0183	0.0396
N rate for corn in 2017										
3			10.6	63.2	5.95 B	0.550	1.79	196	18.2	59.0
120			10.5	61.8	5.99 B	0.533	1.79	193	17.2	57.7
150			10.5	62.4	6.13 A	0.546	1.77	199	17.9	58.1
P > F:			0.373	0.494	0.036	0.753	0.835	0.332	0.531	0.628
Interaction (cover crop × N rate)										
P > F:			0.093	0.209	0.211	0.203	0.273	0.062	0.136	0.107

Appendix Table 2. Yield, nutrient concentration, and nurtrient removal in soybean seed in 2020 as affected by cover crops and nitrogen rates for corn.

	Treatments		Soybean seed							
					Seed Concentration			Nutrient removal		
Trt	Cover crop	N rate (corn)	H_2O	Yield	N	P	K	N	P	K
#			%	bu/ac	------------------	%	------------------	---------------	lb/ac	---------------
1	None	3	9.3	80.4 a	5.78	0.617	1.85	243	25.9 a	77.7
2	None	120	9.2	74.1 cd	5.67	0.516	1.80	220	20.0 bc	69.5
3	None	150	9.4	71.2 ef	5.66	0.522	1.80	210	19.5 bc	66.9
4	Cereal rye	3	9.1	77.2 bc	5.89	0.499	1.75	237	20.2 bc	70.6
5	Cereal rye	120	9.2	70.5 f	5.63	0.480	1.76	208	17.7 c	64.9
6	Cereal rye	150	9.3	73.0 de	5.69	0.528	1.76	217	20.1 bc	67.1
7	Annual blend	3	9.3	78.0 ab	5.76	0.542	1.77	234	22.1 b	72.0
8	Annual blend	120	9.2	73.1 de	5.52	0.533	1.75	211	20.4 bc	66.9
9	Annual blend	150	9.3	73.6 de	5.67	0.509	1.80	218	19.5 bc	69.0
Stats for RCB Design with a two-factor factorial arrangement										
Cover crop										
None			9.3	75.2	5.70	0.552	1.81	224	21.8	71.3
Cereal rye			9.2	73.5	5.73	0.502	1.76	221	19.3	67.5
Annual blend			9.2	74.9	5.65	0.528	1.77	221	20.6	69.3
P > F:			0.1700	0.5189	0.7293	0.2479	0.1103	0.8816	0.2499	0.1661
N rate for corn in 2017										
3			9.2	78.5 A	5.81	0.553	1.79	238 A	22.7 A	73.4 A
120			9.2	72.6 B	5.61	0.510	1.77	213 B	19.4 B	67.1 B
150			9.3	72.6 B	5.67	0.519	1.79	215 B	19.7 B	67.7 B
P > F:			0.274	0.001	0.148	0.218	0.699	0.001	0.019	0.005
Interaction (cover crop × N rate)										
P > F:			0.515	0.016	0.911	0.22	0.581	0.337	0.099	0.166

Appendix Pictures

Pic. 1. Schematic diagram of tile drainage system.

Pic. 2. Tile drainage well access culvert, data logger, and coolers for holding water sample collection bottles.

Pic. 3. Plumbing inside culvert: sump well, pump, and water meters.

Pic. 4. Strip tillage on 24 October 2016, injecting P and K fertilizer at time of tillage.

Pic. 5. Spraying cereal rye with glyphosate on 17 April 2017 to terminate it prior to planting corn.

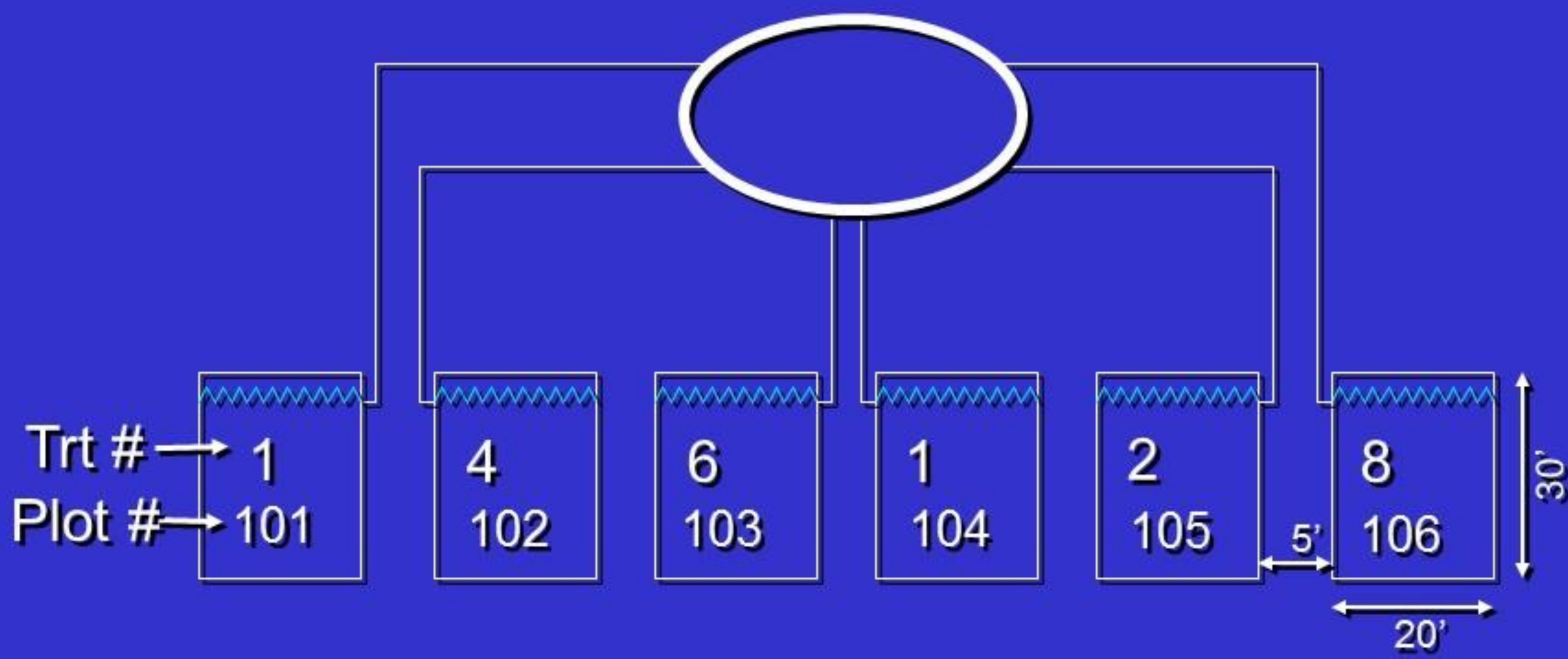
Pic. 6. Planting corn into strip-till bands on 7 May 2017. Applying liquid starter fertilizer (10-34-0 and UAN) at planting.

Pic. 7. Nitrogen deficiency on lower leaves at R5 (6 September) with 120 lb N/ac and cereal rye cover crop.

Pic. 8. Planting soybean into strip tilled bands and cereal rye cover on 17 May 2018.

Pic. 9. Very little cereal rye growth on 1 November 2018.

Drainage Research Facility at Waseca, SROC




Oct. 24, 2016
Gandy
Orbit-Air


April 17, 2017


May 7, 2017


120 lb N/ac w/cereal rye
150 lb w/cereal rye, Sept. 6

FINAL REPORT

PROJECT TITLE: Best management practices to integrate cover crops and manure
PROJECT NUMBER: 6054-21DD
PRINCIPAL INVESTIGATOR AND CO-INVESTIGATOR(S): Melissa Wilson, Chryseis Modderman, Manuel Sabbagh

ABSTRACT

There is a growing interest in using cover crops for improving soil health and water quality. In cool, northern climates, however, adoption is low due to the short growing season. On the other hand, interseeding cover crops allows more time for growth and is becoming popular. Liquid manure application, which often happens in the fall in this region, is one practice that could benefit from the use of cover crops. Newer injection technologies have made manure application into cover crops possible, but many questions remain. With a mix of on-farm and small plot research, we studied the effectiveness of a variety of cover crop seeding practices into corn and soybean; fall manure application timing versus spring fertilizer treatments with and without cover crops; soil health characteristics; and the impact of the studied practices on the following corn crop yield. We found that getting the cover crop planted as early as possible was beneficial for biomass production. Following sweet corn, cover crops could be drilled, but broadcast seeding into soybean around leaf-drop was better than drilling after soybean harvest. When it comes to manure application, we were able to successfully inject manure into the cover crop, though weather conditions seemed to dictate how well the cover crop recovered in the injection zones. As far as application timing, early fall applications when soil temperatures were above 50°F resulted in a 20 bushel per acre yield reduction compared with spring fertilizer. Waiting until after soils had cooled to below 50°F resulted in similar or better corn yields than spring fertilizer. This trend happened regardless of whether cover crops were planted or not. In the short time of this study (a two-year period in each field), we did not detect any changes in soil health (pH, bulk density, permanganate oxidizable carbon (POXC)) regardless of the practices used. Future research should evaluate these practices over the longer-term. Overall, this information will help farmers incorporate cover crops into their production systems when fall manure application is involved. This research also re-iterates that waiting until soil temperatures are cool in the fall to apply swine manure is a best management practice.

INTRODUCTION

Keeping the soil covered as much as possible is an important aspect for soil health management. Growing cover crops between cash crops is one way to keep the soil covered and depending on the type(s) of cover crops used, can also be a way to keep living roots in the soil.

In cool climates, however, adoption of cover crops has been limited due to the short growing season. For example, in Minnesota cover crops are more popular following early season vegetable crops like peas and sweet corn that allow for more time for establishment. Fewer acres, however, are seeded following commodity crops such as corn or soybeans. Recent research has successfully addressed this seasonal limitation in corn and soybean systems using interseeding in corn early in the growing season (Noland et al., 2018) or overseeding in soybeans in September (Wilson et al., 2013).

Another soil health promoting practice is the use of animal manure in combination with or in place of commercial fertilizers. This is because manure can improve the microbial diversity in the soil along with providing nutrients. Typically, manure is applied in the spring or fall. While spring application allows for less chance of nutrient loss, it is logistically difficult for farmers in Minnesota due unpredictable temperatures and increasingly wet weather. Thus, it is estimated that a large portion of manure is applied in the fall, leading to the potential for significant nutrient losses via leaching, runoff, or denitrification. The addition of cover crops to this practice could reduce these losses as the plants take up available nutrients throughout the fall and spring then slowly release them for the following cash crop. Combining manure applications with the use of cover crops could have additional beneficial effects on soil health as well, improving microbial diversity further than only applying manure or only using cover crops alone.

Farmers that use cover crops and manure traditionally apply manure following cash crop harvest and then plant cover crops. This leaves a significant amount of time for the manure nutrients to be lost before the cover crop is established and scavenging nutrients. Recent on-farm research in Minnesota (Everett et al., 2019) has demonstrated that with improvements in minimal disturbance manure injection, application of liquid manure into an already-growing cover crop is possible following soybeans and silage corn. This study investigated cover crops drilled after the cash crop was harvested, however, and researchers noted that low biomass accumulation, particularly in the more northern sites, resulted in lower fall nitrogen scavenging than reported in studies in warmer climates. Injection of manure into interseeded or overseeded cover crops, which have had more time to grow, may improve nutrient uptake. Timing of manure application may also impact nutrient dynamics in the soil and needs further testing.

Our primary goals were to develop and demonstrate best management practices for the integration of cover crops and liquid manure injection. Secondarily, we evaluated whether the combination of practices had added beneficial effects on optimizing soil nutrient cycling and soil health when compared to each practice alone.

OBJECTIVE AND GOAL STATEMENTS

- Evaluate cover crop seeding practices prior to liquid manure application
- Assess whether timing of manure application into a cover crop is important for retaining nutrients
- Determine whether manure application, cover crops, or the combination of both impact soil health
- Monitor changes in soil nitrogen and estimate nutrient recovery of the cover crop
- Evaluate the impact of these practices on subsequent cash crop yield and nutrient uptake

MATERIALS AND METHODS

We used a combination of small plot and on-farm research for this project. The small plots located at the Research and Outreach Centers (ROCs) allowed us to better control environmental factors and use a more intense sampling regime to determine whether treatments had an impact on soil parameters. The on-farm research allowed us to demonstrate techniques using full-scale equipment.

Task 1 – Small plot experiments – We conducted two small plot experiments at the Southern ROC (SROC) in Waseca, MN, using sweet corn-corn and a soybean-corn rotations. Winter cereal rye was used for the cover crop in both experiments, as this has been widely studied in Minnesota. In the first experiment, we also used oats, alone and in a mix with rye and radish, as the cover crop treatments. This first experiment also tested manure application timing: an early application when soil temperatures were warm enough for nitrogen cycling, where potential nitrogen losses may occur, and a late application when soil temperatures were cool and nitrogen cycling and losses were likely minimized. The second experiment tested overseeding and drilling cover crops into soybeans (in a corn-soybean rotation). Manure was applied in late fall when soil temperatures were cool. In both experiments, liquid swine manure was injected using sweeps to minimize soil surface disturbance. The “control” plots were treated according to standard practices in the region (the same nitrogen rate was applied pre-plant in the spring as the manured plots and P and K fertilizers were applied based on soil test levels). The cover crop was terminated approximately one to two weeks prior to planting the following cash crop.

- *Task 1A – Set up experiment with sweet corn* – Sweet corn was planted, managed, and harvested following typical practices in the region. For the experimental plots, we used a randomized complete block design with split plots and four replications. A new field was used each year of the experiment. The main factors were manure application timing while the subplots were with or without cover crops. Treatments can be found in Table 1. Cover crops were drilled after sweet corn harvest in early- to mid-August. Manure was tested and applied at the necessary rate to meet the nitrogen needs (minus 40 pounds of N at planting) of the following corn grain crop. In the control plots, fertilizers were applied a few days prior to planting in the spring and incorporated via tillage.
- *Task 1B – Set up experiment with soybeans* – Soybeans were planted, managed, and harvested according to typical practices in the region. We used randomized complete blocks with split plots and four replications for the design where the main plots were whether manure or spring fertilizer was applied, and the subplots were cover crop seeding method/timing (see Table 2). Overseeded winter rye was broadcast by hand to simulate directed broadcast by highboy or aerial seeding. The manure application rate was determined by the manure nutrient analysis and the following year’s corn crop’s nutrient needs (minus 40 pounds of N at planting). In the control plots, fertilizers were applied a few days prior to planting in the spring and incorporated via tillage.
- *Task 1C – Collect and analyze samples for both experiments* – To evaluate the impacts of cover cropping and manure injection practices on nutrient cycling and soil health, we

collected soil and plant samples over time. All samples were analyzed according to appropriate standard laboratory methods.

  - Rye biomass growth was monitored by collecting above-ground biomass samples in late fall and in the spring prior to cover crop termination.
  - Soil health was evaluated around the time of cover crop termination and near the end of the following corn season using several of the USDA-NRCS approved Standard Indicator Soil Health tests (2019).

- *Task 1D – Determine impacts on yield of the following crop in both experiments* – The following cash crop, grain corn, was planted, managed, and harvested according to typical practices in the region. Cash crop yield was determined to assess any impacts of the manure and cover crop treatments.

Table 1. Treatments for small plot experiments following sweet corn at the Southern Research and Outreach Center in Waseca, MN.

Main plots (manure application timing)	Subplots (cover crop seeding method/timing)
Early manure (shortly after harvest)	• Drilled winter rye • Drilled oats • Drilled rye/oat/radish mix • No cover crop
Late manure (late October to early November)	• Drilled winter rye • Drilled oats • Drilled rye/oat/radish mix • No cover crop
Spring fertilizer applied prior to planting (no manure)	• Drilled winter rye • Drilled oats • Drilled rye/oat/radish mix • No cover crop

Table 2. Treatments for small plot experiments with soybean at the Southern Research and Outreach Center in Waseca, MN.

Main plots (manure application)	Subplots (cover crop seeding method/timing)
Manure applied after harvest	• Broadcast seeding in September • Drilling after harvest • No cover crop
Spring fertilizer prior to planting (no manure)	• Broadcast seeding in September • Drilling after harvest • No cover crop

Task 2 – On-farm experiments – The on-farm experiment was located near Trimont, MN in cooperation with AJ Krusemark. Due to issues with planting cover crops in fall 2019 (an extremely wet season), the experiment was only conducted one time (fall 2020-2021 growing season). We used farm scale equipment in a soybean-corn rotation where the crops were planted, managed, and harvested following typical practices in the region.

- *Task 2A – Setting up experimental strips* - For the experimental plots, we used field-length strips that were arranged in randomized complete blocks with three replications (table 3). We tried to minimize the number of treatments on the farm for logistical reasons and timing of other farm operations. The cover crop mix was chosen by the farmer and included winter rye. It was drilled after soybean harvest. Liquid swine manure was injected with strip tillage. We analyzed the manure for nutrient content and then applied at the necessary rate to meet the P needs of the following crop. Fertilizer was applied in the non-manured plots via strip tillage based on the soil test levels. The cover crop was terminated at two different times in the spring: 1-2 weeks prior to planting and after planting. All remaining N (or full N rate in the fertilizer-only plots) was sidedressed.
- *Task 2B – Collect and analyze samples* – The number of samples collected at these sites was not as intense as the small-plot studies. We monitored the winter rye growth and nutrient uptake by collecting above-ground biomass samples in the spring prior to each termination date. Corn was harvested by hand from each plot from two randomly selected 10-foot section of rows, shelled, then dried to get moisture content.

Table 3. Treatments for on-farm experiment

Experiment	Strip Treatments	Split plots within strips
Soybean – Corn Rotation	Strip-tilled manure + cover crops	Early, pre-plant termination of spring cover crops
	Strip tilled fertilizer + cover crops	Late, post-plant termination of cover crops

RESULTS AND DISCUSSION

Sweet Corn – Corn Rotation – Small Plot Trials

<u>Cover crop biomass</u> – Above-ground cover crop biomass for the oat and mixed cover crop averaged approximately 400 pounds per acre in the fall after planting, while winter rye produced significantly less at 200 pounds per acre (Figure 1). Significant differences were not found for nutrient source/timing. In the spring prior to termination, the oats and radish had completely winter killed but there were no significant differences between rye and the cover crop mix. Nutrient source/timing did not affect cover crop biomass production in 2020, but in 2021, the early-fall applied manure increased cover crop biomass production relative to the plots where nothing had been applied yet (spring fertilizer was applied after cover crop termination). The late-fall applied manure significantly decreased cover crop production, however (Figure 1). This is likely due to drought conditions from mid-fall 2020 through spring 2021 and the late applied manure application did not allow for the cover crops to recover.

