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# Vegetative Cover Crops as a Nitrate Reduction Strategy for Tile Drainage Water
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### 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) were planted at 135,000 seeds/ac on 9 May 2016 and 17 May 2018 (Appendix Pic. 8). Weeds were controlled with broadcast applications of glyphosate (24 oz/ac of PowerMax) on 3 and 28 Jun 2016, 19 May 2018, and 7 and 27 Jun 2018. Soybean seed yield and moisture were measured by combine harvesting four rows on 10 Oct 2016 and 21 Oct 2018.

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, 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 yield was measured by cutting and collecting all material from 6.25 sq. ft. on 21 Oct 2016, 17 Apr 2017, 1 Nov 2017, 16 May 2018, 4 May 2019 and 26 Oct 2019. No biomass harvest was conducted in Nov of 2018 due to very little cover crop growth (Appendix Pic. 9). Since the blend cover crop 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.

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 on __ 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 data [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 and 2019 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). 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. Weather data were measured at the SROC weather station located 0.4 miles from the drainage research site.

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.

Soybean production in 2016 (setup year)

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.

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 species 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 DM/ac among N rates for corn in 2017 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.

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.

Corn production in 2019

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.

*Equation 1* $$total\ nitrate\ lost \div total\ flow\ = flow\ adjusted\ loss$$

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.

Tile drainage and nitrate concentrations and loss in 2019 (corn)

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 meter) 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.

The effects of cover crop treatments and crop rotation on 3-month (seasonal) FW $NO_3$-N concentrations during the entire research study (Sep 2016 through Nov 2019) are presented in Figure 6. Due to a historically wet 2016 (record precipitation and tile flow) $NO_3$-N concentrations were quite low (<4 mg/L) in the S-N of 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. Tile drainage was minimal during the summer and fall of 2017, thus no data. Cereal rye had lower $NO_3$-N concentrations in spring (M-M18) and summer (J-A18) of 2018 than with no cover and blend. Cover crops treatments did not affect $NO_3$-N concentrations during the corn year of 2019. Concentrations peaked near 10 mg/L in summer (J-A19) of 2019 and then declined to about 3 mg/L in the fall (S-N19). In summary, these data showed 1) $NO_3$-N concentrations were < 10 mg/L and often < 5 mg/L throughout this 3-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. About one-half of the 3-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 and 2018, due to minimal tile flow in 2017 and very low $NO_3$-N concentrations in 2018. Nitrate-N losses were 1) reduced by cereal rye in 2017; 2) not affected by cover crops in 2018; and numerically greater with cereal rye in 2019. This resulted in 3-year cumulative $NO_3$-N losses totaling 34, 31 and 31 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). Three-year cumulative $NO_3$-N losses totaled 27, 37 and 32 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. 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 was influenced treatment main effects and interactions at 3 of the 4 sampling depths (Figure 7b). 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.

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. 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. Genearlly, soil TIN was greater in the fall than in spring.

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 ($NO_3^-$) 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 $NO_3$ losses 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, $NO_3$-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, $NO_3$-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 $NO_3$-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. To date this study has shown a cereal rye cover crop can reduce $NO_3$-N in tile drainage water if weather permits adequate 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 $NO_3$-N 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 7 Mar 2019, and North American Farm and Power Show 14 Mar 2019, the SROC Agronomy tour on 18 Jun 2019, ACS International Annual Meeting on 13 Nov 2019 in San Antonio, Texas, and Ag Expo on 23 Jan 2020. Plus several media (radio, podcasts, TV, newspapers, and ag press) interviews.

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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 |

Table 2. Soybean seed yield in 2016 (setup year) and 2018 as affected by cover crops and N rates applied for corn in 2017.

| Cover crop | Nitrogen rate for corn in 2017: 3 | 120 | 150 | Mean† |
|---|---|---|---|---|
| | -------------- 2016 yield, bu/ac -------------- | | | |
| None | 78.4 | 75.9 | 76.3 | 76.9 A |
| Cereal rye | 73.7 | 73.0 | 75.4 | 74.1 B |
| Annual blend | 72.9 | 74.2 | 74.7 | 73.9 B |
| 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 | |

† Within each row or column uppercase letters indicate significance of main effects and lowercase letters indicate significant interaction of main effects at *P*<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 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.

