# Establishment and Function of Cover Crops Interseeded into Corn

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## ABSTRACT

Cover crops can provide ecological services and improve the resilience of annual cropping systems; however, cover crop use is low in corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] rotations in the upper Midwest due to challenges with establishment. Our objective was to compare three planting methods to establish cover crops (winter rye [*Secale cereale* L. 'Rymin'], red clover [*Trifolium pretense* L. 'Medium'], hairy vetch [*Vicia villosa* Roth], field pennycress [*Thlaspi arvense* L. 'MN-106'], and a mixture of oat [*Avena sativa* L.], pea [*Pisum sativum* L.], and tillage radish [*Raphanus sativus* L.]) (MIX) in corn at the seven-leaf collar stage. Planting methods included directed broadcast into the inter-row (DBC), directed broadcast with light incorporation (DBC+INC), and a high-clearance drill (DRILL). The DRILL method achieved greater fall biomass than DBC for all species except pennycress, and DRILL and DBC+INC increased red clover and hairy vetch spring biomass compared with DBC. Cover crops did not affect corn grain or silage yield and reduced yield of the subsequent soybean crop by 0.4 Mg ha$^{-1}$ (10%) only when poor termination of hairy vetch occurred at one site. Cover crops with >390 kg ha$^{-1}$ of spring biomass reduced soil nitrate-N compared with the no-cover control. These results support that cover crops can be interseeded into corn at the seven-leaf collar stage in the upper Midwest to reduce soil nitrate-N while maintaining corn and subsequent soybean yields; however, effective cover crop termination is critical to avoid competition with the subsequent soybean crop.

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**Abbreviations:** a.e., acid equivalent; CHK, control treatment with no cover crop; DBC, directed broadcast of cover crop seed into the inter-row; DBC+INC, directed broadcast into the inter-row with light soil incorporation; DM, dry matter; DRILL, high-clearance no-till drill; GDU, growing degree unit; MIX, mixture of oat (48%), pea (48%), and tillage radish (4%); PAR, photosynthetically active radiation.

EFFECTIVE cover cropping practices can mitigate negative environmental impacts and enhance the resiliency of annual cropping systems. Corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] were planted on 18.2 million ha (85% of cropland) in the upper Midwest in 2016 (USDA-NASS CDL, 2016), and corn–soybean rotations in the upper Midwest are susceptible to nutrient loss via surface runoff, leaching, and subsurface tile drainage (Randall et al., 2003; Strock et al., 2004). This offsite movement of nutrients has negative environmental and economic repercussions, including contributions to nitrate (NO$_3$) loading in municipal water supplies and hypoxia in the Gulf of Mexico (Gilliam and Skaggs, 1986; Mitsch et al., 2001). The greatest risk of N loss in annual cropping systems in the upper Midwest occurs during the spring prior to establishment of the primary crop. Randall et al. (2003) reported that 69% of annual NO$_3$–N loss via drainage occurs in April through June in corn–soybean rotations in the upper Midwest. Winter annual cover crops can be integrated into annual-based cropping systems to sequester N and reduce losses (Feyereisen et al., 2006; Qi and Helmers,

2010; Blanco-Canqui et al., 2015). In the Mid-Atlantic, winter cereal cover crops reduced $NO_3$–N leaching by 50 to 95% from a simulated corn–soybean crop rotation (Meisinger and Ricigliano, 2017). Cover crops can also protect soil from erosion, contribute to soil organic matter, and improve soil aggregate stability and soil water retention (Reicosky and Forcella, 1998; Dabney et al., 2001). Despite these demonstrated benefits, cover crops are uncommon in corn–soybean rotations in the upper Midwest (Singer et al., 2007).

The difficulty of establishing cover crops after corn is a primary factor limiting adoption in the upper Midwest (Singer, 2008; SARE-CTIC, 2016), where relatively short growing seasons create an adverse environment for successful postharvest establishment (Singer et al., 2007). For example, Feyereisen et al. (2006) modeled cover crop growth in the upper Midwest and found that winter rye (*Secale cereale* L.) should be planted on or before 15 September to achieve the greatest reductions in N loss. To bypass this issue, cover crops can be interseeded into standing corn, allowing sufficient time to establish before winter (Wilson et al., 2013; Belfry and Van Eerd, 2016). Previous research on interseeding cover crops in the upper Midwest has assessed only aerial broadcast planting. Wilson et al. (2013) reported that the success of winter rye establishment when aerial broadcast planted into mature corn (late August to mid-September) was correlated with the occurrence and quantity of precipitation within 1 wk of planting. Reliable methods of cover crop establishment need to be identified to facilitate adoption of cover cropping practices in the upper Midwest.