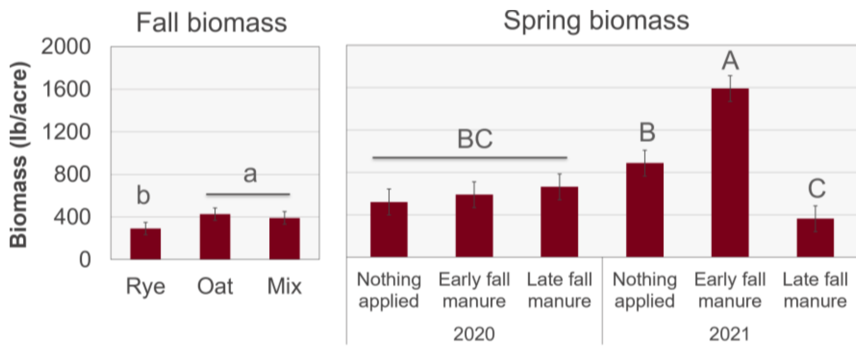


Figure 1. Average above-ground biomass for different cover crops in the fall after planting and the following spring prior to termination. There was a significant year by cover crop type interaction for spring biomass collections. Bars with different letters above them for each season are significantly different (*P*<0.05).

<u>Corn yield following cover crops</u> – There was an effect of nutrient source/timing and cover crop types on yield, but there was no interaction between the two (Figure 2). In both 2020 and 2021, early-fall applied manure (applied in September when soil temperatures were >50°F) significantly decreased corn yield compared with the spring fertilizer treatment, regardless of whether cover crops were used or not. The yield decrease was approximately 13-15 bushels per acre. On the other hand, the late-fall applied manure (applied in late October or November when soil temperatures were <50°F) increased yield by 33 bushels per acre in 2020 or had a statistically similar yield compared to the spring fertilizer treatment in 2021. There was a drought in 2021, so it is likely that the manure nitrogen did not mineralize as well that year. This really emphasizes the need for applying swine manure at the right time in the fall when the soil temperatures have cooled. A significant amount of nitrogen was likely lost when the manure was applied too early.

Cover crops also affected yield. The oat cover crop treatment yielded similarly to the no cover crop control. The rye and mixed treatments, however, decreased yield by about 19-20 bushels per acre. This was possibly due to two issues. First, the rye had grown very large in the spring and was difficult to properly incorporate. The seedbed was affected, and the seed likely had poor seed-to-soil contact. The other issue was that the incorporated rye may have tied up nitrogen early in the growing season. We observed nitrogen deficiency symptoms (yellowing of lower leaves) in the corn in the treatments with rye.

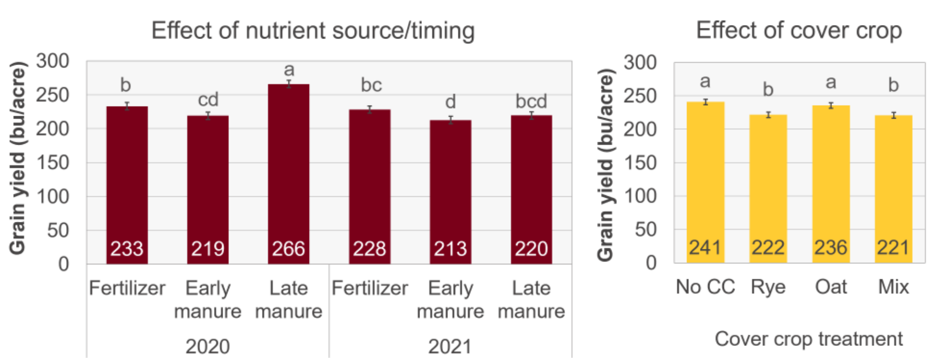


Figure 2. Effect of nutrient source/timing and cover crops on corn yield following sweet corn. For nutrient sources, fertilizer was spring applied and compared with early manure (applied mid- to late-September) and late manure (applied late October). A winter rye, oat, or winter rye-oat-radish mix was compared to a no cover crop control (no CC). Bars with different letters above them for each graph are significantly different (*P*<0.05).

Soil health parameters – Bulk density was measured every spring, prior to cover crop termination from the 0-6" soil layer. There were no significant differences in relation to the interaction of nutrient source and cover crop treatment (Figure 3). Although no differences were observed, bulk density was in the optimal range for clay loams and fields should not have impacted plant growth.

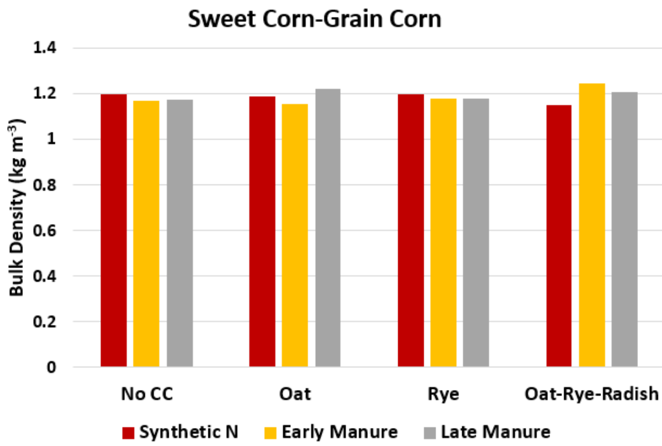


Figure 3. Soil bulk density in the sweet corn-corn rotation from the top 0-6" of soil in relation to nutrient source and cover crop treatment.

Similarly to bulk density, pH was not significantly different in relation to the interaction of cover crops and nutrient source in either spring after cover crops were planted or in fall after the following crop was grown (Figure 4). Soil pH fall in the optimal pH range for soils for crop production (6-7).

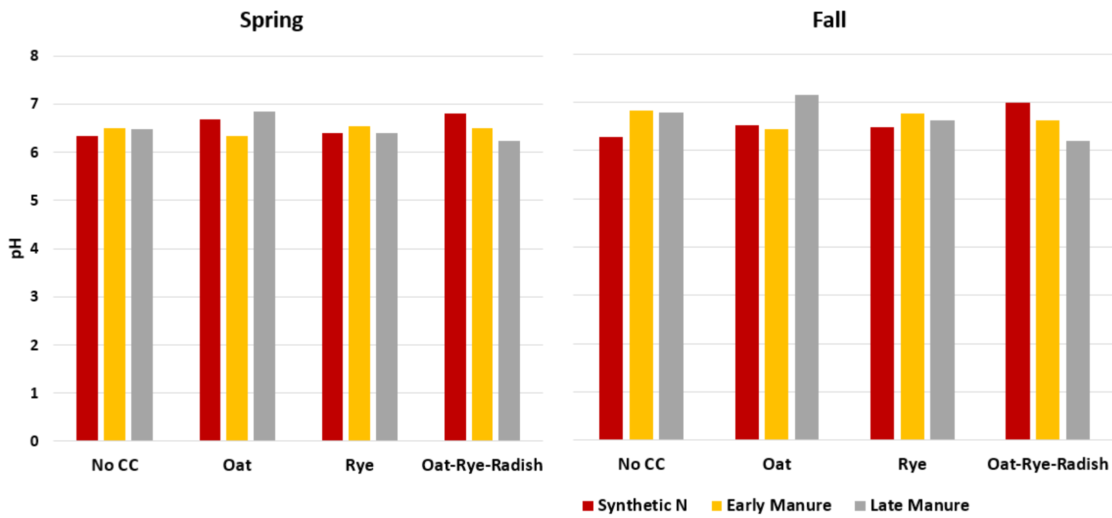


Figure 4. The interaction of cover crops and nutrient source on soil pH in the sweet corn-grain rotation. Soils were taken from the 0-6" soil layer in spring and fall.

Permanganate oxidizable carbon (POXC) measures the labile carbon in soils that can be utilized by microbes. In addition, POXC is a sensitive tool that can track changes in soil carbon quickly when soil management practices change. In both rotations, POXC was not affected by the interaction of cover crops and liquid injected manure in both spring after cover crops were planted or in fall after the following crop was grown (Figure 5). The lack of significant differences across the year may also be the result of the inherently high percent soil organic matter in both these studies. Cover crops may have also not produced enough biomass to have a significant effect in relation to carbon inputs from root exudates and inputs from decomposing biomass.

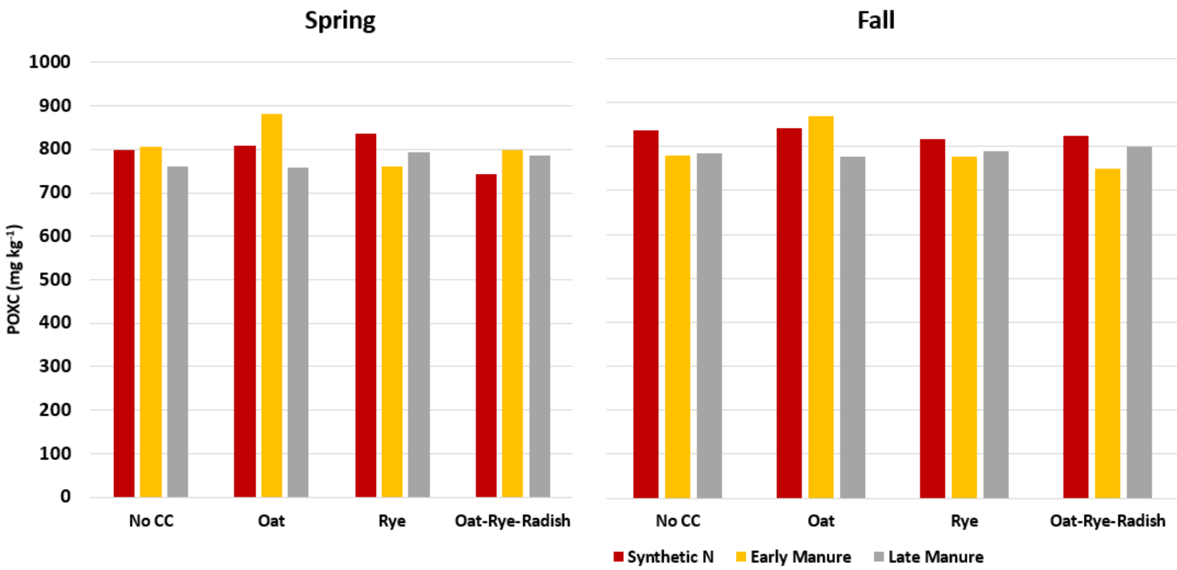


Figure 5. The interaction of cover crops and nutrient source on permanganate oxidizable carbon in soil in the sweet corn-corn rotation. Soils were taken from the 0-6” soil layer in spring and fall.

Soybean – Corn Rotation – Small Plot Trials

Cover crop biomass – Above-ground cover crop biomass production was much lower following soybean than following sweet corn, less than 100 pounds per acre in the fall and less than 400 pounds per acre in the spring prior to termination (Figure 6). Cover crops that were drilled after harvest failed in one of two years, and produced very little biomass in the years that they were successfully established. Overseeding the cover crops around soybean leaf drop was a better method for getting the cover crops established earlier. Manure application affected cover crops in the fall when averaged over both years. By the spring, cover crops had recovered in the manured plots in 2020 but we did not see that trend in 2021. As mentioned above, we had a significant drought develop in late fall 2020 so it is likely that the cover crop could not recover after application with so little moisture in the soil profile.

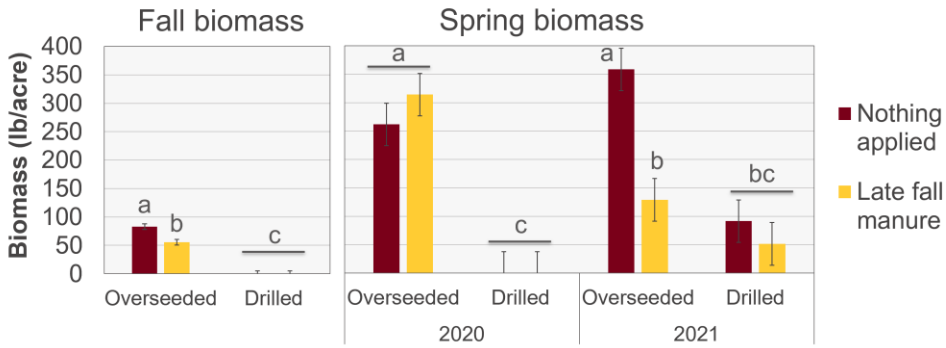


Figure 6. Average above-ground biomass for different cover crops in the fall after planting and the following spring prior to termination. Cover crops (annual ryegrass and winter rye mix) were overseeded at soybean leaf drop or drilled after harvest. In the fall, manure was applied and compared to plots where nothing was applied until spring following cover crop termination. Bars with different letters above them for each season are significantly different ($P<0.05$).

<u>Corn yield following cover crops</u> – In the soybean-corn rotation, we did not find an effect of fall manure versus spring fertilizer or an effect of cover crop (Figure 7). This is likely because corn following soybean is more resilient when it comes to nitrogen needs. The decay of soybean reside provides some nitrogen to the following crop. As for the cover crops, they did not produce much biomass in this rotation, so it is likely they did not tie up nitrogen or cause seedbed issues like was seen in the sweet corn-corn rotation.

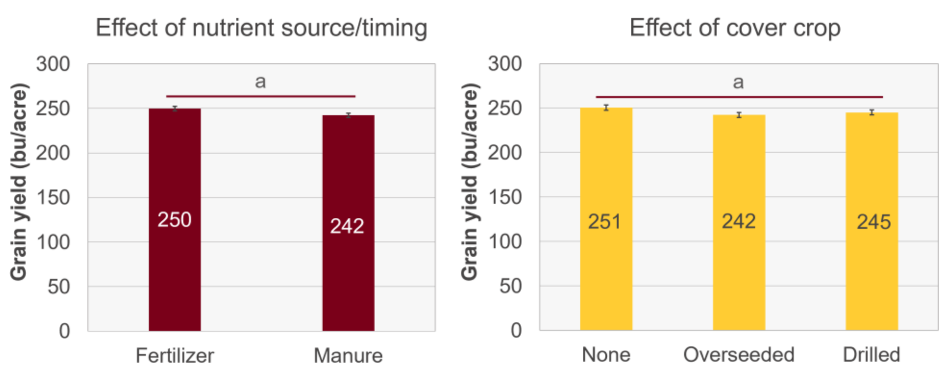


Figure 7. Effect of nutrient source/timing and cover crops on corn yield following soybean. For nutrient sources, fertilizer was spring applied and compared with fall manure (applied late October). The cover crop included a winter rye-annual ryegrass mix. It was overseeded near soybean leafdrop or drilled after harvest. Both were compared with a no cover crop (no CC) control. Bars with different letters above them for each graph are significantly different ($P<0.05$).

<u>Soil health parameters</u> – None of the treatments affected soil bulk density (Figure 8), pH (Figure 9), or POXC (Figure 10). As mentioned above, the fields in the study had high soil organic matter to begin with, so it was unlikely to see changes to soil health over a small period of time.

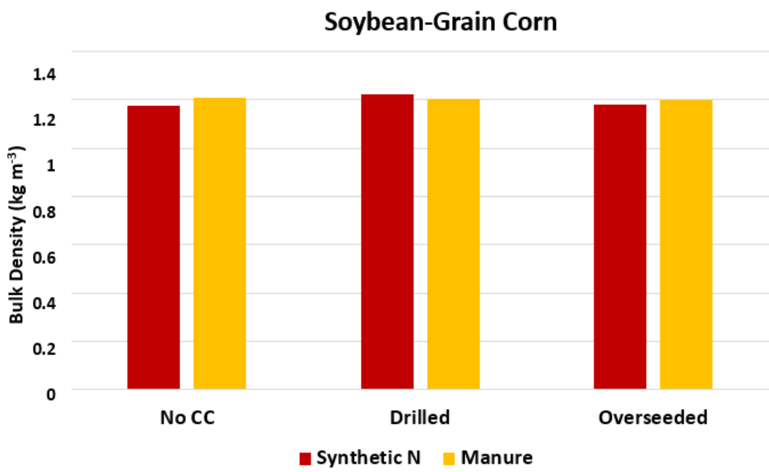


Figure 8. Soil bulk density in the soybean-corn rotation from the top 0-6” of soil in relation to nutrient source and cover crop treatment. Cover crops (annual ryegrass and winter rye mix) were overseeded at soybean leafdrop or drilled after harvest and compared to plots with no cover crop (CC).

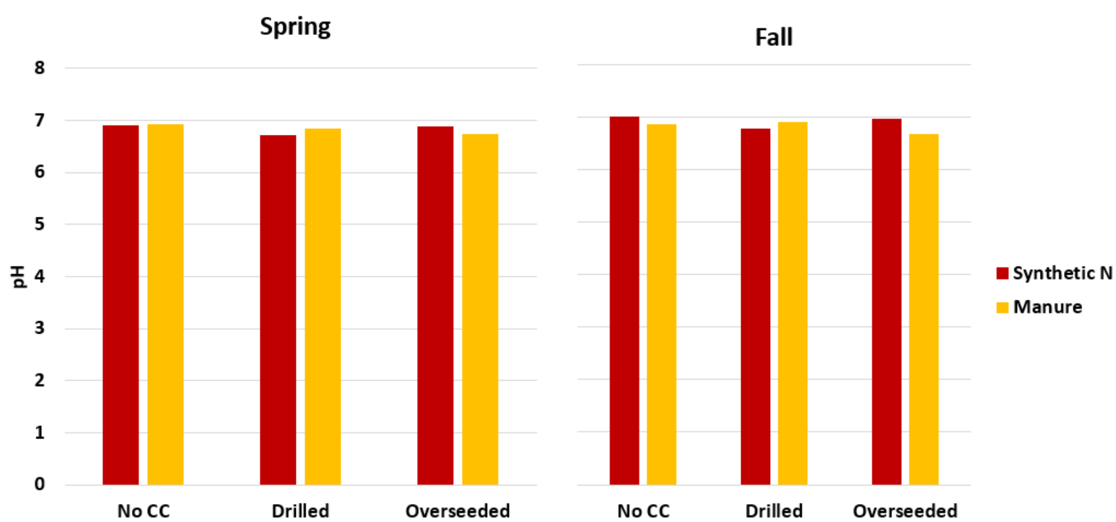


Figure 9. The interaction of cover crops and nutrient source on soil pH in the soybean-grain rotation. Soils were taken from the 0-6” soil layer in spring and fall.

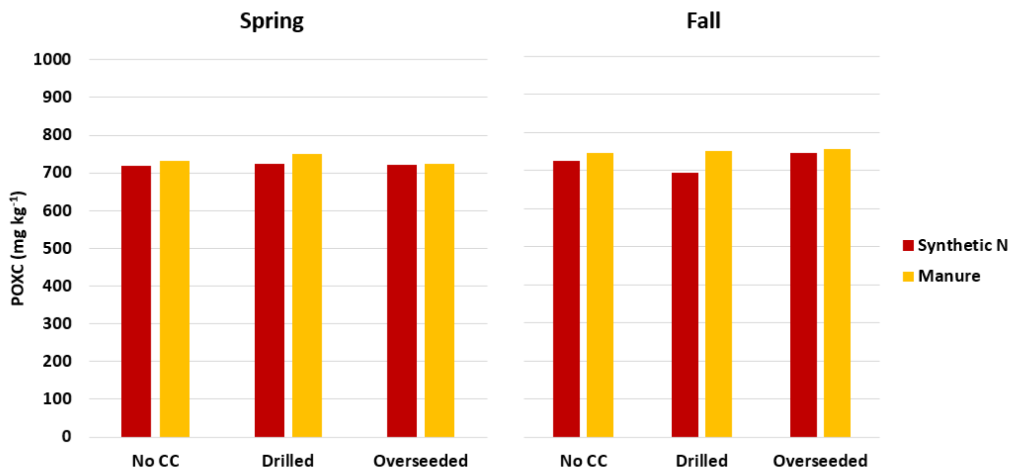


Figure 10. The interaction of cover crops and nutrient source on permanganate oxidizable carbon in soil in the soybean-corn rotation. Soils were taken from the 0-6” soil layer in spring and fall.