| | 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 | 2.9 | 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 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 | | | | |
| 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 | | | | |
| 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 | | | | |
| Mean: | 21.2 | 20.1 | 20.1 | | 9.5 | 8.4 | 8.8 | | 14.9B | 18.3A | 18.4A | | | | | |
| | 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 | | | | |
| 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 | | | | |
| 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 | | | | |
| Mean: | 15.4 | 15.9 | 16.3 | | 8.7 | 8.1 | 8.8 | | 13.9B | 15.8AB | 18.4A | | | | | |
| | 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 | | | | |
| 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 | | | | |
| 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 | | | | |
| Mean: | 23.1 | 22.2 | 23.9 | | 19.4 | 17.8 | 19.1 | | 20.5 | 25.4 | 25.4 | | | | | |
| | 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 | | | | |
| 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 | | | | |
| 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 | | | | |
| Mean: | 16.8 | 15.1 | 17.3 | | 17.5 | 13.7 | 17.6 | | 19.1B | 17.7B | 25.2A | | | | | |

† 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 | | | | |
| 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 | | | | |
| 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 | | | | |
| Mean: | 36.3 | 35.0 | 35.6 | | 21.0 | 19.6 | 20.4 | | 21.0B | 24.8A | 25.7A | | | | | |
| | 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 | | | | |
| 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 | | | | |
| 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 | | | | |
| Mean: | 30.2 | 28.1 | 28.3 | | 15.0 | 14.8 | 15.6 | | 16.2B | 18.6B | 22.1A | | | | | |
| | 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 | | | | |
| 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 | | | | |
| 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 | | | | |
| Mean: | 45.2 | 41.4 | 44.5 | | 29.2 | 29.3 | 31.5 | | 24.2 | 28.9 | 30.1 | | | | | |
| | 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 | | | | |
| 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 | | | | |
| 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 | | | | |
| Mean: | 39.5 | 35.1 | 38.8 | | 28.5 | 26.3 | 29.6 | | 23.6B | 21.3B | 31.0A | | | | | |

† 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.