Successful establishment of cover crops depends on both the timing and method of planting. Competition for solar radiation is often a primary limiting factor in the establishment and survival of interseeded cover crops (Humphreys et al., 2003). The percentage of incoming photosynthetically active radiation (PAR) absorbed by the corn canopy increases rapidly from ~20 to 90% between the 5- and 12-leaf collar growth stages (Gallo et al., 1985), necessitating precise timing for successful cover crop interseeding. Cover crops interseeded prior to closure of the primary crop canopy must be planted early enough to establish roots while sufficient solar radiation is reaching the soil surface, yet late enough to avoid direct competition with the primary crop for water, nutrients, and solar radiation (Abdin et al., 1997). Cover crop establishment can also be improved by planting methods that increase seed-to-soil contact (Boyd and Van Acker, 2003; Wilson et al., 2013). New planting methods have been adapted to place seed directly in the inter-row and increase seed-to-soil contact when interseeding cover crops. These include high-clearance drills (Roth et al., 2015) and other high-clearance implements that broadcast cover crop seed directly into inter-rows beneath the canopy of the primary crop.

Suitable cover crop species and reliable establishment methods need to be assessed to identify viable cover cropping strategies that provide environmental benefits while maintaining productivity in corn–soybean rotations in the upper Midwest. Several species have been identified with potential for use as winter annual cover crops (SARE-CTIC, 2016). Winter rye is an extremely cold-tolerant and efficient scavenger of excess N (Wilson et al., 2013). Nitrogen assimilation by cover crops can protect water quality and retain otherwise labile N in the field for future mineralization and crop use. Field pennycress (*Thlaspi arvense* L.) is a winter annual brassica that has been adapted as an oilseed crop for relay- and double-cropping systems in the upper Midwest (Johnson et al., 2015). Red clover (*Trifolium pretense* L.) and hairy vetch (*Vicia villosa* Roth) are legumes that have both shown potential in previous interseeding research (Belfry and Van Eerd, 2016). Legume cover crops are of particular interest for biological N fixation and potential to reduce fertilizer N requirements for subsequent nonleguminous crops. However, legume crops such as soybean can also benefit from available N, and greater understanding of optimum establishment practices for interseeded legume cover crops will help inform the transfer of practices to nonlegume crop rotations. A non-winter-hardy mixture (MIX) consisting of oat (*Avena sativa* L., grass), tillage radish (*Raphanus sativus* L., brassica), and field pea (*Pisum sativum* L., legume) is also of interest as a cover crop option capable of providing ecological services in the fall and not requiring termination in the spring. A cover crop that readily winterkills will not likely assimilate and retain as much N as winter-hardy species, but it could be a valuable option if an early-spring herbicide application is undesirable, or in no-till organic systems. The objectives were (i) to gauge establishment success of a range of cover crop species and planting methods, and (ii) to determine whether successfully interseeding cover crops into corn can provide ecological benefits through utilization of excess N and water without reducing corn and subsequent soybean yields.

## MATERIALS AND METHODS

Field experiments were established in 2014 and 2015 at the University of Minnesota Southern Research and Outreach Center at Waseca, MN (44°03′41.77′′ N, 93°30′47.53′′ W), on a Webster clay loam (fine-loamy, mixed, superactive, mesic Typic Endoaquolls) and at the University of Minnesota Southwest Research and Outreach Center at Lamberton, MN (44°10′04.35′′ N, 95°18′02.80′′ W) on an Amiret loam (fine-loamy, mixed, superactive, mesic Calcic Hapludolls). Precipitation (Table 1) and air temperature data were obtained from weather stations located within 1 km of the experiments. Fertilizers were applied in the spring prior to seedbed preparation and corn planting according to preplant soil analysis and University of Minnesota guidelines for corn production (Kaiser et al., 2011). In all experiments, ammonium sulfate $[(NH_4)_2SO_4]$ was applied to supply 17 kg