Soybean – Corn Rotation – On-farm trial

Cover crop biomass – In this trial, swine manure or commercial fertilizer was strip-tilled in the fall after cover crops were drilled following soybean harvest. In the spring, cover crops were either terminated early (one to two weeks prior to planting) or late (after planting). Samples were collected on May 7, 2021 and May 19, 2021 prior to each termination date. Fertility treatments did not affect cover crop biomass, but termination timing did. There were 352 pounds of above-ground biomass produced by the early termination date and 1,113 pounds of biomass produced by the late termination date, a more than 3-fold increase over 12 days.

Corn yield following cover crops – Fertility treatment (manure versus commercial fertilizer) did not affect corn yield following the cover crop. Interestingly, the late-terminated cover crops slightly reduced yield (179 bushels per acre) compared to the early-terminated cover crops (190 bushels per acre), but the difference was not statistically significant. The lack of a drastic difference was surprising as 2021 was a dry year and we had anticipated that the cover crop would have consumed excess amounts of water.

CONCLUSIONS

Manure can be successfully injected into growing cover crops in different crop rotations. Depending on the year, the injection equipment may damage some of the cover crop stand, but with good growing conditions the cover crop will recover and flourish. We also found that:

- Getting cover crops established as early as possible is important to allow for more time for growth.
- There is a chance that winter rye will slightly decrease the following corn yield, particularly in corn following corn systems. This could be an equipment issue, however, as seedbed issues made planting difficult.
- Applying swine manure too early in the fall will cause significant decreases in yield. Waiting until the soil temperatures were cool (<50°F) helped improve yield.

- Swine manure was a great nutrient source for corn production, similar to or better than commercial fertilizers.
- Soil health improvements were not detected over the short timeframe of this experiment.

EDUCATION, OUTREACH, AND PUBLICATIONS

Conferences

- Sabbagh, M.J., Wilson, M.L., Pagliari, P.H. (2022). Integration of Liquid Injected Manure and Cover Crops and Their Impact on Soil Health and Grain Yield in the Upper Midwest. In: ASA, CSSA, and SSSA 2022 International Annual Meetings. Baltimore, MD. 6-9 Nov.
- Sabbagh, M.*, Wilson, M., Pagliari, P. (2022). Changes in Soil Health in Response to Cover Crop and Manure Integration in the Upper Midwest. In: World Congress of Soil Science. Glasgow, Scotland, UK, 31 Jul- 5 August.
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- Sabbagh, M., Wilson, M. L., Pagliari, P. H. (2021). Integrating Cover Crops and Manure: Developing Best Management Practices. In: 76th SWCS International Annual Conference. Virtual, 26-28 Jul.
- Sabbagh, M., Wilson, M. L., Pagliari, P.H. (2020). The Impacts Cover Crops and Liquid Manure Have on Soil Health in the Upper Midwest. In: ASA, CSSA, and SSSA 2020 International Annual Meetings. Virtual, 8-11 Nov.

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- Wilson, M. (2020). Cover crops and manure for soil health [Webpage]. ArcGIS Story Maps. https://z.umn.edu/ManureCoverCrops2020
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- Wilson, M., Stahl, L. (2019). Applying manure in late summer or early fall? Try cover crops. In: Minnesota Crop News Blog. 19 Aug. https://blog-crop-news.extension.umn.edu/2019/08/applying-manure-in-late-summer-or-early.html.

Extension Presentations:

- Wilson, M. L. (2022) Injecting manure into cover crops. In: North American Manure Expo. 14 July. Chambersburg, PA. (*102 in attendance*)
- Sabbagh, M., Wilson, M.L. (2022). Integrating Cover Crops and Liquid-injected Manure: Impacts on grain yield. In: MN Ag Expo. Mankato, MN. 19 Jan.
- Wilson, M., Raman, R., Andersen, D. (2022). Manure Application & Cover Crops: Panel Discussion. In: Iowa Pork Congress. Des Moines, IA. 27 Jan. (*31 attendees*)
- Wilson, M. (2022). Injecting manure into a growing cover crop. In: Wisconsin Agribusiness Classic. Madison, WI. 12 Jan. https://vimeo.com/659707510 (*60 attendees*)
- Loeffler, A., Wilson, M.L., Shea, M., Breen, D. (2021). Cover crops and livestock. In: Midwest Cover Crops Council Conference. Guelph, Ontario but held virtually. 25 Feb. (*1 panel presentation, 95 attendees live*)
- Wilson, M.L. (2021). Cover crops and manure research update. In: MN Corn Growers Research and Promotion Board Summer Meeting. Hastings, MN. 9 Jun. (*14 attendees*)
- Wilson, M. (2021). Manure happens: Can cover crops help? In: Stearns SWCD Manure and Cover Crops Field Day. Virtual. 7 Jan. Available at https://www.youtube.com/watch?v=T89zmPnQzq4 (*62 live attendees*, *113 video views*)
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- Wilson, M. L., Hatlewick, H. (2019). Table Talk: Crap and cover crops. In: Conservation Tillage Conference. University of Minnesota Extension. Saint Cloud, MN. 17-18 Dec.
- Wilson, M. L. (2019). Applying Liquid Manure into Cover Crops. In: Crop Pest Management Short Course. Institute for Ag Professionals – University of Minnesota Extension. Minneapolis, MN. 12 Dec.
- Wilson, M.L. (2019). Manure Management in Cover Crops & Side-Dressing Corn. In: Tour de Forage. Midwest Forage Association. Welch, MN. 4 Dec. (*51 attendees*)
- Wilson, M. L. (2019). Manure and Cover Crops: Best Management Practices. In: Soil Health Summit. National Corn Growers Soil Health Partnership. St. Louis, MO. 15 Jan. (*70 attendees*)

Interviews:

- Studying manure and cover crop integration – MN Corn Podcast, Sep. 11, 2022
- Time cover crops, manure in short fall window – Farm Progress, Jul. 25, 2022
- Minnesota Study: How Integration of Cover Crops, Liquid-Injected Manure Impacts Corn Yield, Biomass – Cover Crop Strategies, May 31, 2022
- Study provides insights to how cover crops and manure work together – Brownfield Ag, Mar. 10, 2022
- “Research evaluates soil health benefits of combining manure and cover crops” – MN Corn Blog, Jun. 9, 2020
- “Applying manure to cover crop offers multiple benefits” – MN Farm Guide., Jan. 30, 2019
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Potential for a Rye Cover Crop to Reduce Nitrate Loss in Southwestern Minnesota

Article *in* Agronomy Journal · November 2006

DOI: 10.2134/agronj2005.0134 · Source: OAI

5 authors, including:

Gary R. Sands
University of Minnesota Twin Cities

Paul Max Porter

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Potential for a Rye Cover Crop to Reduce Nitrate Loss in Southwestern Minnesota

G. W. Feyereisen,* B. N. Wilson, G. R. Sands, J. S. Strock, and P. M. Porter

ABSTRACT

Cover cropping practices are being researched to reduce artificial subsurface drainage NO_3–N losses from agricultural lands in the Upper Mississippi watershed. This study was designed to investigate the influences of fall planting date and climate on cereal rye (*Secale cereale* L.) biomass and N uptake in the spring, and to assess subsurface drainage NO_3–N loss reductions. A soil–plant–atmosphere simulation model, RyeGro, was developed and used to predict rye cover crop establishment and growth, soil water balance, N cycling, and drainage NO_3–N losses from mid-September through May in southwestern Minnesota. An imbedded stochastic weather generator provided model climate inputs. Inclusion of a rye cover crop sown on 15 September reduced N losses by 11.1 kg N ha^{-1} or 45% for a corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] crop rotation. Fall sowing dates of 1, 15, and 30 October resulted in reductions of 7.8, 5.8, and 4.6 kg N ha^{-1}, respectively, by the end of May. Desiccation of the rye on 1 May resulted in reductions of 4.5, 2.2, 1.2, and 0.7 kg N ha^{-1}, for the 15 September and 1, 15, and 30 October sowing dates, respectively. Cover cropping practice provides promising opportunities for reductions in N losses for cropping rotations wherein the primary crops are harvested before mid-September and planted after mid-May. We predict that a winter rye crop can reduce drainage NO_3–N losses on average 7.4 kg N ha^{-1} for southwestern Minnesota if planted on 15 September and desiccated on 15 May.

Hypoxic zones occur in several coastal estuaries around the world, and one of the largest zones can be seen in the northern Gulf of Mexico at the mouths of the Mississippi and Atchafalaya rivers (Rabalais et al., 2001). The low levels of O_2 in the Gulf waters can be traced to a cycle that is exacerbated by high levels of N entering the Gulf from these rivers (Rabalais et al., 1996). Nutrient loading in the Mississippi River has been increasing in quantity since the 1950s (Antweiler et al., 1995). Analysis of the sources of the N in the Mississippi River indicates that the Upper Mississippi watershed, including Minnesota and Iowa, is a significant contributor. Agricultural subsurface drainage systems can exacerbate N losses from agricultural lands to surface waters (Zucker and Brown, 1998). These systems are used to increase crop productivity and reduce the risk of lowered crop yields from root zone excess water stress during wet years (Fausey et al., 1995); however, agricultural drainage systems have created a pathway by which nutrients can escape from the fields they are intended to enhance (Skaggs et al., 1994).

One general strategy to mitigate the loss of NO_3–N through subsurface drainage systems is to minimize the amount of nutrients reaching the drains (Mitsch et al., 2001; Randall and Mulla, 2001; Dinnes et al., 2002). Examples of methods proposed to implement this strategy include managing nutrient application more effectively, changing cropping systems, and using appropriate tillage practices. One of the methods related to cropping system modification is the use of fall-planted cover crops to assimilate residual soil NO_3^- before establishment of the succeeding summer crop. Cover crops can affect the water balance, reduce the soil NO_3–N level, and provide residue cover on agricultural fields that are normally fallow between summer crops. A cover crop growing in fall and spring takes up soil NO_3–N, which is a leachable mineral form of N, and produces a nonleachable pool of organic N (ON) in the biomass of the plant (Hoyt and Mikkelsen, 1991). The ON in the plant residue is left on the surface of the ground, where it will be broken down and recycled during a period of months and years. Because of their ability to reduce NO_3–N leaching, cereal cover crops have become a major part of the proposed strategies to reduce nutrient loadings to the Chesapeake Bay (Boesch et al., 2001). In addition to N scavenging benefits, cover cropping can provide the advantages of surface cover, erosion protection, snow trapping, and weed suppression on fields from which silage corn or shorter season canning crops are harvested.

The majority of research to date on the use of winter cover crops to reduce NO_3–N leaching to groundwater or drainage effluent has been performed in warm, humid climates where the majority of nutrient loss occurs during the winter. In colder climates where the soil profile freezes during the winter, the majority of nutrient loss through subsurface drainage occurs during the spring, before significant biomass accumulation of the summer row crop. Moreover, the precipitation regimes are considerably different between the warm, humid climates and the drier, colder northern climates. For example, the percentages of average annual precipitation falling during the period of October through March for a Washington state experimental site (Kuo et al., 1997), a Maryland site (Ranells and Wagger, 1997), and Lamberton, MN (Strock et al., 2004), are 75, 45, and 26%, respectively.

The challenge of obtaining the benefits of winter cover crop use in the northern Corn Belt is the short and cold growing season between summer row crops (Dinnes et al., 2002). There is a lack of research quantifying how effective the technique of growing cover crops between

G.W. Feyereisen, USDA-ARS Southeast Watershed Research Lab., Tifton, GA 31793-5737; B.N. Wilson and G.R. Sands, Dep. of Biosystems and Agricultural Engineering, Univ. of Minnesota, St. Paul, MN 55108-6005; J.S. Strock, Southwestern Research and Outreach Center and Dep. of Soil, Water, and Climate, Univ. of Minnesota, Lamberton, MN 56152-1326; and P.M. Porter, Dep. of Agronomy and Plant Genetics, Univ. of Minnesota, St. Paul, MN 55108-6026. Received 5 May 2005. *Corresponding author (gfeyereisen@tifton.usda.gov).

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Abbreviations: ON, organic nitrogen; RSN, residual soil nitrate; SMC, soil moisture content; SWROC, Southwest Research and Outreach Center.

summer crops is in reducing NO_3–N losses through agricultural drainage effluent in the northern Corn Belt, given variations in climate. Strock et al. (2004) conducted a 3-yr field study of rye as an N-scavenging cover crop in southwestern Minnesota. The expense and time required to continue such a field study long enough to gain insight into water quality changes across decadal and longer time frames is prohibitive. Computer modeling has become a common technique for investigating the long-term consequences of changes to agronomic systems based on knowledge gained from short-term field research.

The Stanford Watershed Model is one of the earliest examples of a computer routine developed to simulate the processes involved in the hydrologic cycle (Crawford and Linsley, 1966). During the ensuing decades, models were developed to simulate biochemical processes as well as the hydrologic ones. Examples of models that have been used to investigate agronomic and water quality impacts of agricultural practices at the field level include: DRAINMOD (Skaggs, 1978), CREAMS (Knisel, 1980), EPIC (Williams et al., 1984), CERES-Wheat (Ritchie and Otter, 1985), DSSAT (Jones et al., 2003), AGNPS (Young et al., 1987), GLEAMS (Leonard et al., 1987), ADAPT (Alexander, 1988; Ward et al., 1988), and RZWQM (Great Plains Systems Research Unit, 1999). These models vary in the complexity of the underlying algorithms and of the input variables required to use them.

Long-term assessments require weather inputs from a weather record of sufficient length. Jin and Sands (2003) used an 85-yr historic weather record to perform a long-term hydrologic assessment of subsurface drainage systems for a southern Minnesota location. When access to such lengthy records has been limited, or when long-term weather patterns have been changing, the use of stochastically generated weather inputs to soil–plant–atmosphere models has been widely practiced. For example, the Climate Generator (CLIGEN; Nicks et al., 1995) has been used to generate climate input variables for several hydrologic and water quality simulation models, including EPIC, GLEAMS, SWRRB, and WEPP (Nicks and Gander, 1994). The advantages of employing a stochastic weather generator include the opportunity to create a wide range of possibilities for weather sequences and the ability to increase the certainty of the mean output values. The generator can be programmed to execute high numbers of simulation runs to the point that the sample mean of each model output has very low variance.

A soil–plant–atmosphere model, RyeGro, was developed, calibrated, and previously described by Feyereisen (2005) and Feyereisen et al. (2006a, 2006b). RyeGro was developed as a spreadsheet application, providing ease of use. Model inputs include basic soil and climate information; there are few parameters to be calibrated, which supports a straightforward calibration process. RyeGro was specifically developed to simulate cover crop growth during the fall through spring period and more closely estimated rye biomass accumulation for the calibration seasons than another widely used crop growth model.

We used RyeGro with the following objectives: (i) to develop a probabilistic assessment of the potential for using fall-planted cereal rye, also known as winter rye, to reduce NO_3–N leaching to field subsurface drainage effluent in southwestern Minnesota; (ii) to predict field losses of NO_3–N through artificial subsurface drainage for a corn–soybean crop rotation that includes, or does not include, a fall-planted cover crop of cereal rye after the corn harvest; and (iii) to investigate the influences of fall planting date and climate on rye biomass yield and N uptake in the spring.

METHODS

RyeGro Model

The soil–plant–atmosphere model RyeGro was developed to predict aboveground biomass production and N uptake of rye planted after the fall harvest of corn in the corn–soybean crop rotation common to southwestern Minnesota and to simulate subsequent artificial subsurface drainage NO_3–N losses at the field scale during the fall through spring period. The hydrology and N submodels of RyeGro were documented by Feyereisen et al. (2006a) and the plant growth submodel by Feyereisen et al. (2006b).

The available data set for the rye cover crop study in southwestern Minnesota contained only basic soil, weather, and crop growth information. In view of the nature of the input information, a decision was made to simulate physical processes in RyeGro only to a level of complexity necessary to meet the study's objectives. An example of the approach of sufficient complexity in model development is given by Hammer and Muchow (1994), who developed a simple, yet mechanistic crop simulation model for sorghum [*Sorghum bicolor* (L.) Moench]. They reported that their model was successful in accounting for 94% of the variability in biomass production on 38 data sets covering a broad range of environments.

In RyeGro, the soil profile was represented as a series of three soil layers: a surface layer, approximately the depth of the plow layer; Soil Layer 2, extending from the surface layer to the depth of the artificial subsurface drain tube; and Soil Layer 3, which extended below the drain tube to a calibrated depth. Percolation from one layer to the next lower layer was calculated when soil moisture content (SMC) in the higher layer exceeded field capacity. The infiltration scheme of Holtan (1961) was used to determine infiltration and surface runoff. The infiltration equation is:

$$f(t) = a\, S_a^{1.4}(t) + f_c \qquad [1]$$

where $f(t)$ is infiltration rate with time; f_c is the constant rate of infiltration after the storage capacity reaches zero and is typically given the value of the saturated hydraulic conductivity of the surface soil, k_{sat}; a is associated with surface-connected porosity; S_a, available storage capacity, is defined as:

$$S_a(t) = [\theta_{sat} - \theta(t)]D \qquad [2]$$

where θ_{sat} is saturation soil moisture content, $\theta(t)$ is soil moisture content during the current time step, and D is the depth of the surface soil layer. Percolation between layers, Perc, is governed by Eq. [3]:

$$\text{Perc} = k_{sat}\left[\frac{(\theta(t) - \theta_{fc})}{(\theta_{sat} - \theta_{fc})}\right]^e, \text{ for } \theta(t) > \theta_{fc}$$

$$\text{Perc} = 0, \text{ for } \theta(t) \le \theta_{fc} \qquad [3]$$

where θ_{fc} is field capacity soil moisture content, k_{sat} is the saturated hydraulic conductivity of the soil in the layer through which soil moisture is percolating, and e is an exponent that can be calibrated. Subsurface drainage occurs from Soil Layer 2 when the soil moisture content in Soil Layer 3 becomes saturated and $\theta(t)$ in Soil Layer 2 is $>\theta_{fc}$. Depending on available climate inputs, evapotranspiration was determined by either the Priestley–Taylor method (Priestley and Taylor, 1972) or the Penman method (Penman, 1948). A simplified N cycle was used to estimate net mineralization, fresh ON mineralization, plant uptake, and mass flow of NO_3–N. Given that air and soil temperatures are near or below freezing in Minnesota during much of the season under study (fall–spring), mineralization of cellulose and lignin in the fresh stover, denitrification, and volatilization were ignored. Net mineralization is calculated on a daily basis by Eq. [4] (Arnold et al., 1998):

$$\text{ONminN} = [\text{ONact} - \text{ONact}\exp(-\text{MinRate})] \times (K_{\text{wON}}\, K_{\text{tON}})^{\text{MinExp}} \quad [4]$$

where ONminN is daily net mineralized N, ONact is the active pool of readily mineralizable ON, MinRate is the daily net mineralization decay rate constant, K_{wON} and K_{tON} are soil water and temperature coefficients varying from 0 to 1, and MinExp is a calibrated parameter. A value for MinRate of 0.0077 d^{-1} is used in RyeGro, a value originating with Stanford and Smith (1972).