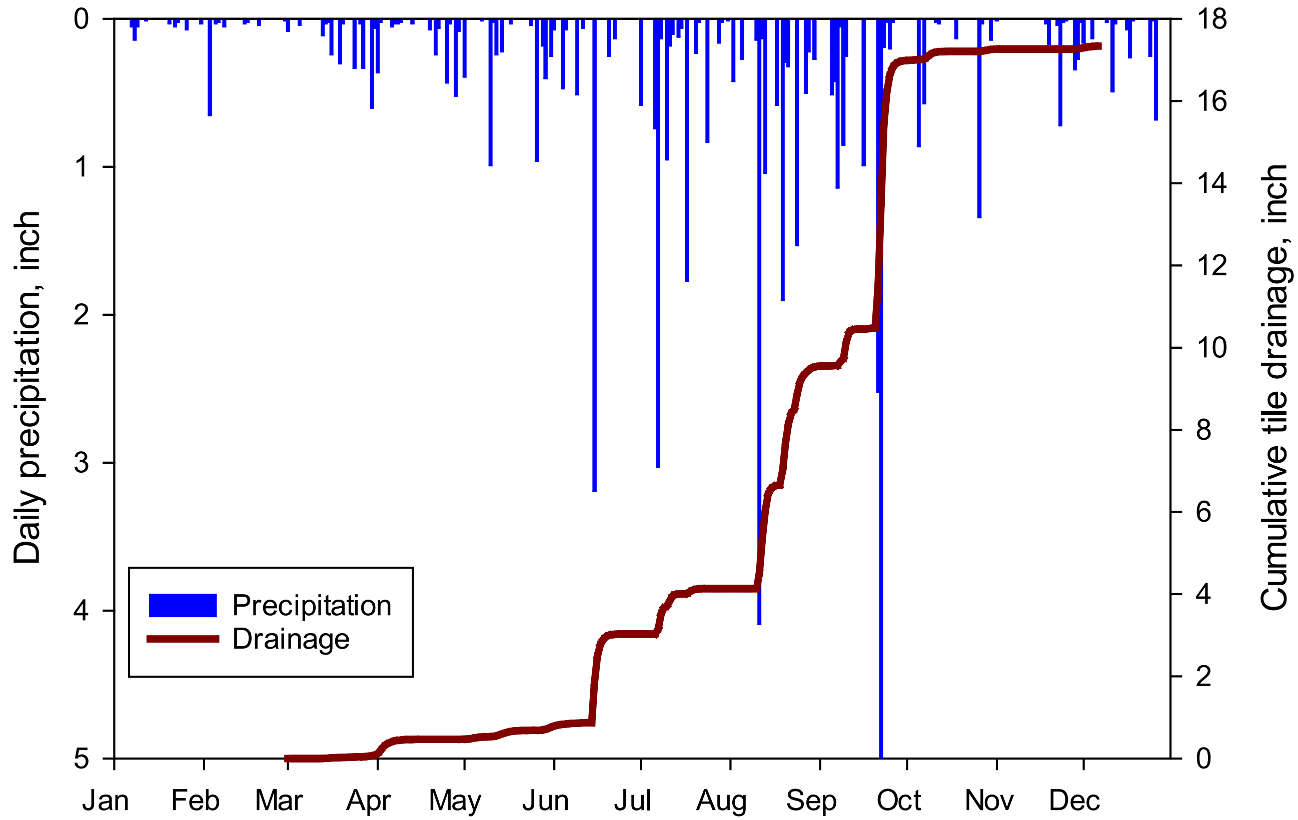



Figure 1. Daily precipitation and cumulative tile drainage in 2016.

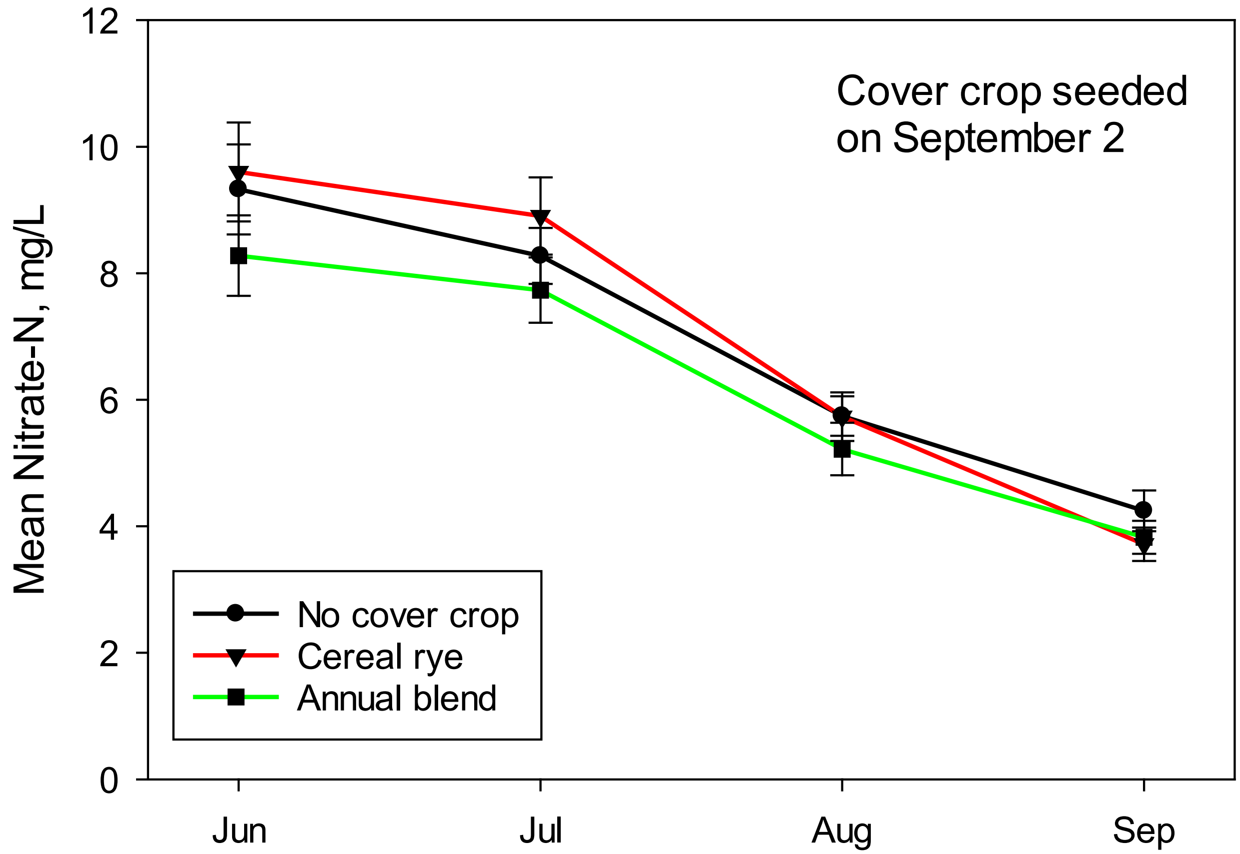



Figure 2. Nitrate-N concentration in tile drainage as affected by cover crop treatments in 2016 (setup year).