**Table 1. Monthly total precipitation in 2014, 2015, and 2016 and departures from the 30-yr (1984–2013) averages at Lamberton and Waseca, MN.**

| Month | Lamberton | | | Waseca | | |
|-------|-----------|--|--|--------|--|--|
| | 2014 | 2015 | 2016 | 2014 | 2015 | 2016 |
| | ————————————————————— mm ————————————————————— | | | | | |
| January | 17.5 (3)† | 11 (–4) | 8 (–7) | 36 (4) | 19 (–13) | 11 (–20) |
| February | 13.0 (0) | 5 (–8) | 18 (5) | 40 (15) | 19 (–6) | 22 (–4) |
| March | 25 (–16) | 10 (–31) | 51 (10) | 35 (–29) | 29 (–35) | 56 (–7) |
| April | 87 (11) | 31 (–44) | 85 (9) | 141 (60) | 70 (–12) | 50 (–31) |
| May | 46 (–37) | 139 (57) | 141 (59) | 73 (–27) | 121 (21) | 95 (–5) |
| June | 188 (82) | 128 (23) | 66 (–40) | 328 (210) | 194 (74) | 121 (2) |
| July | 30 (–65) | 96 (1) | 176 (81) | 30 (–82) | 188 (76) | 227 (115) |
| August | 94 (1) | 113 (20) | 135 (41) | 81 (–40) | 152 (32) | 297 (177) |
| September | 154 (70) | 87 (3) | 134 (49) | 59 (–34) | 149 (56) | 376 (283) |
| October | 12 (–40) | 41 (–11) | 72 (19) | 35 (–33) | 31 (–37) | 79 (11) |
| November | 13 (–21) | 84 (50) | 47 (13) | 28 (–27) | 101 (46) | 41 (–13) |
| December | 25 (6) | 34 (15) | 29 (10) | 18 (–20) | 88 (50) | 54 (16) |

† Parenthetical values show departures from 30-yr averages at Lamberton and Waseca, MN.

S ha$^{-1}$. A total of 224 kg N ha$^{-1}$ was applied in both years at Waseca, with 15 kg N ha$^{-1}$ from ammonium sulfate and 209 kg N ha$^{-1}$ as urea [CO(NH$_2$)$_2$] in 2014, and 15 kg N ha$^{-1}$ from ammonium sulfate, 196 kg N ha$^{-1}$ as anhydrous NH$_3$, and 12 kg N ha$^{-1}$ as urea in 2015. Totals of 183 and 252 kg N ha$^{-1}$ were applied at Lamberton in 2014 and 2015, respectively, with 15 kg N ha$^{-1}$ from ammonium sulfate and the remainder as urea (168 and 237 kg N ha$^{-1}$ in 2014 and 2015, respectively). Fertilizer P and K were also applied at Lamberton in 2015 at rates of 112 kg P ha$^{-1}$ as calcium dihydrogen phosphate [Ca(H$_2$PO$_4$)$_2$·H$_2$O] and 67 kg K ha$^{-1}$ as potassium chloride (KCl). Corn ('Pioneer P0193AM') was planted in rows spaced 76 cm apart at both locations between 28 April and 5 May at 86,500 seeds ha$^{-1}$. Weeds were controlled with glyphosate [N-(phosphonomethyl) glycine] (0.84 kg a.e. ha$^{-1}$) prior to corn planting, and immediately prior to cover crop interseeding.