The plant growth submodel uses the solar radiation interception concept of Monteith (1977) and reiterated by Campbell and Norman (1998) to calculate assimilated biomass:

$$A_{\text{nPOT}} = \varepsilon \int f_{\text{PAR}} \text{PAR}\, \text{d}t \quad [5]$$

where A_{nPOT} is potential net assimilated biomass, ε is radiation use efficiency, f_{PAR} is the fraction of incident light intercepted by the rye canopy, and PAR is the photosynthetically active radiation portion of total solar radiation. A photosynthetic reduction factor, K_p, is used to reduce the quantity of daily potential biomass due to temperature stress or water stress. Each day the smaller of the stress reduction factors for temperature, K_t, or soil moisture, K_w, becomes the photosynthetic reduction factor. The photosynthetic reduction factor is multiplied by the daily potential biomass to calculate actual daily biomass production:

$$A_{\text{nACT}} = A_{\text{nPOT}} K_{\text{p}} \quad [6]$$

where A_{nACT} is actual assimilated biomass. Using an empirical relationship between rye biomass accumulation and tissue N content derived from rye growth studies in Minnesota, the model calculates the amount of N accumulated in the growing rye crop and subtracts the assimilated N from the soil NO_3–N pool.

Stochastic Weather Generator

Daily weather input variables required by RyeGro include maximum and minimum air temperature, precipitation, and solar radiation. Additionally, maximum and minimum relative humidity and average wind speed were necessary for use of the Penman method to calculate reference evapotranspiration. Weather input variables to RyeGro were either read from an input file or generated stochastically by an imbedded weather generator.

Weather inputs for the RyeGro calibration and validation simulations were available from the 43-yr record (1961–2003) at the Southwest Research and Outreach Center (SWROC) at Lamberton, MN (44°15′00″ N, 95°18′36″ W). The record of shortwave solar radiation readings during the same period was less complete: 24 yr of solar radiation values, with a minimum of 330 d of daily values recorded during the year, existed.

Since the objective of the research was to assess probabilistically the long-term effects of using a fall-planted rye cover crop, stochastic generation of weather variables was used to extend the number of years of investigation beyond the available his-

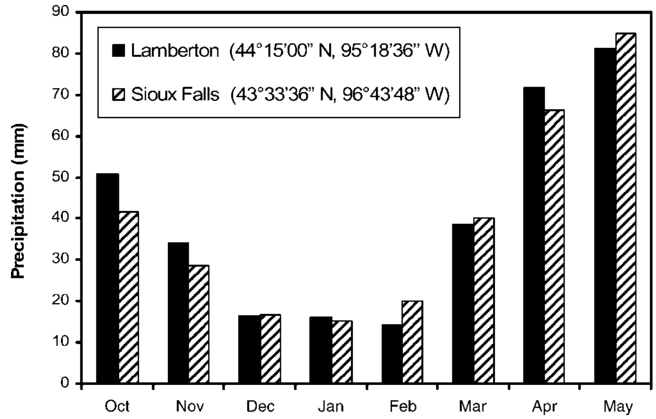

Fig. 1. Average monthly precipitation at Lamberton, MN, and Sioux Falls, IA.

toric record by creating synthetic weather sequences with the same statistical properties as the measured variables. Because the SWROC record was quite short for solar radiation, wind speed, and relative humidity, an approach developed by Wilson and Hayes (2004) was used to estimate the variance, skewness coefficient, and serial coefficients of all the weather variables based on a 72-yr record from Sioux Falls, SD (43°33′36″ N, 96°43′48″ W), which is located 122 km from Lamberton and has similar geography and climate. The basic assumption was made that the variability of the weather variables and serial correlations was similar for Lamberton and Sioux Falls. A comparison of average monthly precipitation for Lamberton and Sioux Falls for the October through May time period is shown in Fig. 1.

The weather generator calculates precipitation occurrence and depth, maximum and minimum air temperature, shortwave solar radiation at the earth's surface, average wind speed, and maximum and minimum relative humidity on a daily basis. Weather variable estimates are generated independently of one another. See Feyereisen (2005) for additional details of the weather generator.

Model Inputs for Long-Term Stochastic Investigation

The calibration and validation of the plant growth submodel were performed using data from a rye growth trial at St. Paul, MN (44°58′48″ N, 93°10′48″ W) and a 3-yr field study involving fall sowing of rye after corn and before soybean, conducted from fall 1998 to spring 2001 at the SWROC. The calibration and validation of the hydrologic and drainage submodels were performed using data from the 3-yr study and from field measurements recorded on the same set of plots during a previous 6-yr study, conducted from 1988 to1993 by Randall

Table 1. Soil input values used for simulations.

Property	Surface layer	Layer 2	Layer 3
Depth, cm†	30	90	45
Saturated soil moisture content, $cm^3\ cm^{-3}$	0.526	0.400	0.400
Field capacity, $cm^3\ cm^{-3}$	0.320	0.308	0.300
Wilting point, $cm^3\ cm^{-3}$	0.195	0.191	0.200
Saturated conductivity, $cm\ h^{-1}$	0.91	0.30	0.0006
Percolation exponent†	0.5	0.5	1
Surface depressional storage, cm†	0.95	n/a‡	n/a
Holtan's surface parameter a, $in.^{-0.4}\ h$†	0.3	n/a	n/a
Holtan's infiltration parameter f_c, $cm\ h^{-1}$	0.91	n/a	n/a
Soil transmissivity, $mm\ d^{-1}$	3.5	n/a	n/a

† Calibrated parameter.
‡ Not applicable.

Table 2. Plant growth, soil N cycle, and soil temperature input values used for simulations.

Input parameter	Value
Plant growth	
Radiation use efficiency, kg dry matter MJ^{-1} photosynthetically active radiation	2.8
Initial shoot biomass†, kg dry matter ha^{-1}	30
Base temperature†, °C	1
Optimum temperature†, °C	18
Heat units to emergence†, °C d	50
Maximum days to emergence†, d	14
Heat units to maturity†, °C d	2050
Maximum leaf area index	7
Maximum canopy height, m	1.14
Maximum root depth, m	0.6
Soil N cycle	
Soil organic matter, surface layer, %	6.03
Soil organic matter, Layer 2, %	2.76
Soil organic matter, Layer 3, %	1.55
Soil organic C/organic N ratio	10.5
Soil mineralization potential†, % of soil organic N	20
Net mineralization rate constant, wk^{-1}	0.54
Mineralization temperature and soil moisture exponent†	2.5
Corn stover carbohydrate N, kg ha^{-1}	9.6
Soil temperature	
Soil thermal conductivity, W m^{-1} °C^{-1}	1.042
Soil thermal diffusivity, cm^2 s^{-1}	0.004
Snow thermal conductivity, W m^{-1} °C^{-1}	0.625
Rain–snow dividing temperature, °C	0
Snowmelt base temperature, °C	2
Snowmelt coefficient, mm °C^{-1} d^{-1}	5

† Calibrated parameter.

et al. (1997). Details of the field trials are available in Strock et al. (2004) and Randall et al. (1997).

Soil and Crop Inputs

Tables 1 and 2 contain model inputs used for the simulations. The soil moisture contents, saturated hydraulic conductivity, and organic matter contents were obtained from the SSURGO (Soil Survey Geographic) database. The crop parameters were values for rye obtained from the literature, or, if values for rye were unavailable, crop parameter values for oat (*Avena sativa* L.) or wheat (*Triticum aestivum* L.) were used. The settings used for soil, crop, N, and soil and snow thermal inputs remained unchanged from the calibration and validation of the plant growth, hydrologic, and N submodels (Feyereisen et al., 2006a, 2006b).

Initial Soil Moisture Content

The initial SMC in each of the three soil layers is estimated at the time of rye sowing. Initial SMC of each of the soil layers is calculated as a function of the cumulative precipitation and average air temperature from 1 July until the fall sowing date. The relationships were obtained by regression analysis from the 1998 to 2001 rye field study at the SWROC (Strock et al., 2004). The equations for the surface soil layer (0–30 cm deep), Soil Layer 2 (30–120 cm deep), and Soil Layer 3 (120–165 cm deep) are as follows:

$$\theta_{Surf_{init}} = 0.315 - 0.0221\text{J1T}_{ave} + 0.0019\text{J1cumPrecip} \quad [7]$$

$$\theta_{Layer2_{init}} = 0.23 - 0.00201\text{J1T}_{ave} + 0.000173\text{J1cumPrecip} \quad [8]$$

$$\theta_{Layer3_{init}} = 0.29 - 0.00602\text{J1T}_{ave} + 0.000518\text{J1cumPrecip} \quad [9]$$

where $\theta_{Surf_{init}}$, $\theta_{Layer2_{init}}$, and $\theta_{Layer3_{init}}$ are initial SMCs of the surface layer, Soil Layer 2, and Soil Layer 3, respectively, J1T_{ave} is average air temperature from 1 July, and J1cumPrecip is cumulative precipitation from 1 July. The minimum value permitted for the initial SMC is the wilting point. The maximum value permitted for the initial SMC is field capacity, except for the case of Soil Layer 3, which has a maximum value of 0.95 times field capacity.

Initial Residual Soil Nitrate

The initial residual soil NO_3^- (RSN_{init}) in each of the three soil layers is also determined at the time of rye sowing. The equations for RSN_{init} are based on regression analysis of field data collected on the experimental plots at the SWROC for the 9-yr period from 1988 to 1996 and reported by Randall et al. (1997) and Huggins et al. (2001). The RSN_{init} values were measured, in the above studies, in the autumn following corn harvest in a corn–soybean rotation. Several regression models were tested with combinations of parameters including current, previous, and second-previous season precipitation as measured during the growing season, hydrologic year, or calendar year. The relationships that produced the best correlations were those that calculated RSN_{init} as a function of the previous year's annual precipitation and the second-previous growing season precipitation. The equations used in the model are as follows:

$$\text{RSN}_{\text{SurfaceLayer init}} = 84.2 - 0.05886\text{PrevAnPrecip} - 0.03546\text{Prev2GSPrecip} \quad [10]$$

$$\text{RSN}_{\text{Layer2 init}} = 222 - 0.1623\text{PrevAnPrecip} - 0.1081\text{Prev2GSPrecip} \quad [11]$$

$$\text{RSN}_{\text{Layer3 init}} = 57.0 - 0.0342\text{PrevAnPrecip} - 0.0317\text{Prev2GSPrecip} \quad [12]$$

where PrevAnPrecip is the cumulative annual precipitation, and Prev2GSPrecip is the cumulative precipitation during the growing season of the second-previous year, measured from 15 April to 1 October. The multiple coefficients of determination, R^2, for the three relationships are 0.49, 0.69, and 0.66, respectively.

Climate Inputs

The RyeGro model was prepared to be executed for hundreds of simulation years by stochastically generating weather inputs having the same statistical characteristics as the much shorter actual climate record. An initial simulation with one planting date was run for 5500 yr to evaluate the stability of the statistics of the meteorological variables. From the initial run, it was determined that the statistics were stable after 2500 yr and therefore the simulation runs with the various planting dates were conducted for 2500 yr.

Sensitivity Analysis

The purpose of a sensitivity analysis is to identify model parameters that have the greatest influence on model results (Hamby, 1994). Sensitivity is determined by identifying calibrated base values for a set of input parameters, then perturbing the inputs and comparing the change in the model output of interest to the change in model input parameter. An initial local sensitivity analysis was performed for 24 RyeGro input parameters on the cumulative subsurface drainage NO_3–N loss output for the 1998 to 1999 calibration year. Relative sensitivity coefficients, S_r, were calculated using the technique documented by Haan (2002):

$$S_r \cong \frac{(O_{P+\Delta P} - O_{P-\Delta P})}{O} \Big/ (2\Delta P/P) \quad [13]$$

where O is the model output (cumulative subsurface drainage NO_3–N loss, in this case) with input parameters set at base values, $O_{P+\Delta P}$ and $O_{P-\Delta P}$ are model outputs with the input parameter being studied set at a value equal to the base value plus or minus a specified percentage (often taken to be in the range of 10–25%), P is the initial value of the input parameter, and ΔP represents the prescribed absolute change in the value of the input parameter. Relative sensitivity coefficients are unitless and therefore can be used to compare sensitivities among parameters (Haan, 2002). Negative values indicate that a change to an input parameter results in a change of opposite direction to the output value. The division of parameters into various degrees of sensitivity is subjective. For example, Haan and Skaggs (2003a) considered hydrologic parameters with absolute values for S_r of >0.15 and N cycle parameters with absolute values for S_r of >0.20 (Haan and Skaggs, 2003b) to be sensitive and warranting additional uncertainty analysis. We chose to perform additional analysis on 14 RyeGro input parameters for which $|S_r| > 0.20$ for the 1998 to 1999 calibration year. Simulations were performed on these 14 parameters for the 2000 to 2001 calibration year. The S_r values presented below represent the average values for the 2 yr.

Simulation Modeling Methodology

Two field treatments were simulated: the first was corn–fallow–soybean and the second was corn–winter rye–soybean. Four fall sowing dates were selected for study to analyze the influence of sowing date on rye biomass accumulation and subsurface drainage N losses in the spring: 15 September and 1, 15, and 30 October. Each simulation run was executed until 30 May, at which time the rye crop growth was assumed to be stopped either by chemical desiccation or by mechanical means. The end date of the simulation was set at the end of May for two reasons. First, the rye treatment is not intended to interfere with the yield of the subsequent summer crop. Extending the period of rye growth into June would interfere with timely planting of the subsequent soybean crop. Second, there is an increasing probability that certain assumptions made in the development of RyeGro would be violated, such as the assumption of no soil moisture upward flux. Estimates of rye biomass accumulation and subsurface drainage losses were recorded at several dates during the simulation runs: 1 December, 1 January, 1 February, 1 March, 1 and 15 April, and 1, 15, and 30 May.

Two simulations were performed with each of the 2500-yr simulation input variables: one with and one without the rye crop grown between the corn and soybean crops. Thus, the stochastic inputs were identical for each year's dual simulation.

RESULTS

Meteorological Variable Outputs

Statistics for the meteorological variables generated for the long-term simulations—precipitation, maximum and minimum air temperatures, and solar radiation—are shown in Table 3. Some differences between the generated variables and the values measured at Lamberton were expected because the wet–dry transitional probabilities, standard deviations, and skewness coefficients for the generated variables were based on the weather record at Sioux Falls. The generated annual precipitation values were 1.9% higher than the 43-yr mean measured at Lamberton, although the number of wet days estimated was slightly less than measured, 87.2 vs. 88.0. The transitional probabilities used to predict days with or without precipitation were those from the long-term record at Sioux Falls. Since Sioux Falls is slightly drier and has fewer wet days than Lamberton, it is reasonable to expect underprediction of wet days.

Table 3. Comparison of 43 yr of measured weather variables from Lamberton, MN, and 5500 yr of generated weather outputs used in model simulations.

Weather variable	Measured mean (SD)	Simulation mean (SD)
Annual precipitation, mm	668.4	681.1
Mean daily precipitation, mm	1.83 (6.15)	1.87 (6.46)
Skewness coefficient daily precipitation	6.39	6.81
Annual wet days	88.0	87.2
Air temperature max., °C	13.18 (13.8)	13.23 (12.9)
Air temperature min., °C	0.81 (12.5)	0.82 (7.8)
Solar radiation, MJ m^{-2} d^{-1}	13.94	14.47 (7.74)

The shortwave solar radiation prediction was 14.47 MJ m^{-2} d^{-1}, or 3.8% higher than the mean solar radiation from the 24-yr record at Lamberton. Sioux Falls has more clear sky throughout the year than does Lamberton, thus the slightly higher value of predicted vs. measured solar radiation seems reasonable.

Sensitivity Analysis

Table 4 contains a list of the 14 input parameters that were tested for sensitivity to cumulative subsurface drainage output, along with the base values of the parameters and their S_r values. The S_r values are ranked by absolute value; the greatest is for the field capacity SMC of Soil Layer 2, at −1.55, and the smallest is for the RSN of the surface soil layer, at −0.12. Five of the six most sensitive parameters are related to soil water content. Three of the

Table 4. Relative sensitivity coefficients, S_r, for 14 RyeGro input parameters.

Parameter	Parameter base value, P	S_r
Field capacity soil moisture content, Soil Layer 2, cm^3 cm^{-3}	0.308	−1.55
Saturation soil moisture content, Soil Layer 3, cm^3 cm^{-3}	0.400	−1.39
Initial soil moisture content, Soil Layer 3, cm^3 cm^{-3}	0.29	0.92
Initial soil moisture content, Soil Layer 2, cm^3 cm^{-3}	0.23	0.88
Residual soil N, Soil Layer 2, kg N ha^{-1}	50.9	0.70
Field capacity soil moisture content, surface layer, cm^3 cm^{-3}	0.320	−0.53
Radiation use efficiency, kg dry matter ha^{-1} MJ^{-1} m^{-2}	2.8	−0.48
Maximum leaf area index, m^2 m^{-2}	7	−0.47
Initial soil moisture content, surface layer, cm^3 cm^{-3}	0.32	0.39
Saturation soil moisture content, surface layer, cm^3 cm^{-3}	0.526	0.36
Initial aboveground shoot biomass, kg dry matter ha^{-1}	30	0.23
Saturated hydraulic conductivity, Soil Layer 3, cm h^{-1}	0.0006	0.20
Mineralization potential, %	20	−0.16
Residual soil N, surface layer, kg N ha^{-1}	15.0	−0.12

five include parameters that affect the available water capacity of the three soil layers. The other two parameters are the initial SMCs of Soil Layer 3 and Soil Layer 2. Since RyeGro's hydrology model is based on the simple representation of the soil as three layers, it can be expected that the subsurface drainage response, which is simulated from Soil Layer 2 when the SMC exceeds the field capacity SMC, will be sensitive to both the available water content and the initial values for the moisture content in these layers. Three N cycling parameters were tested: the RSN of Soil Layer 2, the mineralization potential of the soil organic matter content, and the RSN of the surface soil layer. These parameters were ranked 5th, 13th, and 14th in sensitivity. The three plant-related parameters included in the analysis: radiation use efficiency, maximum leaf area index, and initial aboveground shoot biomass, were ranked 7th, 8th, and 11th in sensitivity. Thus, the hydrologic parameters are more influential in the prediction of cumulative subsurface drainage NO_3–N losses than are either the N cycling or plant growth parameters. Knowing which parameters are most sensitive provides the model user guidance as to which parameters require careful selection when setting up a simulation scenario.

Initial Residual Soil Nitrate and Soil Moisture Content

The mean value of the initial residual soil NO_3^- in the three soil layers on the fall rye sowing date was calculated as 108 kg N ha^{-1} (SD of 36 kg N ha^{-1}), which is slightly lower than an estimate of 123 kg N ha^{-1} expected in the ground to a depth of 1.5 m after the corn portion of a corn–soybean crop rotation in southwestern Minnesota (G. Randall, personal communication, 2004).