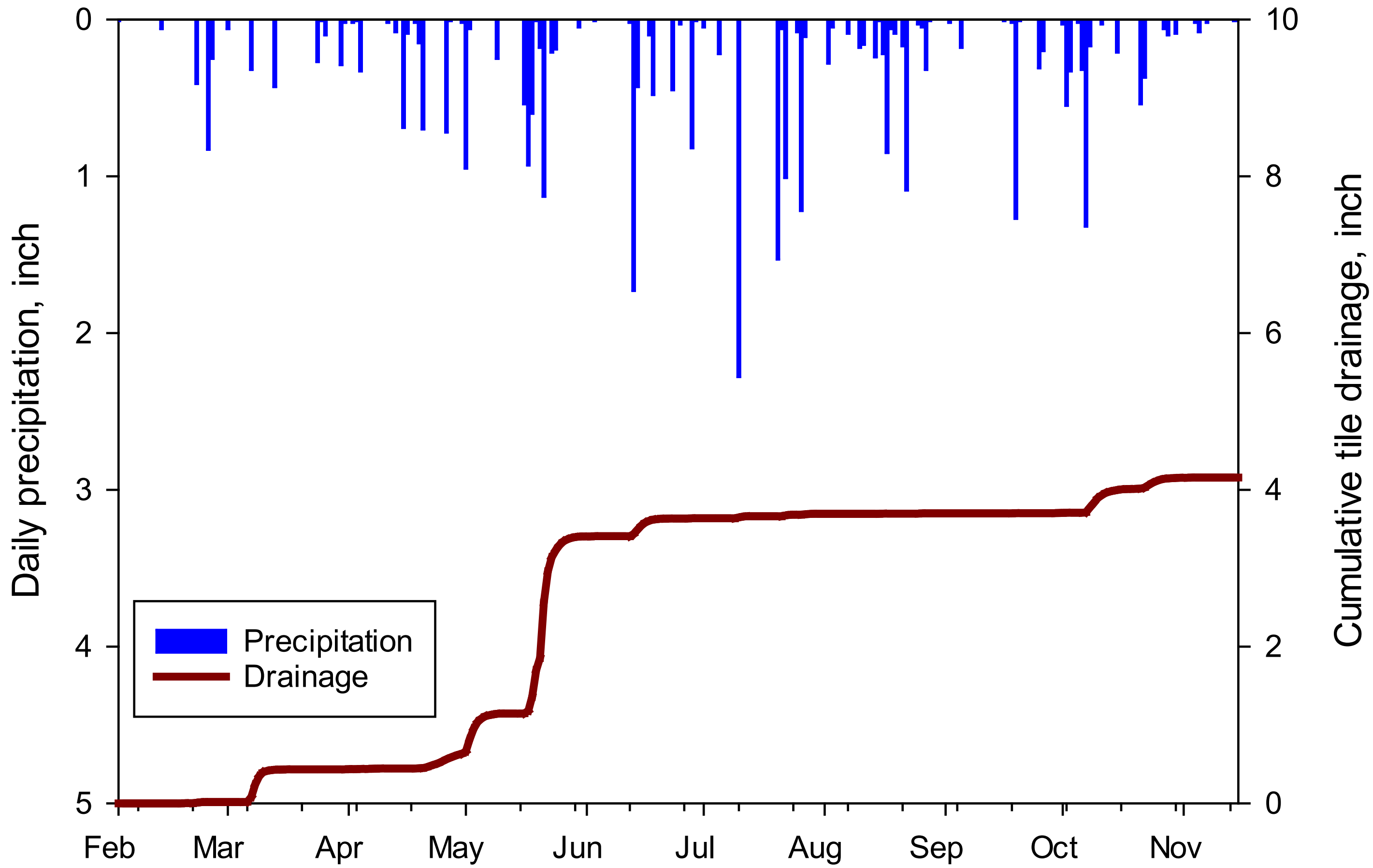



Figure 3. Daily precipitation and cumulative tile drainage in 2017.