The experimental design was a randomized complete block with six replications. Plots were 3 × 15 m (four corn rows wide). Treatments were a factorial arrangement of five cover crop options (four species and one mixture) planted with three interseeding methods and an experimental control with no cover crop planted (CHK). Cover crops were interseeded into corn at the seven-leaf collar stage between 23 and 26 June. Cover crop species were rye, pennycress, red clover, hairy vetch, and MIX planted at 168, 10, 13, 35, and 140 kg pure live seed ha$^{-1}$, respectively. Seeding rates were selected to ensure ample opportunity for comparable establishment with all three planting methods. All legumes were inoculated with appropriate rhizobia species by thoroughly mixing fresh inoculant and seed at planting, using N-Dure True Clover Inoculant for the red clover, and Pea/Vetch Inoculant (INTX Microbials, LLC, Kentland, IN) for the hairy vetch and MIX. Cover crop planting methods included directed broadcast of seed into the inter-row (DBC), directed broadcast into the inter-row with light soil incorporation (DBC+INC), and a high-clearance no-till drill (DRILL; 3-in-1 InterSeeder, InterSeeder Technologies). The DRILL treatment had three drill units spaced 19 cm apart and centered within each of three inter-rows per plot, leaving a 38-cm-wide gap for each corn row. Rye, pennycress, red clover, hairy vetch, and MIX were planted at depths of 4.4, 0.3, 0.6, 4.4, and 4.4 cm, respectively, with the

DRILL planting method. The DBC+INC planting method was performed with modifications to the high-clearance no-till drill that involved raising the drill units so that the seed fell onto the soil surface, followed by custom-made incorporation units installed on the drill that consisted of a harrow-tine rake and a light closing chain to achieve light soil disturbance (Fig. 1). The no-till drill tires and drive-wheel tracked behind the planter in the three inter-rows of each plot; therefore, cover crops planted with the DBC method were broadcast by hand directly into the three inter-rows of each plot to achieve broadcast seeding with no soil disturbance. Cover crop seed was measured and applied per inter-row such that seed was broadcast throughout each inter-row with a minimum of two passes through the plot to ensure uniform seed distribution representative of mechanical directed-broadcast seeding.

After cover crop emergence, time-domain transmittance soil moisture sensors (Acclima Digital TDT) were installed between 3 and 16 July in each experiment. Sensors were placed at depths of 30 and 60 cm in DRILL-planted winter rye and MIX plots and in the CHK plots. Data loggers (DataSnap SDI-12, Acclima) were installed in each replication and configured to record volumetric water content on 1-h intervals. In each experiment, soil volumetric water content was recorded through the duration of the corn–soybean cropping cycle and ended just prior to soybean harvest.

Cover crop and corn biomass and subsequently N content was measured at corn physiological maturity (between 25 and 29 September), and cover crop biomass was also measured in the spring prior to termination (between 6 and 17 May). All aboveground cover crop biomass within a 91-cm × 76-cm sample area was hand harvested between the center two corn rows in each plot. At the spring assessments, the dead biomass of the MIX treatment could not be effectively separated from the soil and corn stover; therefore, cover crop biomass and N uptake of MIX are only reported from the fall assessment. Corn biomass was measured by hand harvesting all plants from 3 m of row in each plot at corn maturity. Ears were removed from plants, after which stalks were cut 15 cm above the soil surface and weighed fresh. Seven stalks were randomly subsampled and ground. Ground stover samples were mixed and thoroughly

Fig. 1. Incorporation units consisting of a harrow-tine rake and light closing chain, installed with drill units lifted above the soil surface to simulate directed broadcast interseeding with light incorporation. Incorporation units were removed and the drill was lowered to achieve the high-clearance drill planting method.

subsampled (~1 kg), and subsamples were immediately weighed in the field. All cover crop biomass samples, stover subsamples, and ears were dried at 60°C in a forced-air oven until constant mass, after which cover crop biomass samples and stover subsamples were weighed. Dried ears were shelled using a single-ear electric sheller, and grain and cob weights were recorded. Corn stover, cob, and grain weights were then summed to compute corn aboveground biomass and adjusted to 650 g kg$^{-1}$ moisture to report as silage yield. Corn stover, cob, and grain samples from the DRILL and CHK treatments and all cover crop biomass samples were ground to pass through a 1-mm screen using a Cyclotec Sample Mill (FOSS North America), and total N concentration was measured by combustion using an Elementar VarioMAX (Elementar Analysensysteme). Cover crop and corn N concentrations were then converted to N content (kg N ha$^{-1}$) according to corresponding biomass measurements.