The mean values of the predicted SMC in the three soil layers were 9.2, 11.2, 12.5, and 13.7 cm for the 15 September and 1, 15, and 30 October sowing dates, respectively. The long-term, observed mean values at the SWROC under continuous corn to a depth of 1.5 m for the same sowing dates were 10.9, 10.9, 11.4, and 12.2 cm, respectively. The predicted values are comparable to the measured values for the 1 October and 15 October sowing dates. Soil moisture was underestimated on average by 1.7 cm for the 15 September sowing date and overpredicted by 1.7 cm for the 30 October sowing date. The predicted initial soil moisture contents follow the expected trend of a wetter soil profile toward the end of autumn.

Rye Aboveground Biomass Accumulation

The mean estimate of aboveground biomass production on a dry matter basis as a function of fall sowing date is shown in Fig. 2. In terms of growth relative to sowing date, the model predicts that, until the first week of May, rye planted in mid-September will produce twice as much aboveground biomass as rye planted in October. In May, the late-planted rye eventually develops a complete canopy and is able to convert intercepted solar energy to biomass at the same rate as the earliest planted rye; however, the difference in cumulative biomass due to planting date is not overcome. The consequences of lower cumulative biomass production are lower NO_3–N uptake and hence less reduction in NO_3–N subsurface drainage loss due to the scavenging effect of the growing rye crop.

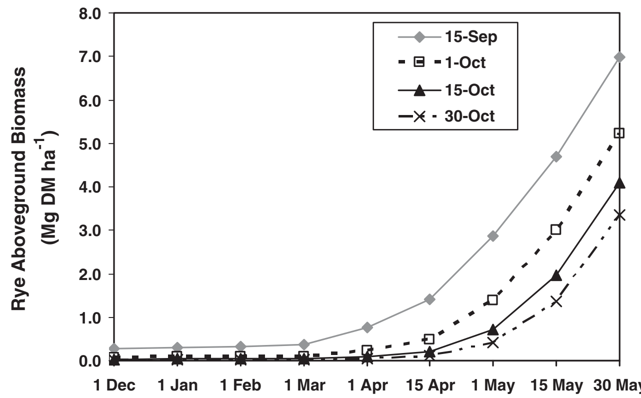

Fig. 2. Cumulative rye aboveground biomass (DM, dry matter) for four fall sowing dates; the data represent mean values after 2500 simulation years.

Rye growth is highly variable, depending on soil and climate conditions in the fall, winter, and spring. The weather generator provided a means by which rye growth could be predicted given numerous patterns of weather. The estimated variability of biomass production is shown in Table 5.

Artificial Subsurface Drainage Nitrate-Nitrogen Losses

The long-term simulation results quantify the mean reduction in NO_3–N losses at the field scale through artificial subsurface drainage systems due to N uptake and reduction in drainage volume due to a growing rye cover crop. The model predicted a mean value of 25 kg N ha^{-1} for drainage NO_3–N losses for the mid-September through May time frame without a growing rye crop. Figure 3 illustrates the mean drainage NO_3–N losses of treatments with and without a rye cover crop for four fall planting dates. The mid-September sowing effects a mean reduction in NO_3–N losses of 11 kg N ha^{-1} by the end of May, more than twice that predicted when the rye was planted at the end of October. The simulation outcomes for the four sowing dates are presented as a percentage reduction in NO_3–N losses in Fig. 4.

Average subsurface drainage NO_3–N losses from 15 September to 30 May were predicted to be 24.9 kg N ha^{-1} for a standard corn–soybean rotation (Fig. 3). Inclusion of a rye cover crop sown on 15 September reduced the

Table 5. Means and standard deviations of aboveground biomass production for 2500 simulation years for four fall planting dates.

	Biomass production			
Sowing date	15 Apr.	1 May	15 May	30 May
	Mg dry matter ha^{-1}			
15 Sept.	**1.4 (0.7)**	**2.9 (0.9)**	**4.7 (1.1)**	**7.0 (1.2)**
1 Oct.	**0.5 (0.3)**	**1.4 (0.7)**	**3.0 (0.9)**	**5.2 (1.0)**
15 Oct.	**0.2 (0.1)**	**0.7 (0.4)**	**2.0 (0.7)**	**4.1 (0.9)**
30 Oct.	**0.1 (0.1)**	**0.4 (0.3)**	**1.4 (0.6)**	**3.3 (0.9)**

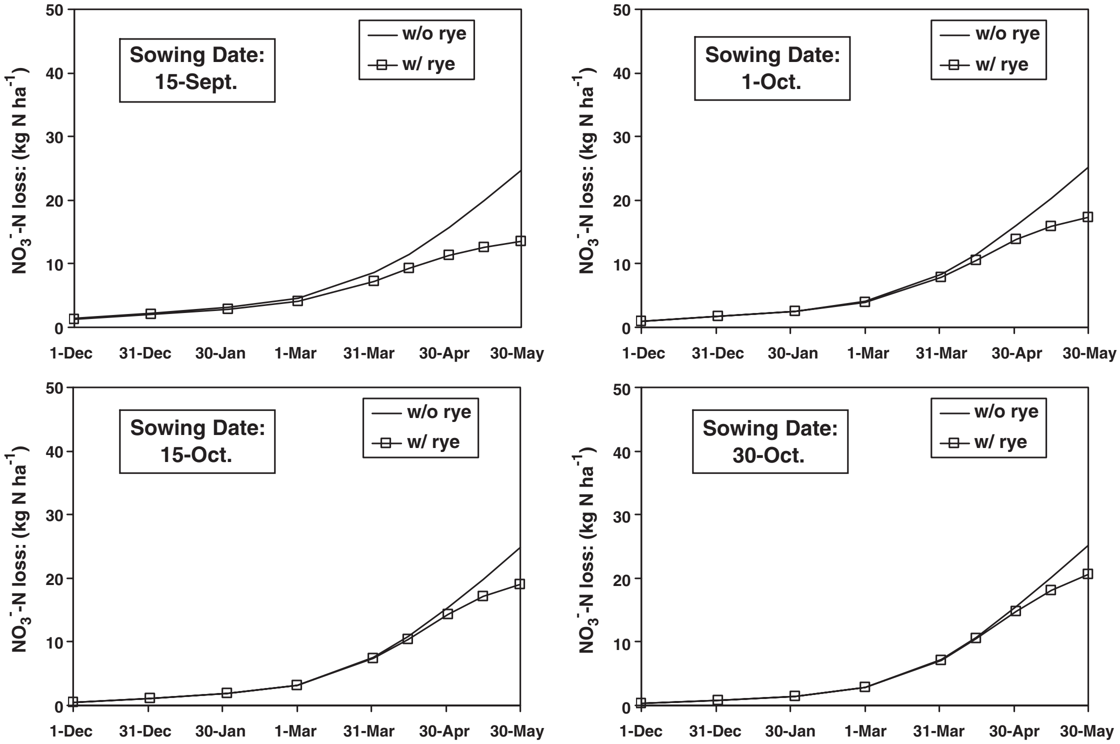

Fig. 3. Predicted cumulative subsurface NO_3–N losses for corn–soybean and corn–rye–soybean treatments for four fall rye sowing dates.

losses by 11.1 kg N ha^{-1} or 45%. Fall sowing dates of 1, 15, and 30 October resulted in reductions of 7.8, 5.8, and 4.6 kg N ha^{-1}, respectively, by the end of May. Desiccation of the rye on 1 May resulted in reductions of 4.5, 2.2, 1.2 and 0.7 kg N ha^{-1}, for the 15 September, and 1, 15, and 30 October sowing dates, respectively (Fig. 3).

The calculation of drainage N losses terminated each year at the end of May. No attempt was made to analyze the effects of the rye cover crop on drainage volume after desiccation of the rye. Conceivably the rye would reduce available soil water and thus reduce drainage volume and subsequent N losses both while growing and for some period of time after having been killed.

The exceedance probabilities for the difference in NO_3–N drainage losses given the four fall sowing dates and four spring kill dates under investigation are depicted in Fig. 5. The values for the reductions or changes in NO_3–N losses at 50% exceedance probability correspond to the differences between average values for the NO_3–N losses with and without rye shown in Fig. 3. The set of graphs clearly shows the influence of early sowing dates and later kill dates on NO_3–N reductions due to a rye cover crop. As the rye is sown later, the curve for the 30 May kill date shows increased separation from the curves for the other kill dates, indicating that to effect more than modest reductions in NO_3–N losses, the rye must be permitted to grow until late May.

Figure 6 combines on one graph the exceedance probabilities for one spring kill date, 30 May, given the four sowing dates. Just as the plots of cumulative aboveground biomass and exceedance probabilities of changes in NO_3–N loss indicated separation between values for the 15 September sowing date and the 1, 15, and 30 October sowing dates, the graphs of exceedance probability evidence the marked reduction in NO_3–N losses when the rye was sown in mid-September.

In 3 yr out of 4 (exceedance probability = 75%), rye effected reductions in drainage NO_3–N loss from 2.6 to 7.0 kg N ha^{-1} through 30 May for fall rye sowing dates from 15 September through 30 October. In 1 yr in 4, drainage N loss reductions ranged from 6.2 to 14.8 kg N ha^{-1} for the same sowing dates, and for 1 yr in 10, from 8.3 to 19.1 kg N ha^{-1}.

Under favorable climatic conditions for cover crop growth, growing fall-sown rye after corn in the corn–soybean crop rotation can make a substantial difference in the amount of NO_3–N leaving the field via subsurface drainage systems. On the other hand, there are years

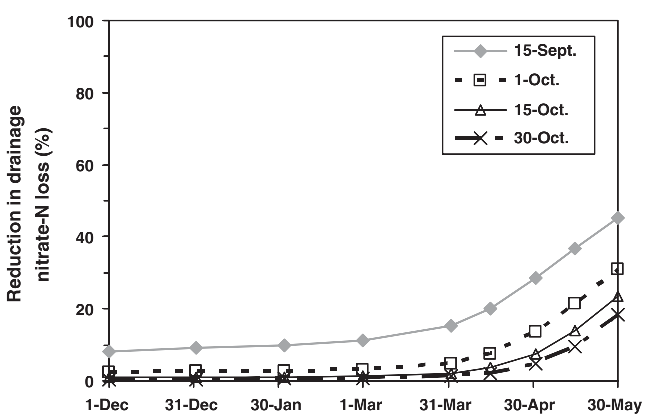

Fig. 4. Reduction in subsurface drainage NO_3–N losses for the corn–rye–soybean treatment compared with the corn–soybean treatment for four different planting dates.

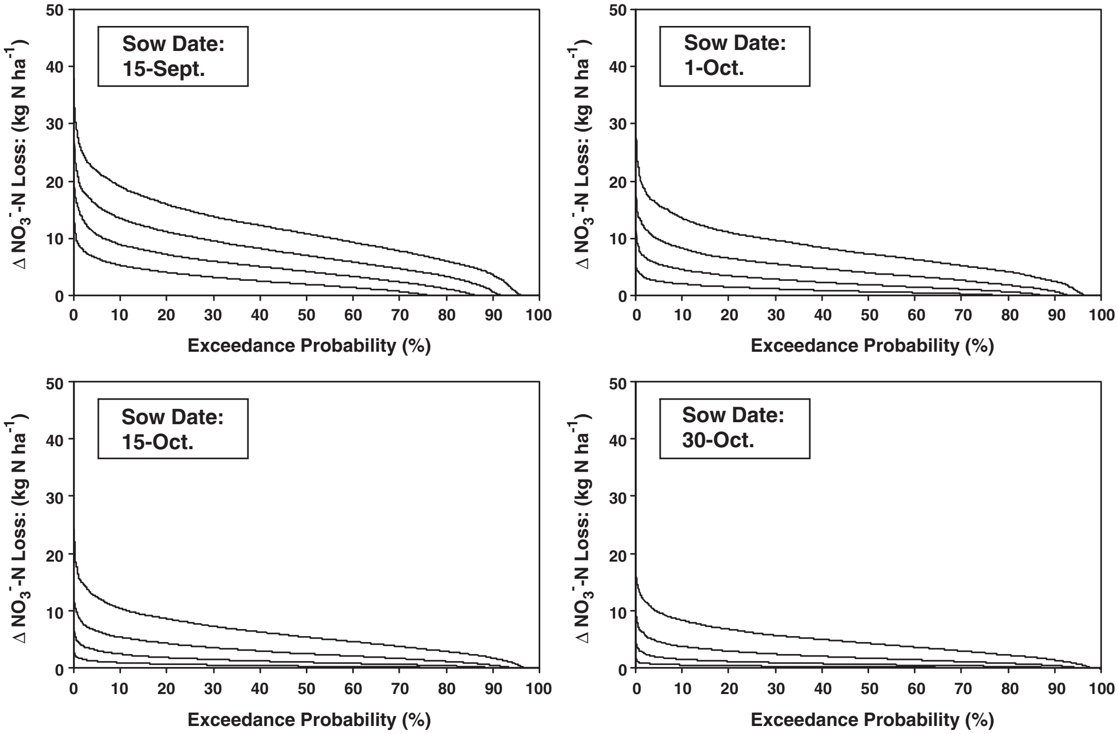

Fig. 5. Exceedance probability of the difference in subsurface drainage NO_3–N losses between the corn–soybean and corn–rye–soybean treatments for four spring dates and four different fall sowing dates. The four curves in each graph display results for the four spring kill dates: 30 May, 15 May, 1 May, and 15 April (top to bottom).

during which the use of fall-sown rye makes no difference in drainage system effluent losses (Fig. 7). During years when the drainage volume was estimated to be zero, growing rye made no difference in NO_3–N losses. Figure 7 shows the percentage of years during which there were no drainage N losses for treatments with and without rye, given a planting date of 1 October.

DISCUSSION

Seasonal crop production constraints in Minnesota make the use of winter cover crops challenging. A winter rye crop can be expected to reduce subsurface drainage losses of NO_3–N an average of 2.8 kg N ha^{-1}, or 11%, if planted on 15 October and desiccated on 15 May. Over the long term, farm operations now using the current standard field corn–soybean crop rotation, with a typical October corn harvest and mid-May soybean planting date, will realize a minimal benefit in reduction of off-field transport of N through subsurface drainage systems by the conventional use of a fall-planted cover crop; however, creative planting solutions of rye before summer crop harvest, for example aerial seeding when soil moisture conditions are conducive to germination, and of soybean into standing rye before chemical desiccation or shredding of the rye in spring, have the potential to

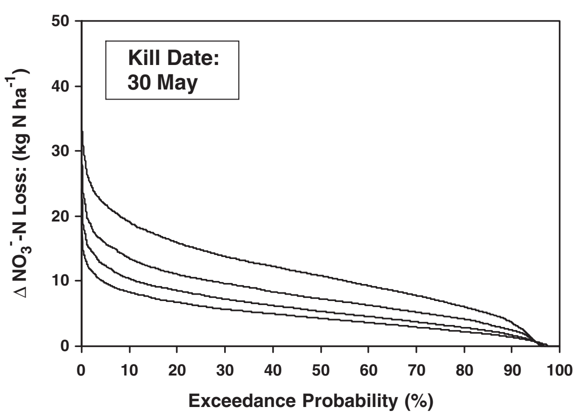

Fig. 6. Exceedance probability of the difference in subsurface drainage NO_3–N losses between the corn–soybean and corn–rye–soybean treatments on 30 May given four different sowing dates. The four curves display results for the four sowing dates: 15 September and 1, 15, and 30 October (top to bottom).

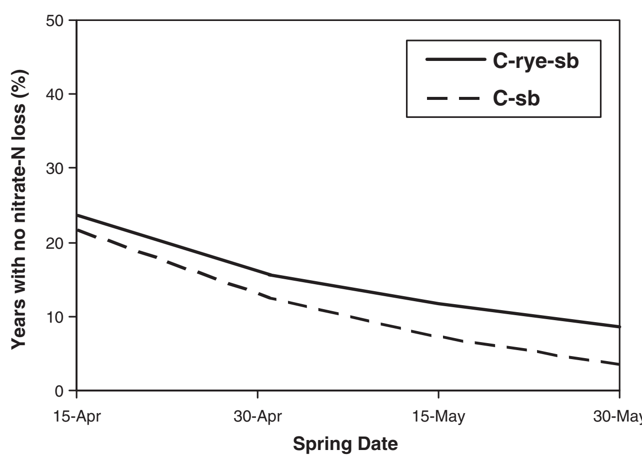

Fig. 7. Percentage of years having no NO_3–N drainage losses through the spring date shown on the *x* axis, given a rye sowing date of 1 October. C-rye-sb = corn–rye–soybean; C-sb = corn–soybean.

extend the N reduction benefits of cover crops within the confines of the current corn–soybean crop rotation.

Cover cropping practice offers promising opportunities for reductions in N losses for cropping rotations wherein the primary crops are harvested before mid-September and planted after mid-May. A winter rye crop can be expected to reduce drainage NO_3–N losses on average 7.4 kg N ha^{-1} if planted on 15 September and desiccated 15 May, and on average 11.1 kg N ha^{-1} if desiccated 30 May (Fig. 3). The obvious conclusion is that early autumn sowing of the cover crop substantially reduces drainage NO_3–N losses. Also, the longer the cover crop is allowed to grow in the spring, the greater the reduction in N losses.

Although the routine, conventional use of cover crops in the standard corn–soybean rotation appears to provide a small benefit in off-field export of N, strategic use of cover crops could provide important N scavenging services when climatic and soil conditions favor high spring drainage losses. Research in Minnesota has shown that RSN levels rise in dry years, setting the stage for large NO_3–N losses in wet years (Randall, 1998; Strock et al., 2004). Since crops are often harvested early during the drier years, cover crops could be planted early in an effort to scavenge N that is positioned for spring loss. In this case, the cover crop would need to be managed in the spring, given the climatic conditions at the time, to avoid loss of soil moisture needed by the subsequent summer crop.

In support of the research objectives, the soil–plant–atmosphere model RyeGro was developed as an analysis tool for investigation of the water quality effects of a winter rye cover cropping practice in the northern Corn Belt. RyeGro uses a relatively simple and approximate approach to represent key physical biogeochemical processes. The level of model complexity was appropriate for providing estimates of approximately ±20% for subsurface drainage N losses, given the existence of spatial variability in soil properties and real-world field variables such as snow accumulation, drifting, and thawing, soil freezing and thawing, and the extent and effects of soil macropores. The modeling approach suitably fit the field input data, which were limited in scope.

The use of a stochastic climate generator was an effective method for estimating the probabilities of subsurface N loss reduction by a winter rye cover crop. Weather variables generated through the summer months during each simulation year were used to reestablish fall initial soil moisture and residual soil NO_3^- values, key components to predicting rye establishment and spring drainage N losses, respectively. The continuous generation of weather variables maintained realistic probabilities for the values of the initial variables each year. The use of a centuries-long generated climate record provided the range of climate conditions possible for cover crop establishment and growth and reduced the variation about the model's mean predictions. Thus, the stochastic weather generator contributed to meeting the research objective of determining the influence of climate on the efficacy of the winter rye cover cropping practice.

The objective that the model be user friendly was achieved. Once the relationships were established in the various model components, calibration and operation of the model were performed with a modest investment of time and effort. The use of the model in another location will require basic soil property inputs, data from which fall initial soil moisture content–RSN–climate relationships can be determined, data from which drainage event flow decay rate can be obtained, and climate inputs.