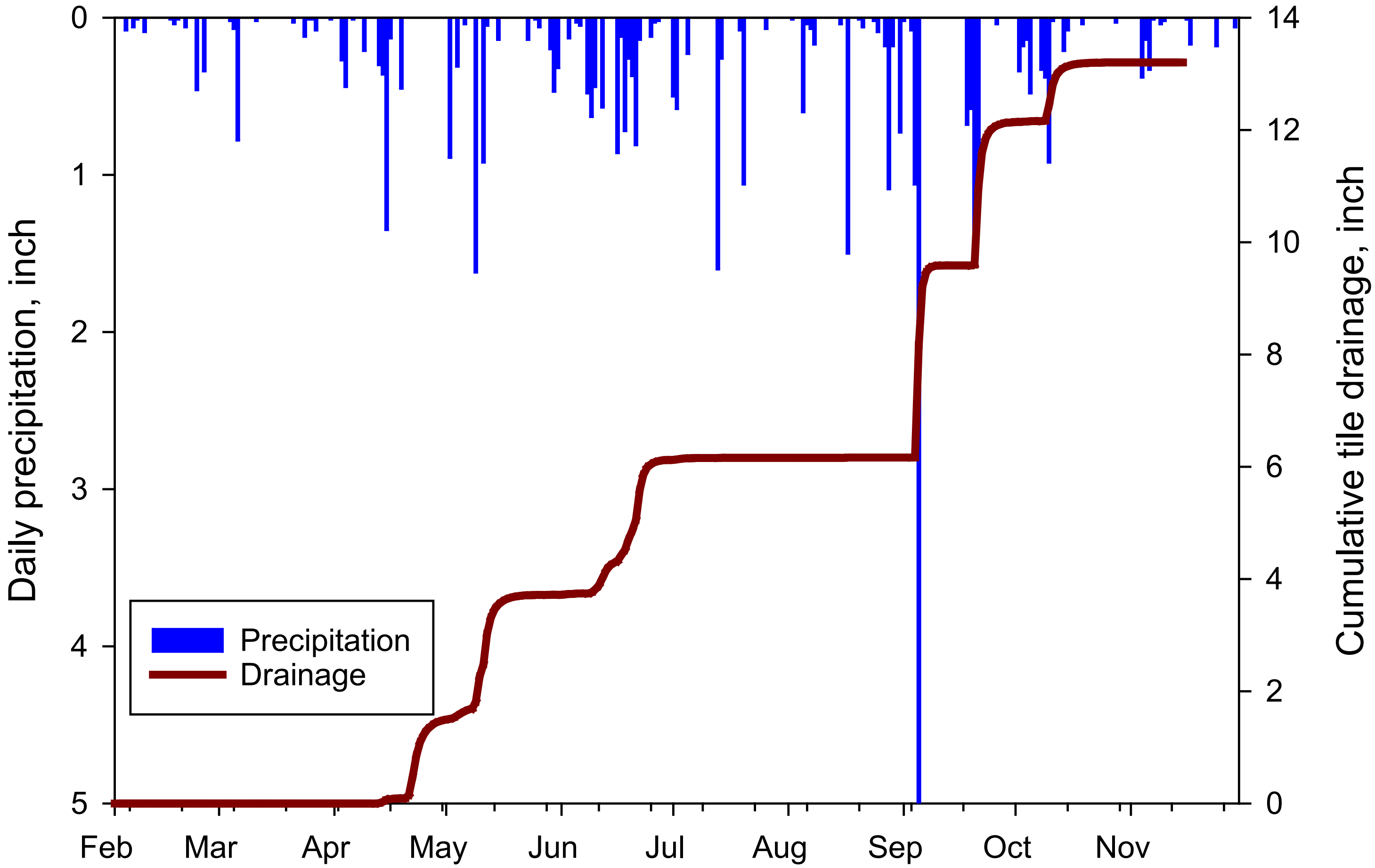



Figure 4. Daily precipitation and cumulative tile drainage in 2018.