Corn grain yield was measured by harvesting the central 13 m of the center two rows of each plot with a plot combine, and yields were adjusted to 155 g kg$^{-1}$ moisture. The combine header was kept directly below the height of the ears to minimize the quantity of stover deposited on cover crops and serve as a snow catchment to enhance winter survival of cover crops. In each experiment, cover crops were terminated with glyphosate [N-(phosphonomethyl) glycine] (0.84 kg acid equivalent [a.e.] ha$^{-1}$) between 12 and 20 May, and soybean (ASGROW 'AG1733') was no-till planted between 19 and 28 May at 395,000 seeds ha$^{-1}$ in rows spaced 76 cm apart. At the time of termination, the rye was in the early stem elongation phase (growth stages 31–35) (Zadoks et al., 1974), red clover and hairy vetch were vegetative, pennycress maturity ranged from late stem elongation to early bud, and the MIX treatment did not overwinter. In each experiment, red clover and hairy vetch cover crops were not completely terminated with the first application of glyphosate, so a second application of glyphosate at the same rate and formulation was applied after soybean emergence between 10 and 20 June; however, some of the hairy vetch survived at Lamberton in both years and remained under the soybean canopy, where it was protected from subsequent applications of herbicide. Soybean grain yield was measured by harvesting the central 13 m of the center two rows of each plot with a plot combine between 6 and 20 October, and yield was adjusted to 130 g kg$^{-1}$ moisture.

Soil $NO_3$–N was measured in the DRILL and CHK plots immediately after corn grain harvest, and the following spring prior to cover crop termination. Soil was sampled to a depth of 1.2 m using a hydraulically driven soil probe (3.8 cm i.d.). Three cores from each plot were divided into 30-cm increments, composited by depth, mixed, subsampled (~300 g), and dried at 35°C. Dried soil samples were ground to pass through a 2-mm screen and analyzed for soil $NO_3$–N concentration by Cd reduction (Nathan and Gelderman, 2015) using a flow injection analyzer (Technicon AutoAnalyzer, Technicon Systems). An additional core was taken from each plot, divided into the same increments, dried at 105°C until constant mass, and weighed. Dry weights were divided by soil volume to calculate bulk density (Blake and Hartge, 1986). Soil bulk density was used to convert soil $NO_3$–N concentration to content at each of the 30-cm increments.

## Statistical Analyses

Statistical analyses were performed using the MIXED procedure of SAS 9.4 (SAS Institute, 2013). Fixed effects were location, cover crop species, cover crop planting method, and their interactions for cover crop biomass in the fall and spring, cover crop tissue N content in the fall and spring, corn grain yield, corn silage yield, and soybean seed yield. Since total aboveground corn N uptake, corn grain N uptake, and fall and spring soil $NO_3$–N contents were measured only from DRILL and CHK plots, fixed effects for these response variables were location, cover crop species, and their interaction. Random effects were year, block nested within year by location, and corresponding interactions with fixed effects. Individual analyses by day were conducted for soil volumetric water content throughout the cropping cycle, with separate analyses for each experiment to enable comparison of specific environmental and cover crop

factors in relation to soil water. To meet the requirements of normality and common variance, power transformations were applied to cover crop biomass and N content response variables according to the Box–Cox method (Box and Cox, 1964). Means for all response variables were separated using Fisher's LSD at $P = 0.05$.

## RESULTS AND DISCUSSION

Monthly average air temperatures were within 2°C of 30-yr averages throughout the growing season (April–September) in all experiments except September 2015, when mean air temperatures were 4°C greater than normal at both locations. From the time of cover crop planting to fall biomass sampling, cumulative growing degree units (GDUs) with a base temperature of 0°C ranged from 1810 to 1950 GDUs in all experiments, and from 1 March to the time of spring biomass sampling, cumulative GDUs ranged 496 to 614 GDUs. Precipitation totals (April–September) were above average in all experiments (Table 1) and exceeded the 30-yr average at Waseca by 247 and 539 mm in 2015 and 2016, respectively. In all experiments, 5 to 23 mm of precipitation occurred within 7 d of cover crop planting and 10 to 38 mm occurred within 10 d.