Estimates of plant N uptake and determination of spring soil thaw and subsequent first drainage events were two model outcomes that require more detailed, mechanistic representation of relevant processes to improve their predicted accuracies. By design, the N uptake curve in RyeGro represents an average value derived from a scatter of field measurements. More accurate prediction of plant N uptake would require determination of the causes of seasonal variations in uptake and development of algorithms to better represent the processes involved. The processes of soil freezing and thawing have been represented in existing models to a higher level of detail than in RyeGro. Even with additional complexity, however, the modeling of spring thaw drainage events is challenging (Sands et al., 2003) and more detailed snow–freeze–thaw algorithms are still being sought for agronomic systems models (Malone et al., 2004).

SUMMARY AND CONCLUSIONS

The objectives of this research were to investigate the influences of fall planting date and climate on rye biomass yield and N uptake in the spring and to assess the probability that a fall-planted cereal rye reduces NO_3–N loss through artificial subsurface drainage systems in southern Minnesota. Computer simulation modeling was used to predict rye cover crop establishment and growth, soil water balance, N cycling, and drainage NO_3–N losses from mid-September through May. A soil–plant–atmosphere model, RyeGro, was developed for the analysis. A stochastic weather generator imbedded in RyeGro estimated the necessary climate variables to carry out the probabilistic analysis for 2500 simulation years (Feyereisen, 2005), thus providing an opportunity to investigate outcomes across the broad range of climatic conditions experienced in this geographic region.

We conclude that the simulation techniques used by this research provide reasonable insight into the effect of autumn planting date of a rye cover crop on subsurface drainage NO_3–N losses. To reduce average field NO_3–N losses by >11%, the cover crop will need to be planted before 15 October and permitted to grow until 15 May. Reduction in average field NO_3–N losses of 30% or more are possible if the cover crop is planted 15 September and permitted to grow until 30 April, or is planted 1 October and grown until 30 May. Used in an appropriate cropping system and managed properly, cover crops in southwestern Minnesota offer promise to reduce field losses of NO_3–N through artificial subsurface drainage systems.

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PLOS ONE

RESEARCH ARTICLE

Towards sustainable maize production in the U.S. upper Midwest with interseeded cover crops

Hannah L. Rusch[1☯], Jeffrey A. Coulter[1☯], Julie M. Grossman[2‡], Gregg A. Johnson[1,3‡], Paul M. Porter[1‡], Axel Garcia y Garcia[1,4☯]*

1 Department of Agronomy and Plant Genetics, University of Minnesota, St. Paul, Minnesota, United States of America, **2** Department of Horticulture, University of Minnesota, St. Paul, Minnesota, United States of America, **3** Southern Research and Outreach Center, University of Minnesota, Waseca, Minnesota, United States of America, **4** Southwest Research and Outreach Center, University of Minnesota, Lamberton, Minnesota, United States of America

☯ These authors contributed equally to this work.
‡ These authors also contributed equally to this work.
* axel@umn.edu

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Abstract

The incorporation of cover crops into the maize (*Zea mays* L.)-soybean [*Glycine max* (L.) Merr.] rotation in the U.S. upper Midwest may improve sustainability. Long, cold winters in the region make identifying successful cover crop species and management practices a challenge. Two experiments were conducted in Minnesota, USA from fall 2016 through spring 2019 to examine the effect of cover crops interseeded at four- to six-leaf collar (early-interseeded) and dent to physiological maturity (late-interseeded) on biomass and grain yield of maize. Annual ryegrass (*Lolium multiflorum* L.) and cereal rye (*Secale cereale* L.) were evaluated as monocultures and in mixtures with crimson clover (*Trifolium incarnatum* L.) and forage radish (*Raphanus sativus* L.). Differences in canopy cover and biomass of late-interseeded cover crops were observed at the southernmost location in 2018. Additional accumulated growing-degree days in fall 2018 did not translate into increased cover crop canopy coverage of late-interseeded cover crops. Differences in cover crop canopy cover and biomass of early-interseeded cover crops were observed by fall frost at all locations in 2017 and at the northernmost location in 2018. Cover crop canopy cover and biomass at termination before planting maize, soil moisture at maize planting as well as maize aboveground biomass and yield were not affected by spring cereal rye regrowth of cover crops late-interseeded the previous year. Similarly, early-interseeded cover crops did not affect maize aboveground biomass or yield. We attribute these results to limited cover crop growth. This highlights the potential of a variety of cover crop strategies interseeded into maize in the U.S. upper Midwest; however, efforts to fine-tuning cover crop management and weather conditions are needed to benefit from such practice.

analysis, decision to publish, or preparation of the manuscript.

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Introduction

The maize (*Zea mays* L.)-soybean [*Glycine max* (L.) Merr.] rotation dominates agricultural production in the U.S. upper Midwest. This system is characterized by mechanization, high external inputs, and an extended fallow period. During the fallow period between harvest and planting, soils are vulnerable to erosion and essential plant nutrients can be lost to ground and surface waters. Incorporating cover crops into the maize-soybean rotation can help prevent these losses and thereby increase sustainability.

Cover crops deliver multiple ecosystem services [1], such as reduced nutrient leaching [2,3] through nutrient uptake [4], reduced soil erosion [5], enhanced soil fertility [6] and improved soil-water dynamics [7], weed suppression [8,9], and forage production [10]. Cover crops are promoted as a best management practice to avoid water quality impairment [11] and as a soil management tool [5], but their adoption remained low by the mid 2010s [12]. In northern climates, the period of time for cover crop establishment after the maize harvest in October or November is limited by available heat units and daylight hours. However, interseeding cover crops into maize before harvest may improve establishment and function.

Little is known about the potential for integrating cover crops into the maize-soybean rotation. In Minnesota, cover crops interseeded into maize at the seven-leaf collar stage reduced soil nitrate in spring, thus reducing the potential for nitrate leaching without reducing maize yield [13]. Cover crops did, however, reduce soil water content in a dry season and reduced soybean yield when they were not adequately terminated [13]. Another study in Minnesota found that cereal rye (*Secale cereale* L.; CR) aerially interseeded into maize or soybean in mid-August to mid-September produced more than 0.050 Mg ha^{-1} of biomass in 40% of the instances observed [14].

Until more is known about the consequences of interseeding cover crops, the practice is unlikely to be widely adopted by maize producers. Additionally, more information is needed on the viability of alternative cover crops for the region. Until recently, research on cover crops in the U.S upper Midwest focused on a few species. Cereal rye is among the most popular cover crops in the United States [15]. The literature on CR provides insight into the best timing for planting to maximize biomass [16], termination timing to avoid allelopathic effects [17], and establishment options [13,14,18].

This study aims to increase the knowledge of cover crop interseeding options for the U.S. upper Midwest. To this end, six cover crop strategies, including CR as well as underrepresented cover crop species, were early- and late-interseeded into maize. The objectives were to: 1) compare the establishment and growth of cover crops interseeded at four- to six-leaf collar and dent to physiological maturity maize stages of development across multiple environments, 2) evaluate the effect of interseeding CR into maize at dent to physiological maturity stages on regrowth in the springtime and on soil moisture at maize planting, and 3) assess the effect of interseeded cover crops on maize yield. The results of this study provide insight into possible outcomes of alternative cover cropping practices for maize-based cropping systems and additional management options.

Materials and methods

Experimental sites

Two field experiments were conducted from fall 2016 through spring 2019 at three Minnesota locations. Experiment 1 involved interseeding cover crops at maize dent to physiological maturity stages of development (hereafter referred as late-interseeded) and experiment 2 consisted of interseeding cover crops at four- to six-leaf collar stages of development (hereafter referred as early-interseeded). Both studies were conducted at the University of Minnesota Research and Outreach Centers in Grand Rapids (47˚18'N, -93˚53'W), Lamberton (44˚24'N, -95˚31'W), and Waseca (44˚06'N, -93˚53'W), Minnesota, USA. The late-interseeded study was conducted within the Minnesota Long-Term Agricultural Research Network (http://ltarn.cfans.umn.edu/). These three locations span a range of soil types, precipitation, and weather gradients. Soils were a well-drained Nashwauk loam (fine-loamy, mixed, superactive, frigid Oxyaquic Glossudalfs) at Grand Rapids, a moderately well drained Normania clay loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls) at Lamberton, and a somewhat poorly drained Nicollet clay loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls) at Waseca. Long-term (1990–2015) average annual cumulative precipitation is 700 mm in Grand Rapids, 708 mm in Lamberton, and 922 mm in Waseca; 75% of that precipitation falls during the growing season (April-September). For the same period, the long-term average annual maximum air temperature is 8˚C in Grand Rapids and 13˚C in Lamberton and Waseca. The long-term average annual minimum air temperature for the same period is -1˚C in Grand Rapids, 1˚C in Lamberton, and 2˚C in Waseca.

Experimental design

Both experiments were a randomized complete block design with four replications, except for the late-interseeded study in Grand Rapids, which had three replications. Plot size in the late-interseeded study was 3.0 m wide by 6.1 m long at all locations. Plot size in the early-interseeded study was 3.0 m wide by 9.1 m long at Grand Rapids, 3.0 m wide by 8.8 m long at Lamberton, and 4.6 m wide by 8.5 m long at Waseca.

Treatments included six cover crop strategies and a no cover crop control. Two grass species —annual ryegrass (*Lolium multiflorum* L.; AR) and CR—were used in a monoculture and in mixtures of two and three species. The two-species mixtures consisted of a grass plus crimson clover (*Trifolium incarnatum* L.; CC) and are denoted as ARCC and CRCC. The three-species mixtures included a grass, CC, and forage radish (*Raphanus sativus* L.; FR) and are denoted as ARCCFR and CRCCFR. The CR plots in the late-interseeded study were instrumented with ceramic cups to monitor NO_3-N in the soil solution (not herein reported) and with access tubes to monitor soil moisture, which resulted in frequent visits. To avoid concerns with disturbance, a no cover crop control treatment was assigned to each grass species (Table 1) and are denoted as ARNC and CRNC. Cover crop species were selected based on functional traits (i.e., potential for N uptake and soil fertility improvement), phenological niche (i.e., winter hardiness), suitability for interseeding (i.e., shade tolerance), and seed availability. Cereal rye was the sole winter-hardy cover crop, while AR, CC, and FR winter-kill in this region.

Agronomic management

Plots rotated each year between maize and soybean. During the experimental years all plots in the late- and early-interseeded studies received strip-tillage (15 cm deep, 20 cm wide) one to

Table 1. Cover crop seeding rates in Experiments 1 and 2.

Cover crop	Monoculture		2-species mixture		3-species mixture	
	AR	CR	ARCC	CRCC	ARCCFR	CRCCFR
	Seeding rate (kg ha^{-1})					
Annual ryegrass (AR)	28	-	14	-	14	-
Cereal rye (CR)	-	67	-	33.5	-	33.5
Crimson clover (CC)	-	-	22	22	16.5	16.5
Forage radish (FR)	-	-	-	-	10	10

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15 d before planting maize in 76-cm wide rows at 86,000 seeds ha^{-1} at a depth of 5 cm with a 4-row planter (Table 2). For both studies, springtime regrowth of winter-hardy CR interseeded the previous year was terminated using 0.84 kg ae ha^{-1} of glyphosate [N-(phosphonomethyl) glycine] applied one to seven days before maize planting. Due to differences in growing season length, maize genotypes varied between locations. Maize in the late-interseeded study was a 76 RM hybrid (Pioneer P7632AM) at Grand Rapids and a 103 RM hybrid (DEKALB DKC53-56RIB) at Lamberton and Waseca. Maize in the early-interseeded study was a 76 RM hybrid (Pioneer P762AM1) at Grand Rapids, a 107 RM hybrid (Pioneer P0157AMX) at Lamberton, and a 99 RM hybrid (DEKALB DKC49-72RIB) at Waseca.

Nitrogen fertilizer in the late-interseeded study was broadcast applied at 73 kg ha^{-1} as urea (46-0-0, N-P-K) within one week of maize planting and sidedressed at 70 kg ha^{-1} as urea at the six-leaf collar stage of maize. Nitrogen and S fertilizers were applied in the early-interseeded study at Grand Rapids and Waseca at 63 kg N ha^{-1} as urea and 17 kg S ha^{-1} as gypsum (calcium sulfate dihydrate) within one week of maize planting, and an additional 101 kg N ha^{-1} as urea was sidedressed at the six-leaf collar stage of maize. In Lamberton, no fertilizer was applied at planting due to wet field conditions and 135 kg N ha^{-1} was sidedressed as urea at the six-leaf collar stage of maize. In 2017, fertilization at Lamberton was delayed such that cover crops in the early-interseeded study were interseeded before any fertilization was applied.

Weeds were controlled with a post-emergence herbicide approximately six weeks after maize planting. Weeds in the late-interseeded study were treated with glufosinate {(RS)-2-Amino-4-(hydroxy(methyl)phosphonoyl)butanoic acid} while glyphosate was applied in the early-interseeded study.

Cover crop seed was weighed by species in the lab and mixed at the field. Cover crops were manually broadcast in the early-interseeded study, corresponding to the time of maize side-dressing, and lightly incorporated with a rake in the late-interseeded study at all locations in 2017 and at Lamberton in 2018 as no rainfall was predicted.

Growing-degree days (GDD) for CR were calculated from 1 March through the first frost day (0˚C minimum air temperature) in the fall using a minimum base air temperature of 4.4˚C [19]. For maize, GDD were calculated from planting to harvest using a minimum base air temperature of 10˚C. The maximum air temperature was set to 30˚C for both CR and maize.

Table 2. Calendar of activities at late- and early-interseeded studies.

Activity	Grand Rapids			Lamberton			Waseca		
	2016	2017	2018	2016	2017	2018	2016	2017	2018
Late-interseeded cover crops									
Cover crop sampling	-	7-May	22-May	-	21-Apr	16-May	-	21-Apr	7-May
Cover crop termination	-	10-May	22-May	-	29-Apr	8-May	-	23-Apr	10-May
Maize planting	15-May	10-May	22-May	30-Apr	8-May	16-May	29-Apr	24-Apr	7-May
Cover crop interseeding	20-Sep	3-Sep	10-Aug	14-Sep	31-Aug	14-Aug	14-Sep	4-Sep	13-Aug
Maize harvest	25-Oct	26-Oct	13-Oct	17-Oct	25-Oct	26-Oct	16-Oct	30-Oct	16-Oct
Cover crop sampling	9-Nov	9-Nov	5-Nov	14-Nov	30-Oct	20-Oct	15-Nov	1-Nov	27-Oct
Early-interseeded cover crops									
Cover crop sampling	-	-	15-May	-	28-Apr	7-May	-	-	14-May
Cover crop termination	-	-	22-May	-	4-May	8-May	-	-	17-May
Maize planting	-	10-May	22-May	19-May	12-May	19-May	-	5-May	7-May
Cover crop interseeding	-	27-Jun	26-Jun	29-Jun	15-Jun	15-Jun	-	14-Jun	14-Jun
Maize harvest	-	9-Nov	5-Nov	21-Oct	24-Oct	18-Oct	-	29-Oct	29-Sep
Cover crop sampling	-	26-Oct	13-Oct	16-Oct	26-Oct	26-Oct	-	30-Oct	16-Oct

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Data collection

Cover crop canopy cover and biomass was measured in maize plots both in the fall when freezing air temperature remained consistent for three days (mid-October to early-November) and in the spring in maize stubble prior to termination of CR (late-April to mid-May). In most cases, fall canopy cover and biomass sampling occurred after maize harvest. However, in some cases, especially at Grand Rapids, freezing temperatures occurred before maize harvest and logistical constraints prevented harvesting maize before cover crop sampling in fall. A digital image was captured using the Canopeo app [20] to estimate the percentage of living green cover within a single 0.1-m^2 quadrat per plot. Subsequently, all biomass within the quadrat was collected, placed in a brown paper bag, dried in a forced-air oven at 60˚C until constant mass, and weighed.

Soil moisture was obtained on 7- to 10-d intervals at maize planting in late-interseeded cover crop plots with CR and the corresponding no cover crop control. A factory-calibrated PR2 soil moisture probe with an HH2 handheld readout device (Delta-T Devices, Cambridge, UK) was inserted into an access tube installed in the center of each plot to measure soil moisture as a percentage of volume at 0.10, 0.20, 0.30, 0.40, 0.60, and 1 m depths. The average of three measurements per depth was used as a final soil moisture value, and results from the top 30 cm of soil are presented in this study.

Three maize plants per plot were collected at physiological maturity. Maize was cut at 5 cm above the soil surface and ears were separated from stover. Stover was chopped in the field using a chipper. Maize stover and ears were dried in a forced-air oven at 60˚C until constant mass and weighed. Maize grain weight and moisture content was measured after maize physiological maturity by harvesting the center two rows of each plot using a small-plot combine. Grain yield was calculated at 155 g kg^{-1} moisture.

Statistical analysis

Data from each experiment were analyzed at $P < 0.05$ by analysis of variance with a linear mixed effects model (*lme4* package) [21] using R statistical software (R Core Team, 2013). Location, year, and cover crop strategy were considered fixed effects, and replication was considered a random effect. Soil moisture was analyzed at maize planting only, and depth was considered an additional fixed effect. Early-interseeded cover crop canopy cover and biomass at spring termination were analyzed separately by year due to no CR regrowth at Grand Rapids or Lamberton in 2019. When fixed effects were significant, means were compared with Tukey's honestly significant difference test at $P < 0.05$ using the *lsmeans* package in R [22].

Results

Weather conditions

Compared to the long-term average, the 3-yr study period tended to be drier and warmer at Grand Rapids, but wetter and cooler at Lamberton and Waseca; the starting year 2016 was the wettest and warmest at all locations. Grand Rapids fall periods were wet, with rainfall ranging from 40 to 75 mm above the long-term average, and maximum and minimum temperatures ranging from 4.3 and 2.9˚C above to -1.9 and -1.4˚C below the long-term average, respectively. At Lamberton, the tendency towards wet and cool seasons was very clear, except for the 2016–2017 winter and 2018 spring, when rainfall was 25 and 6 mm below the long-term average, respectively. The 2018–2019 winter, with maximum air temperature at 5.6˚C and minimum air temperature at 5.1˚C below the long-term average, was by far the coldest season at Lamberton. At Waseca, the tendency towards wet and cool seasons was very clear as well; except for spring from 2016 to 2018, when it was drier than the long-term average (Table 3).

Table 3. Long-term (1990–2015) average weather conditions during the study period (2016–2019).