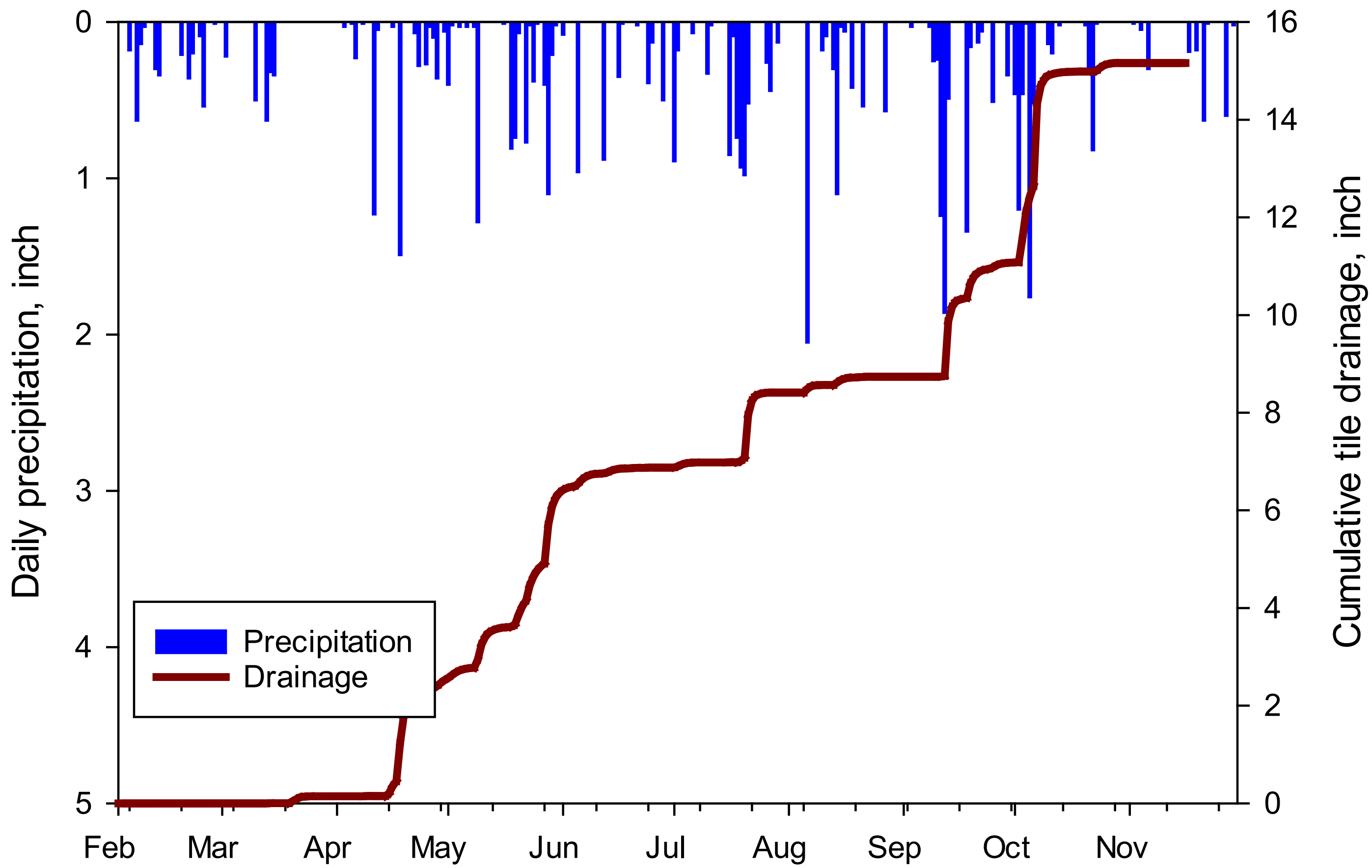



Figure 5. Daily precipitation and cumulative tile drainage in 2019.