Season	Long-term weather[$]			Weather conditions during the study period (deviations from long-term)											
	Rainfall	Tmax	Tmin	Rainfall (mm)				Maximum Air Temperature (˚C)				Minimum Air Temperature (˚C)			
	(1990–2015)			2016	2017	2018	2019	2016	2017	2018	2019	2016	2017	2018	2019
Grand Rapids															
Fall	158	9.7	1.4	75	40	61		4.3	1.4	-1.9		2.9	0.0	-1.4	
Spring	186	8.5	-1.9	-82	-15	-52	-35	3.8	1.9	2.3	0.0	2.4	1.0	-0.5	-1.2
Summer	279	23.9	13.2	18	15	-42		0.9	0.2	1.1		0.4	-1.4	0.0	
Winter	77	-8.8	-16.7	81	-16	-39	-69	5.9	2.7	3.1	-0.2	6.1	1.6	-0.3	-3.8
Year	700	8.3	-1.0	92	23	-72		3.7	1.6	1.2		3.0	0.3	-0.6	
Lamberton															
Fall	161	15.1	2.1	91	44	103		1.9	0.1	-3.1		3.0	0.7	-0.8	
Spring	206	13.0	0.8	72	33	-6	127	2.1	-0.1	-2.5	-2.9	2.2	0.8	-0.5	-1.2
Summer	293	27.2	14.7	83	2	143		0.2	-0.5	-0.2		1.2	-0.1	1.7	
Winter	48	-2.8	-13.2	41	-25	28	9	0.9	2.4	-1.3	-5.6	2.8	3.0	-1.2	-5.1
Year	708	13.1	1.1	287	55	269		1.3	0.5	-1.8		2.3	1.1	-0.2	
Waseca															
Fall	203	14.5	2.9	194	-42	179		4.0	0.2	-2.8		3.6	0.4	-1.3	
Spring	260	12.6	1.7	-59	-20	-7	60	2.6	0.4	-1.5	-2.6	1.9	0.9	-1.0	-2.0
Summer	360	26.6	15.3	184	10	19		1.2	0.6	0.1		1.0	-0.3	0.7	
Winter	99	-3.5	-13.0	76	0	30	10	1.5	2.3	-1.1	-4.1	3.2	2.7	-1.2	-4.5
Year	922	12.6	1.7	396	-52	223		2.3	0.9	-1.3		2.4	0.9	-0.7	

[¶] Spring = Mar–May, Summer = Jun–Aug, Fall = Sep–Nov, and Winter = Dec–Feb.

[$] Rainfall = total seasonal rainfall (mm); Tmax = average maximum air temperature (˚C), Tmin = average minimum air temperature.

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The early-interseeded cover crops study was conducted in 2017 and 2018 at Grand Rapids and from 2016 to 2018 in Lamberton and Waseca; due to flooding on 21–22 September 2016 (158 mm), the study at the Waseca site was abandoned. Early-interseeded cover crops at all locations received precipitation within one to two days of seeding. Cumulative precipitation seven days after seeding in 2016 was 9 mm in Lamberton while in 2017 and 2018 was 18 and 53 mm in Grand Rapids, 3 and 112 mm in Lamberton, and 15 and 80 mm in Waseca. The late-interseeded cover crops study was conducted from 2016 to 2018 at all locations. Late-interseeded cover crops at all locations received precipitation within five days of seeding in all years, except for Grand Rapids in 2018, which did not receive precipitation until 13 d after seeding. Cumulative precipitation seven days after seeding the late-interseeded study in 2016, 2017, and 2018 was 36, 4, and 0 mm in Grand Rapids; 19, 3, and 21 mm in Lamberton; and 89, 5, and 39 mm in Waseca (Fig 1).

Cover crop GDD accumulation varied among locations and years. At Grand Rapids, the early-interseeded cover crops accumulated 1300–1400 GDD from seeding to fall harvest, whereas at Lamberton and Waseca 400–500 more GDD were accumulated. Similarly, the late-interseeded cover crops at Grand Rapids accumulated fewer GDD compared with Lamberton and Waseca. Interseeding cover crops approximately two-weeks earlier in fall 2018 resulted in an additional accumulation of 181, 228, and 199 GDD before fall harvest at Grand Rapids, Lamberton, and Waseca, respectively (Table 4).

Canopy cover and biomass of late-interseeded cover crops

Canopy cover and biomass at fall frost of late-interseeded cover crops were affected by location, year, and strategy; only canopy cover was affected by the location x year interaction. At

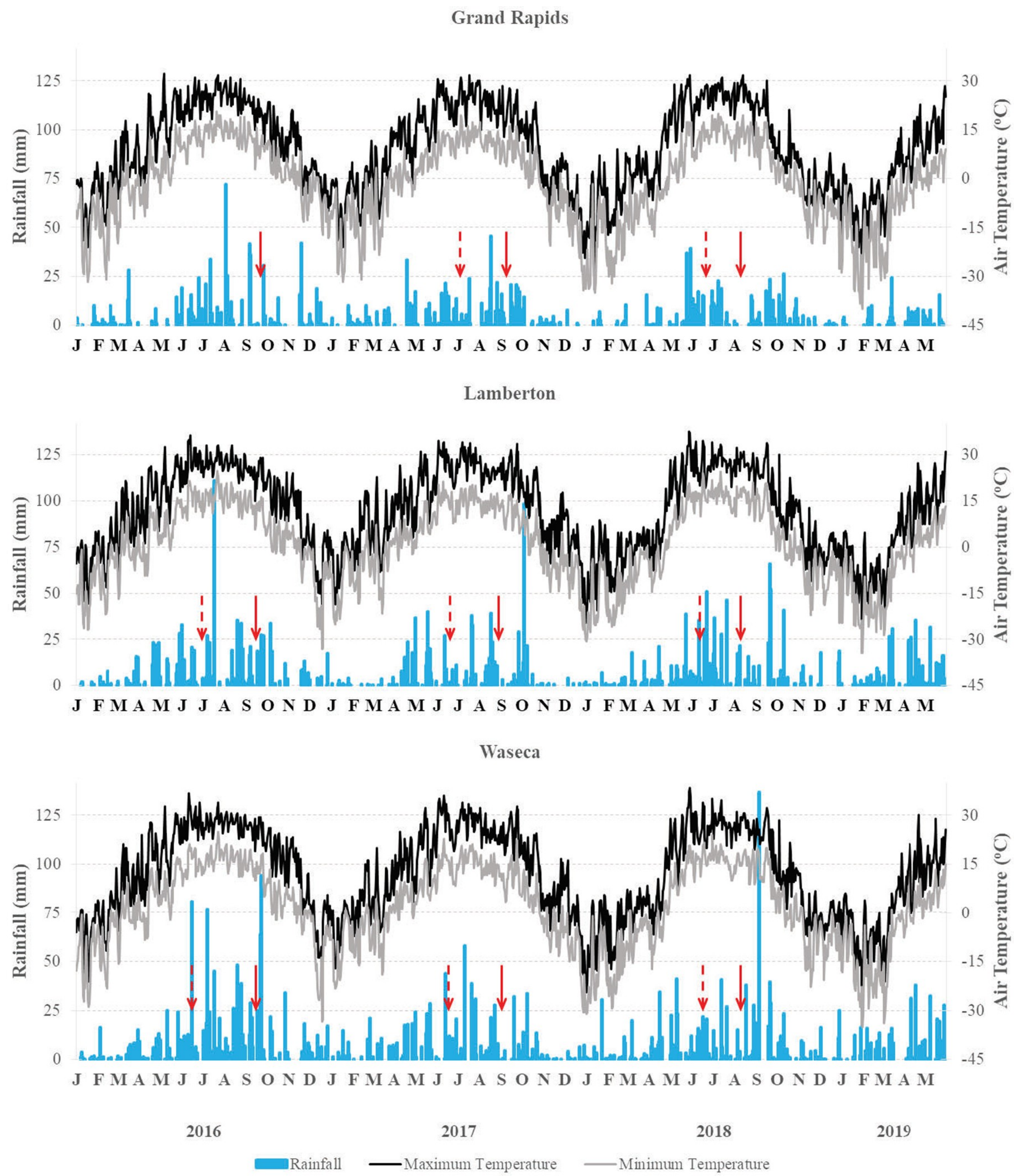

Fig 1. Weather conditions during the experimental years. Red arrows denote early- (dotted) and late-interseeded dates, approximately.

https://doi.org/10.1371/journal.pone.0231032.g001

spring termination; however, canopy cover was affected by location, year, and by the location x year interaction while biomass was affected by year only (Table 5).

Late-interseeded cover crops were seeded into maize at an earlier date in 2018, but greater GDD accumulation did not translate into more development or better canopy cover. At all locations and for all cover crop strategies, the average canopy cover in the fall was 35% or less in 2017 and 2018. Among locations, fall canopy cover of late-interseeded cover crops was least

Table 4. Accumulated growing degree-days (GDD) of early- and late-interseeded cover crops at fall frost and before termination in the spring.

Location	Period	Cumulative Growing-Degree Days (GDD)†					
		Early-interseeded cover crops			Late-interseeded cover crops		
		Fall¶	Spring$	Full Season	Fall¶	Spring$	Full Season
Grand Rapids	2016–2017	-	-	-	-	-	-
	2017–2018	1375	217	1592	445	217	662
	2018–2019	1331	185	1516	627	187	814
	Average	*1353 (±31)*	*201 (±23)*	*1554 (±54)*	*536 (±129)*	*202 (±21)*	*738 (±107)*
Lamberton	2016–2017	1818	270	2088	528	277	805
	2017–2018	1824	210	2034	614	285	899
	2018–2019	1877	266	2143	725	296	1098
	Average	*1840 (±32)*	*249 (±34)*	*2088 (±55)*	*622 (±99)*	*286 (±10)*	*934 (±150)*
Waseca	2016–2017	-	-	-	605	217	822
	2017–2018	1870	268	2138	725	75	792
	2018–2019	1795	236	2031	762	248	998
	Average	*1833 (±53)*	*252 (±23)*	*2085 (±76)*	*697 (±26)*	*180 (±122)*	*871 (±146)*

† Cumulative growing-degree days for cereal rye calculated from seeding using 4.44˚C and 30˚C as absolute minimum and maximum temperatures.

¶ For both early- and late-interseeded cover crops, GDD at fall were calculated from seeding to first day at 0˚C average air temperature.

$ For both early- and late-interseeded cover crops, GDD at spring were calculated from fall of the first year of a given period to termination in the spring of the second year of that period.

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at Grand Rapids in both years, and greatest at Lamberton in 2017 and at Waseca in 2018. No differences in canopy cover were found among cover crop strategies either year of the study, except at Waseca in 2018 when ARCCFR produced significantly more canopy cover than CR or CRCC (Fig 2).

Table 5. Significance of fixed effects (P > F) for late-interseeded cover crop canopy cover and biomass at fall frost and spring termination, soil moisture at maize planting, and maize aboveground biomass and yield response to six cover crop strategies interseeded into maize at Grand Rapids, Lamberton, and Waseca, MN in 2016–2018.

Source of fixed variation†	Fall frost		Spring termination		Soil moisture at maize planting	Maize aboveground biomass	Maize yield at 15.5% moisture
	Cover crop canopy cover	Cover crop biomass	Cover crop canopy cover	Cover crop biomass			
Location (L)	<0.01	<0.01	<0.01	0.63	<0.01	<0.01	<0.01
Year (Y)	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	0.03
Cover crop strategy (C)	<0.01	<0.01	0.23	0.15	0.14	0.76	0.63
Soil depth (D)	-	-	-	-	<0.01	-	-
L x Y	<0.01	0.24	<0.01	0.26	<0.01	<0.01	<0.01
L x C	0.05	0.11	0.954	0.26	0.12	0.37	0.94
Y x C	0.79	0.68	0.27	0.24	0.87	0.26	0.97
L x D	-	-	-	-	<0.01	-	-
Y x D	-	-	-	-	0.97	-	-
C x D	-	-	-	-	0.52	-	-
L x Y x C	0.59	0.82	0.93	0.16	0.90	0.84	0.29
L x Y x D	-	-	-	-	0.01	-	-
L x C x D	-	-	-	-	0.49	-	-
Y x C x D	-	-	-	-	0.90	-	-
L x Y x C x D	-	-	-	-	0.33	-	-

https://doi.org/10.1371/journal.pone.0231032.t005

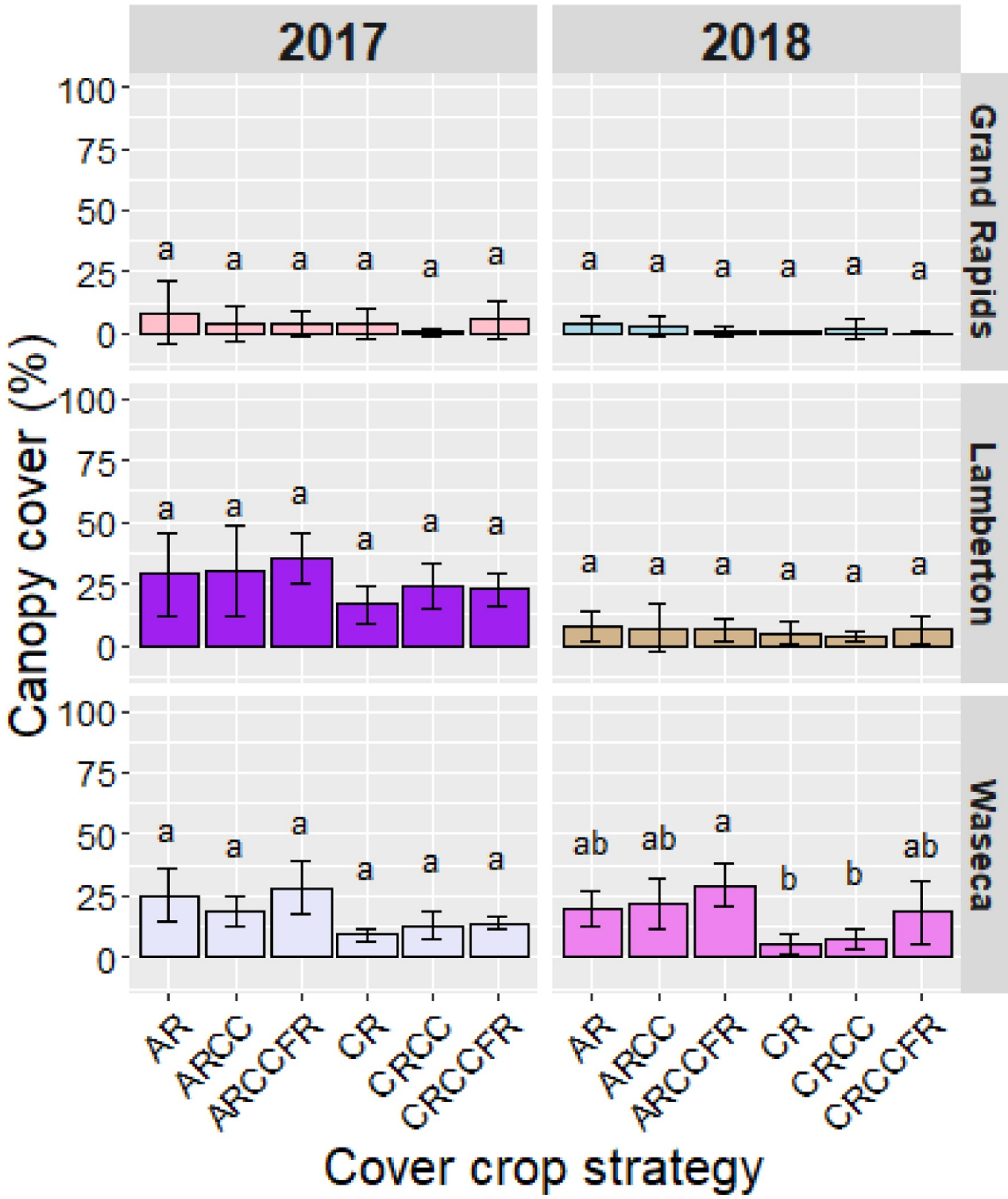

Fig 2. Canopy cover at fall frost of late-interseeded cover crops. For a given year within location, columns with different letters differ significantly at $P < 0.05$. Error bars are standard errors of the mean. AR = annual ryegrass, CC = crimson clover, FR = forage radish, CR = cereal rye.

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Mean fall biomass of late-interseeded cover crops at Grand Rapids was 0.076 Mg DM ha^{-1} in 2017 and significantly less (0.010 Mg DM ha^{-1}) in 2018; at Lamberton was 0.149 and 0.076 Mg ha^{-1} in 2017 and 2018, respectively; and at Waseca, which showed the least year-to-year variation, was 0.158 and 0.134 Mg DM ha^{-1} in 2017 and 2018, respectively.

Mean spring (termination time) canopy cover and biomass of late-interseeded cover crops consisted of CR regrowth only and no differences were observed among cover crop strategies, despite the greater seeding rate of the CR monoculture versus the CRCC and CRCCFR mixtures. Canopy cover was significantly greater in 2017 than 2018 at Lamberton and Waseca for the pooled average of all cover crop strategies while biomass was greater in 2017 than 2018 at all locations (Table 6).

Canopy cover and biomass of early-interseeded cover crops

Fall canopy cover and biomass of early-interseeded cover crops were affected by location, year, cover crop strategy, and their interactions except biomass, which was not affected by the location x year interaction. Canopy cover and biomass of CR at spring termination were not affected by year, cover crop strategy, and their interaction (Table 7).

Fall canopy cover of early-interseeded cover crops varied widely within location and between years. At all locations, instances of canopy cover decreased from 2017 to 2018. In all locations and within a year, AR-based strategies produced greater canopy cover than CR-based strategies. At Grand Rapids, AR-based strategies had greater canopy cover than CR strategies in 2017 and 2018. At Lamberton, AR-based strategies had greater canopy cover than CR and CRCC in 2017, but no differences between cover crop strategies were observed in 2018. At Waseca, AR-based strategies tended to have greater canopy cover than CR-based strategies in both years; however, significant differences were observed only between ARCCFR and CR and CRCC in 2017 (Fig 3).

Fall biomass of early-interseeded cover crops ranged from 1.57 Mg DM ha^{-1} with AR at Grand Rapids in 2017 to 0 Mg DM ha^{-1} with CR at Waseca in 2018. At all three locations, AR-based strategies most frequently produced more biomass in the fall of 2017 compared to CR-based strategies. In fall 2017, CR and CRCC produced the least biomass at Grand Rapids and Waseca while both AR and CR produced the least at Lamberton. Fall biomass of cover crops in 2018 was marginal in all locations, with no differences among strategies at any location (Fig 3).

Cereal rye regrowth of early-interseeded cover crops in spring was low at all locations in 2018 and did not grow at Lamberton in spring 2019. Canopy cover was less than 2.5% and biomass did not exceed 0.035 Mg DM ha^{-1} at any location in 2018 or 2019. As a consequence, location, year, cover crops strategy, and interactions had no effect on spring canopy cover and biomass (Table 7).

Effect of cover crops on soil moisture at maize planting

Soil moisture was only monitored in the CR-based strategies of the late-interseeded study. The mean soil moisture from ground thaw until maize planting was used to determine differences

Table 6. Canopy cover and biomass at spring termination of late-interseeded cereal rye.

Location	Year	Canopy Cover (%)	Biomass (Mg DM ha^{-1})
Grand Rapids	2017	2.88±0.71 a[†]	0.34±0.06 a
	2018	0.63±0.31a	0.03±0.01 b
Lamberton	2017	44.63±3.82 a	0.49±0.06 a
	2018	2.62±0.59 b	0.01±0.00 b
Waseca	2017	18.27±2.38 a	0.43±0.08 a
	2018	1.98±0.54 b	0.03±0.00 b

[†] Within a location in a column, means followed by different letters are significantly different at $P < 0.05$.

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Table 7. Significance of F values for fixed sources of variation for fall and spring canopy cover and biomass of early-interseeded cover crop as well as for above-ground biomass and grain yield of corn.