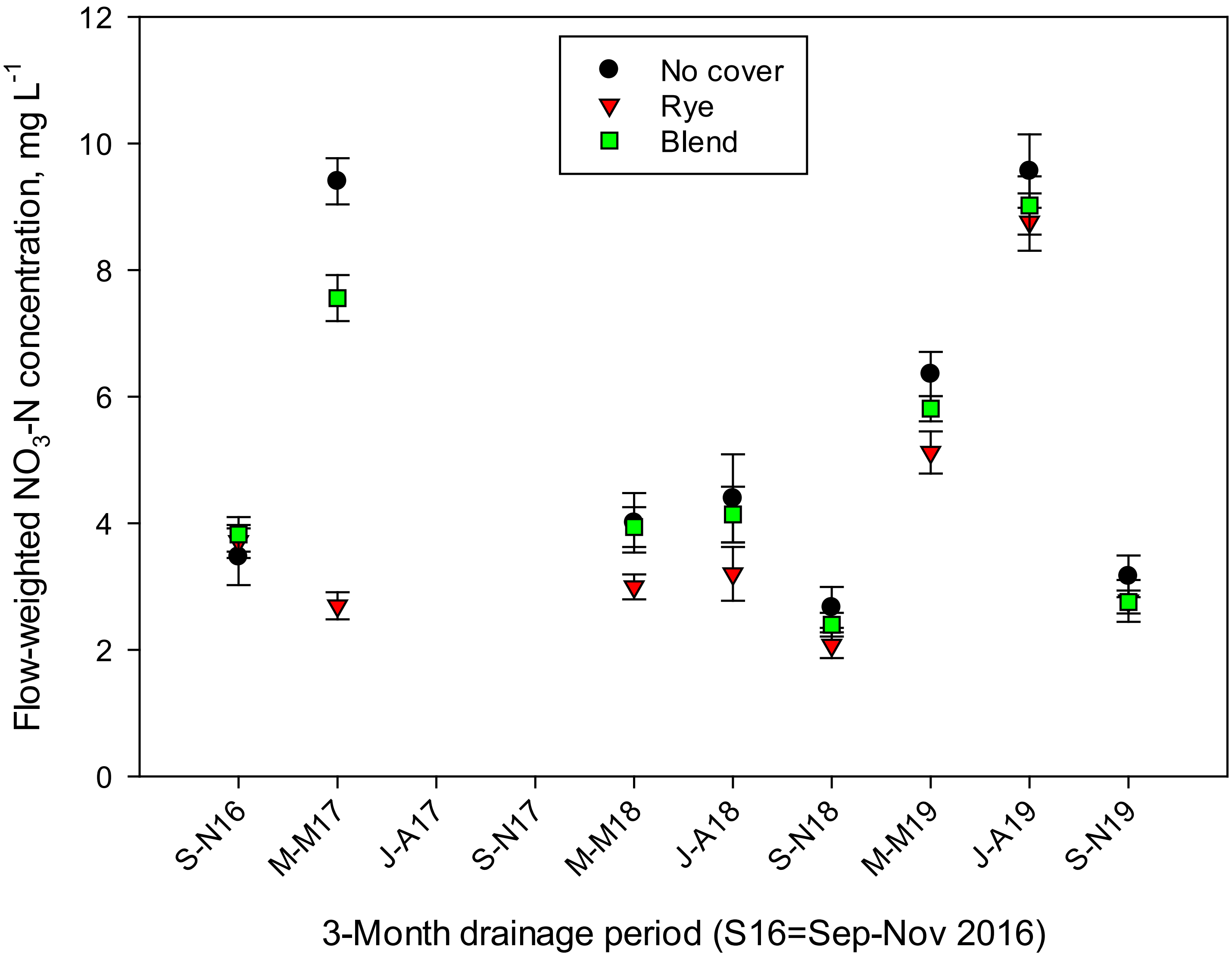



Figure 6. Flow-weighted nitrate-N concentration in tile drainage as affected by the main effect of cover crop specie (3-month periods "drainage seasons" S-N16=Sep-Nov 2016, no data during winter D-F, minimal flow therefore no data during J-A17 and S-N17 seasons, corn in odd years and soybean in even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

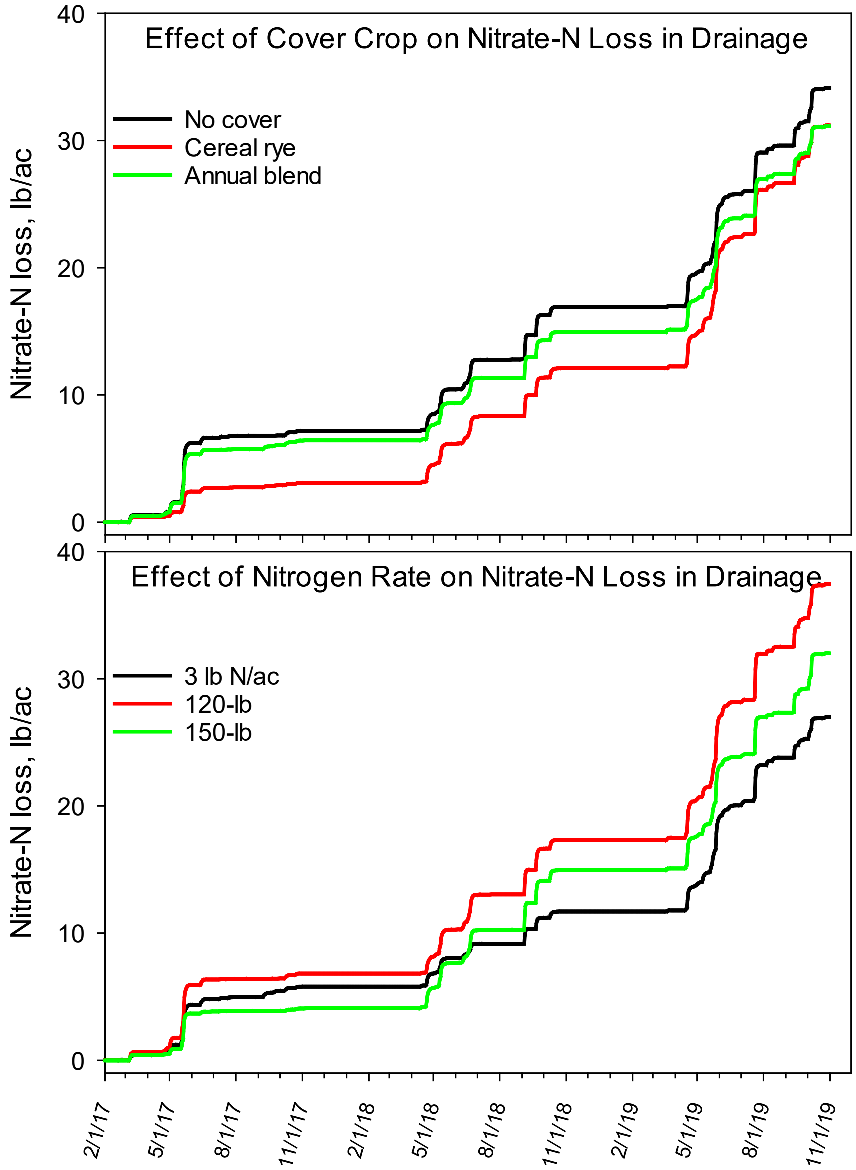



Figure 7. Cumulative nitrate-N loss (load) as affected by the main effects of cover crop specie (top) and N rate (bottom).

# 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 | 0 | 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 | 0 | 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 | 0 | 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** | | | | | | | | | | |
| 0 | | | 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 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.

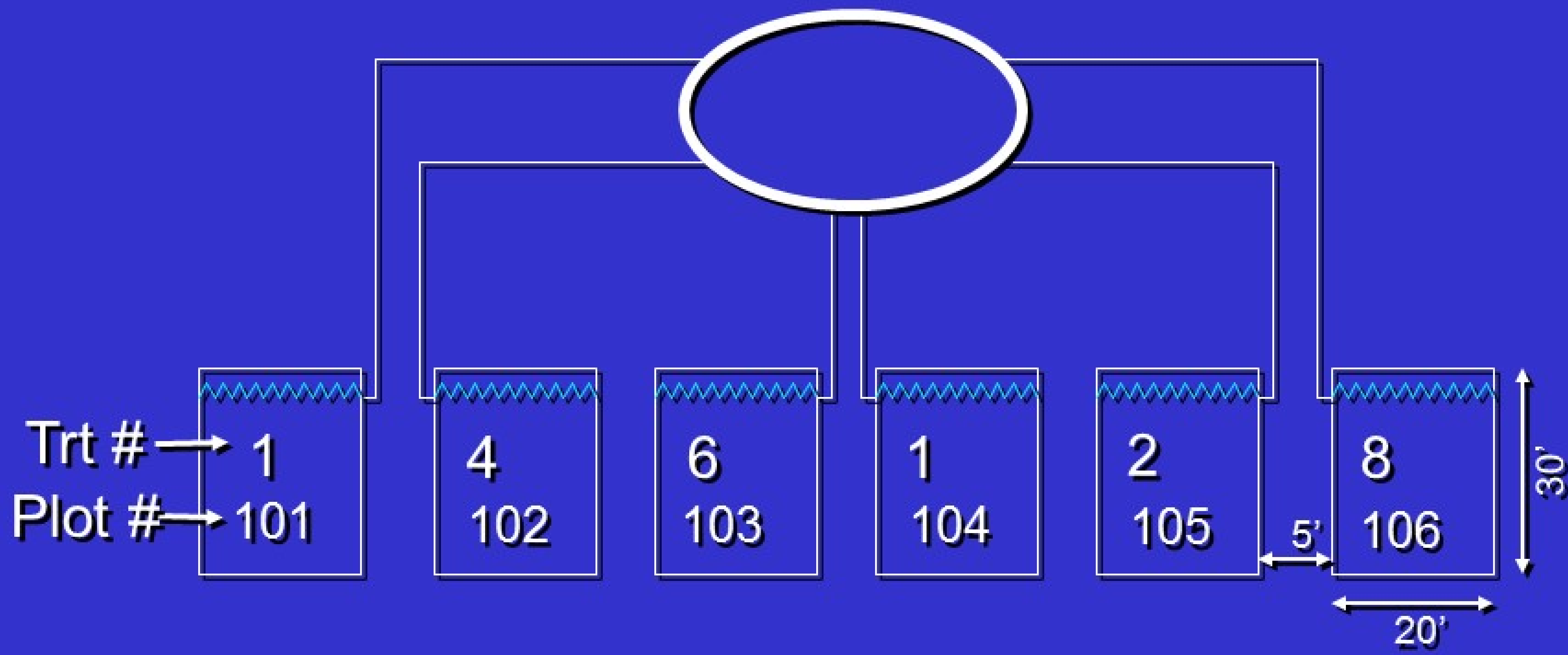
Pic. 6. Planting corn into strip-till bands on 7 May 2017. Applying liquid starter fertilizer (10-34-0 and UAN) at planting.

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