Source of fixed variation	Cover crop at fall frost†		Cover crop at spring termination¶,§		Maize§	
	canopy cover	biomass	canopy cover	biomass	biomass	grain yield
Location (L)	<0.01	<0.01			<0.01	<0.01
Year (Y)	<0.01	<0.01	0.054	0.065	0.0334	<0.01
Cover crop strategy (C)	<0.01	<0.01	0.214	0.600	0.977	0.198
L x Y	<0.01	0.195			<0.01	<0.01
L x C	<0.01	<0.01			0.702	0.351
Y x C	<0.01	<0.01	0.270	0.708	0.542	0.726
L x Y x C	<0.01	<0.01			0.439	0.0960

† 2016, 2017, and 2018.

¶ No spring regrowth at Grand Rapids and Lamberton.

§ 2018 and 2019.

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between cover crop strategies. Our results showed that soil moisture at maize planting was not affected by cover crops, but it was affected by location, year, depth, and by the location x year and location x depth interactions (Table 5). Within a year, significant differences among soil layers were observed at all three locations. In all cases, the top 10 cm soil was drier than the

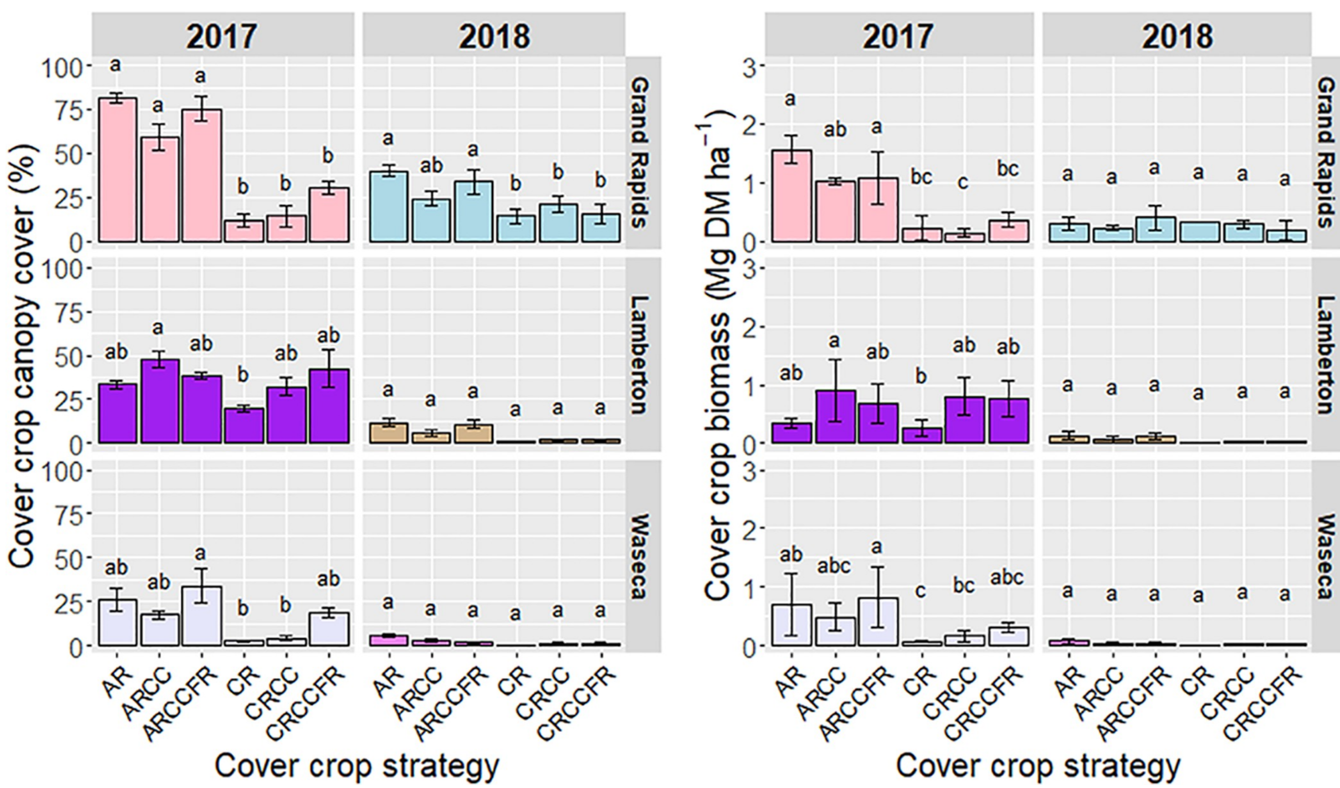

Fig 3. Canopy cover and biomass at fall frost of early-interseeded cover crops. For a given year within location, columns with different letters differ significantly at $P < 0.05$. Error bars are standard errors of the mean. Labels on the x-axis represent cover crop strategies: AR = annual ryegrass, CC = crimson clover, FR = forage radish, CR = cereal rye.

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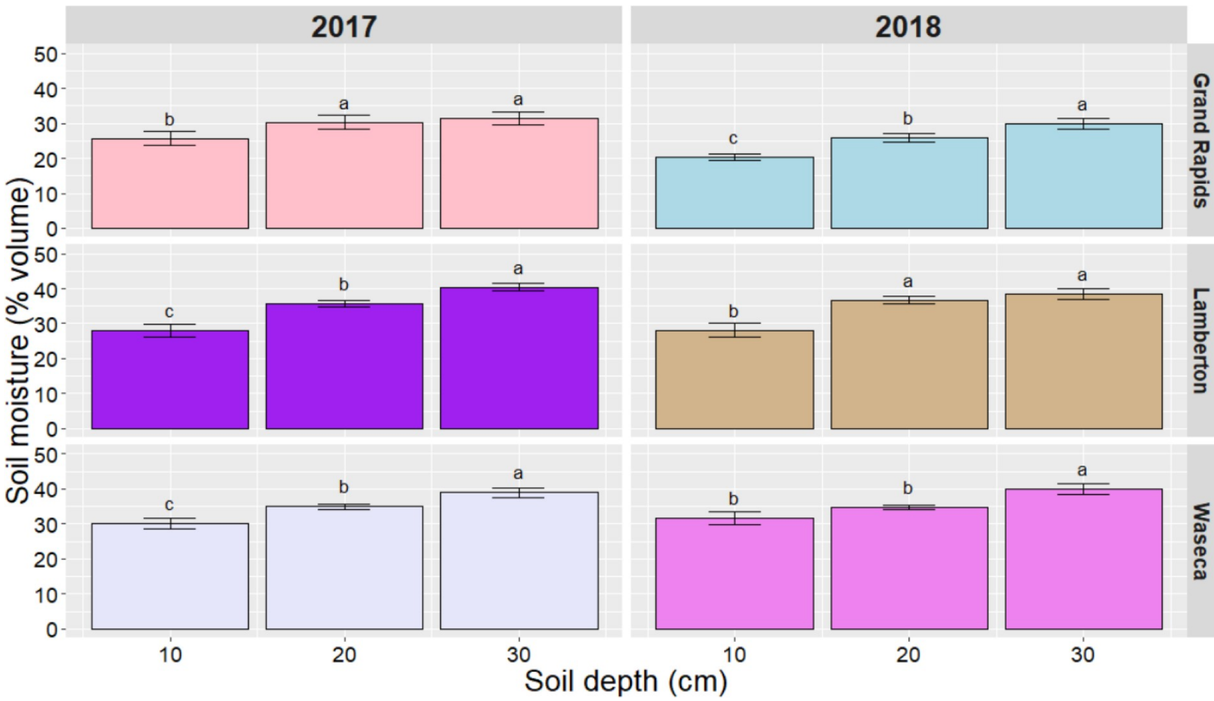

Fig 4. Mean soil moisture in the 0–10, 10–20, and 20–30 cm soil layers at maize planting after cereal rye cover crop termination in 2017 and 2018 at Grand Rapids, Lamberton, and Waseca. Different lowercase letters indicate means that are significantly different at $P < 0.05$. Error bars are standard errors of the mean.

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10–20 and 20–30 cm soil layers. The 0–10 cm soil layer had significantly ($P < 0.05$) less moisture than the other layers, except at Waseca in 2018 when no differences were observed between 0–10 and 10–20 (Fig 4).

Effect of cover crops on biomass and grain yield of maize

Maize aboveground biomass at maturity and grain yield from the late-interseeded cover crops study were both affected by location, year, and by the location x year interaction, but were not affected by cover crop strategy (Table 5). At Grand Rapids in 2017, mean maize biomass (19.0 Mg DM ha^{-1}) and grain yield (9.02 Mg ha^{-1}) were less than in 2018 (22.1 Mg DM ha^{-1} and 9.95 Mg ha^{-1}, respectively). Conversely, at Waseca in 2017, mean maize biomass (24.5 Mg DM ha^{-1}) and grain yield (12.4 Mg ha^{-1}) were greater than in 2018 (20.8 Mg DM ha^{-1} and 10.2 Mg ha^{-1}, respectively). At Lamberton, biomass decreased from 25.6 Mg DM ha^{-1} in 2017 to 22.9 Mg DM ha^{-1} in 2018 while grain yield increased from 11.1 Mg ha^{-1} in 2017 to and 13.6 Mg ha^{-1} in 2018.

Similarly, aboveground biomass at maturity and grain yield of maize from the early-interseeded cover crops study were both affected by location, year, and by the location x year interaction, but no cover crop effect was observed (Table 7). Maize biomass at Grand Rapids was 26.7 Mg DM ha^{-1} in 2017 and 27.4 Mg DM ha^{-1} in 2018, at Waseca was 24.7 Mg DM ha^{-1} in 2017 and 22.7 DM Mg ha^{-1} in 2018, and at Lamberton was 18.2 Mg DM ha^{-1} in 2017 and 22.3 Mg DM ha^{-1} in 2018. Maize grain yield in 2017 and 2018 was 11.8 and 11.1 Mg ha^{-1}, respectively at Grand Rapids; 11.1 and 13.6 Mg ha^{-1}, respectively at Lamberton; and 11.6 and 9.19 Mg ha^{-1}, respectively at Waseca.

Discussion

Factors affecting canopy cover and biomass of cover crop

We argue that in rainfed agriculture of northern climates weather conditions drive the success of cover crops use in conventional maize production systems. In this study, we interseeded cover crops early (four- to six-leaf collar stages) and late (dent to physiological maturity stages) in the maize growing season. At the northernmost location (Grand Rapids), low fall (2018) and spring (2019) biomass in the late-interseeded study was the result of poor establishment due to lack of water, as precipitation occurred 13 d after seeding cover crops. Our results support those from Wilson et al. [14] who reported lack of precipitation within seven days after air seeding as the factor limiting the establishment of cover crops in southeastern Minnesota. In contrast, at the southernmost locations of this study (Lamberton and Waseca), excess water negatively affected the establishment of early-interseeded cover crops; 238 mm of precipitation between 15 June and 14 July 2018 at Lamberton (~ half within one week of seeding) and 158 mm of precipitation on 21 September 2016 at Waseca, resulted in poor establishment and failure. Similarly, prolonged ponding at Waseca in August-September of 2018 led to limited canopy cover and low biomass of cover crops in the fall of that year and spring of 2019. Favorable conditions for CR growth in southwest Minnesota, defined as warmer than normal air temperature and near-average precipitation in fall and spring, have been characterized as occurring in 25% of the years [23]. Such favorable conditions occurred only during the 2016–2017 cover crop growing season in our study. Compared to the long-term averages, fall 2016 was wetter and warmer and the following spring varied from wetter and warmer at Grand Rapids to slightly drier and cooler at Waseca, favoring canopy cover and biomass of CR at spring termination in 2017. The wetter and colder than the long-term average conditions during the following fall and spring seasons along with late-spring snowfall in 2018 and 2019 contributed to the limited canopy cover and biomass of cover crops at spring termination. Wide variation in cover crop biomass is reported from previous studies in the region, with fall and spring biomass of early- and/or late-interseeded cover crops ranging from as little as 0.027 Mg DM ha^{-1} to as much as 2.13 Mg ha^{-1} [13, 14, 24]. Within a study, fall biomass of CR in southeastern Minnesota was reported at 0.027 Mg ha^{-1} in 2009 and 0.506 kg ha^{-1} in 2010 [14], nearly a 20-fold difference. In the present study, late-interseeded CR biomass decreased from 2017 to 2018 by approximately one-half at Waseca, two-fold at Lamberton, and nine-fold at Grand Rapids. Spring biomass of late-interseeded CR was less than 0.5 Mg ha^{-1} at all locations in 2017 and 2018, which is within or below the ranges reported from other studies in the region [14, 23, 25].

The cover crop species in this study are the most common choices for interseeding into maize and other crops in the U.S. [15], but interseeding comes with growth penalties associated with shade intolerance. In both of our studies, observed etiolated growth, and the low canopy cover and biomass obtained suggest that shade played a major role in the growth and development of the cover crops interseeded into maize. Similar results have been observed in studies interseeding cover crops at four- to six- and ten- to twelve-leaf collar stages in Ontario, Canada, reporting successful cover crops germination and establishment but stagnation and death under the maize canopy [26]. While the cover crops in our study did not die, the signs of stress from reduced light were evident. Of the four species we used, and in agreement with previous research results [27, 28], CC appeared to be tolerant to limited light; however, AR, CR, and FR are reported to be shade intolerant [28, 29, 30, 31, 32]. Our observations support previous research on interseeded legume cover crops into continuous irrigated maize reporting CC as more tolerant to shade than other legume species [28].

Our results were variable, but in agreement with survey reports indicating that stands of CR interseeding into maize production systems are highly variable [15]. Modeling studies for conditions in the central and upper U.S. Midwest [33] have also predicted penalties in CR biomass when interseeded into maize. This suggests the need for efforts to advance our understanding of the response of cover crops to shade, which in turn may open the opportunity for breeding efforts, as well as for a comprehensive characterization of cover crops potential for interseeding in maize production systems in the region.

AR-based strategies produced more canopy cover than CR-based strategies. Within the AR-based strategies, AR monoculture most often produced the greatest canopy cover and biomass, followed by ARCCFR and ARCC. Within the CR-based strategies, differences were not always significant, but the CR monoculture was most often the lowest producing for both early- and late-interseeded strategies. The latter suggests that a higher CR seeding rate did not result in greater canopy cover or biomass than other strategies. Previous research has shown that a higher CR seeding rate did not reduce N leaching any more than mixtures with lower seeding rates [34]. While CR may grow longer than AR in the fall due to its better capacity to withstand lower air temperatures, we hypothesize that AR performed better than CR because of its slightly better capacity to tolerate shade conditions [33], and because of a higher relative growth rate [35] compared to CR [36].

Cereal rye-based cover crop strategies did not result in differences in soil moisture at maize planting. This coincides with findings that mechanically terminated diverse cover crop mixtures did not reduce soil moisture [37]. Despite below-average precipitation at all locations in spring 2017 and 2018 (except Lamberton in 2017), cover crop strategies did not affect soil moisture in the 0–30 cm soil layer at maize planting compared with the CRNC treatment, which may be due to low springtime CR regrowth. A Minnesota study of soil moisture in a forage maize system with a CR cover crop showed that soil moisture after CR terminated between 25 to 28 April was similar to the control [17]. These results suggest that interseeding cover crops into maize in the region will have no effects in soil moisture.

Cover crop effects on maize production

Early- and late-interseeded cover crops were not detrimental nor beneficial to maize biomass or grain yield. Our results are in agreement with those from a meta-analysis study [38] as well as those from field studies conducted in the region [13, 17, 18, 39], which found no effect of early- or late-interseeded grass cover crops on yield of maize. It has been reported, however, that cover crops may reduce maize yield when interseeded at two- to three-leaf collar stages [18], which is before our early-interseeded study. When yield penalties have been observed in maize with interseeded cover crops, weather [14, 18, 40] and management [13, 17, 41] have been reported as the major cause of yield reduction.

The low cover crop biomass observed in our study resulted in little to no competition between plant species and therefore had no effect on maize yield. Incidentally, studies reporting no effect of cover crops on yield of maize have also reported very low cover crops biomass. For example, spring biomass of CR interseeded in late season maize in Ontario, Canada, varied from 0.091 Mg ha^{-1} to 0.884 Mg ha^{-1} [41] while biomass of CR interseeded in early season maize in southern and southwest Minnesota, U.S. varied from 0.041 Mg ha^{-1} in the fall to near 1.000 Mg ha^{-1} in the following spring [13]; both studies report that CR cover crop had no effect on maize grain yield.

Conclusion

This study provides new insight into the potential of cover crop monocultures and mixtures and their effect on maize productivity in the U.S. upper Midwest. It highlights the opportunity for broadcast interseeding cover crops early- (four- to six-leaf collar) and late- (dent to physiological maturity) in the maize growing season. Early- and late-interseeded annual ryegrass-based strategies produced greater total cover crop canopy cover and biomass by fall frost than cereal rye-based strategies in most cases. Our findings suggest that annual ryegrass may be an equally good or better option compared with cereal rye in terms of producing canopy cover and biomass as a cover crop. However, annual ryegrass winter kills, eliminating spring cover crop management before planting maize but also eliminating the opportunity to provide environmental services in the springtime. Increased GDD due to early seeding of late-interseeded cover crops did not translate into greater cover crop establishment in 2018. Conversely, early-interseeded cover crops accumulated more GDD thereby had greater development than late-interseeded cover crops in most cases. Our results show that early-interseeded cover crops produced highly variable results but was not detrimental to maize production. Regrowth of late-interseeded cereal rye did not reduce soil moisture at maize planting or subsequent maize biomass and grain yield. In both cases, we attribute these results to limited cover crop growth.

Additional research on the timing and methods of cover crop interseeding (e.g.: direct seeding), along with detailed information on corresponding field conditions, may lead to the identification of optimal interseeding times and potential tradeoffs of interseeding at different times during the growing season. Extending the study period or creating a controlled environment to observe the effects of soil moisture on maize yield might garner additional insight into the impact of spring cereal rye regrowth on maize productivity. Future research may seek to understand the impact of the cover crop strategies explored herein on soybean production to provide valuable information about their suitability and optimal placement within the maize-soybean rotation. Enhanced knowledge of how and when to best manage interseeded cover crops in maize cropping systems vis-à-vis our weather conditions may lead to greater soil cover and associated environmental, ecological, and management benefits during traditional fallow periods in the U.S. upper Midwest.

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Author Contributions

Conceptualization: Gregg A. Johnson, Axel Garcia y Garcia.

Data curation: Hannah L. Rusch, Axel Garcia y Garcia.

Formal analysis: Hannah L. Rusch.

Funding acquisition: Axel Garcia y Garcia.

Investigation: Hannah L. Rusch.

Methodology: Hannah L. Rusch, Jeffrey A. Coulter, Gregg A. Johnson.

Project administration: Hannah L. Rusch, Gregg A. Johnson, Axel Garcia y Garcia.

Resources: Jeffrey A. Coulter, Gregg A. Johnson, Axel Garcia y Garcia.

Supervision: Jeffrey A. Coulter, Julie M. Grossman, Gregg A. Johnson, Paul M. Porter, Axel Garcia y Garcia.

Visualization: Hannah L. Rusch.

Writing – original draft: Hannah L. Rusch.

Writing – review & editing: Jeffrey A. Coulter, Julie M. Grossman, Gregg A. Johnson, Paul M. Porter, Axel Garcia y Garcia.

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