### Cover Crop Biomass and Nitrogen Content

Cover crop planting method and the interaction between planting method and cover crop species affected fall cover crop biomass (Table 2). The DRILL resulted in greater fall biomass than the other two planting methods for hairy vetch, MIX, and rye (Fig. 2). Red clover fall biomass was greater with DRILL and DBC+INC than DBC, and planting method did not affect fall biomass in pennycress. These findings support that increased seed-to-soil contact improves cover crop establishment (Boyd and Van Acker, 2003; Wilson et al., 2013), and they also align with the findings of Hakansson et al. (2013), who reported that optimum planting depth is correlated to seed size, such that species with larger seeds require greater planting depths than species with smaller seeds.

Although planting depth was not directly tested, the DRILL planting method, which achieved the greatest planting depth and seed-to-soil contact, showed the greatest benefit for the large-seeded cover crops in this study (winter rye, MIX, and hairy vetch), whereas red clover, a smaller-seeded species, had a similar increase in fall biomass with DBC+INC and DRILL, and pennycress, the smallest-seeded species in this study, showed no response to planting method (Fig. 2). Averaged by cover crop species, fall biomass ranged from 9 to 84 kg dry matter (DM) ha$^{-1}$ with an overall average of 41 kg DM ha$^{-1}$. Wilson et al. (2013) report winter rye biomass ranging 26 to 506 kg DM ha$^{-1}$ in southeastern Minnesota, yet most sites averaged <50 kg DM ha$^{-1}$. This aligns with winter rye biomass in this study, which averaged 21 kg DM ha$^{-1}$ with DBC and DBC+INC planting methods and 61 with DRILL, although Wilson et al. (2013) planted with aerial broadcast later in the corn growing season (late August to mid-September) and measured cover crop biomass later in the fall (mid-November to early December). Belfry and Van Eerd (2016) report much greater cover crop biomass at corn harvest (725 and 1352 kg DM ha$^{-1}$ for winter rye and hairy vetch, respectively) in seed corn that was detasseled prior to pollination and had male rows (one to three of every four to eight rows) removed after pollination, which likely increased solar radiation reaching cover crops beneath the corn. These considerations suggest that reduced PAR availability was likely the greatest limitation to cover crop growth during the corn-growing season in this study. The corn canopy absorbs ≥80% of incoming PAR from the 12-leaf collar growth stage (V12) to the dough stage of grain fill (R4) (Gallo et al., 1985); therefore, minimal PAR was available for the majority of the cover crop growth period prior to the fall sampling event.

Cover crop biomass in the spring was affected by location, planting method, and the interaction between planting method and cover crop species (Table 2). Overall, spring biomass was greater at Waseca (968 kg DM ha$^{-1}$) than at Lamberton (233 kg DM ha$^{-1}$) and was greater with

Table 2. Significance of fixed effects for cover crop biomass and N uptake, corn yield and N uptake, and soybean yield in response to five cover crop species planted using three methods at Waseca and Lamberton, MN, in 2014 and 2015.

| Dependent variable | Source of variation† | | | | | | |
|---|---|---|---|---|---|---|---|
| | L | M | L × M | S | L × S | M × S | L × M × S |
| | | | | *P > F* | | | |
| Fall cover crop biomass | 0.321 | 0.040 | 0.496 | 0.383 | 0.458 | 0.006 | 0.424 |
| Spring cover crop biomass | 0.001 | 0.004 | 0.147 | 0.079 | 0.197 | 0.015 | 0.677 |
| Fall cover crop N content | 0.325 | 0.198 | 0.710 | 0.206 | 0.115 | 0.058 | 0.188 |
| Spring cover crop N content | <0.001 | 0.001 | 0.141 | 0.159 | 0.082 | 0.002 | 0.522 |
| Corn grain yield | 0.499 | 0.561 | 0.224 | 0.465 | 0.816 | 0.667 | 0.095 |
| Corn silage yield | 0.228 | 0.119 | 0.063 | 0.252 | 0.183 | 0.173 | 0.466 |
| Corn grain N uptake | 0.005 | – | – | 0.049 | 0.955 | – | – |
| Corn silage N uptake | <0.001 | – | – | 0.044 | 0.658 | – | – |
| Soybean grain yield | 0.53 | 0.715 | 0.296 | 0.366 | 0.018 | 0.913 | 0.919 |

† L, location; M, planting method; S, cover crop species.
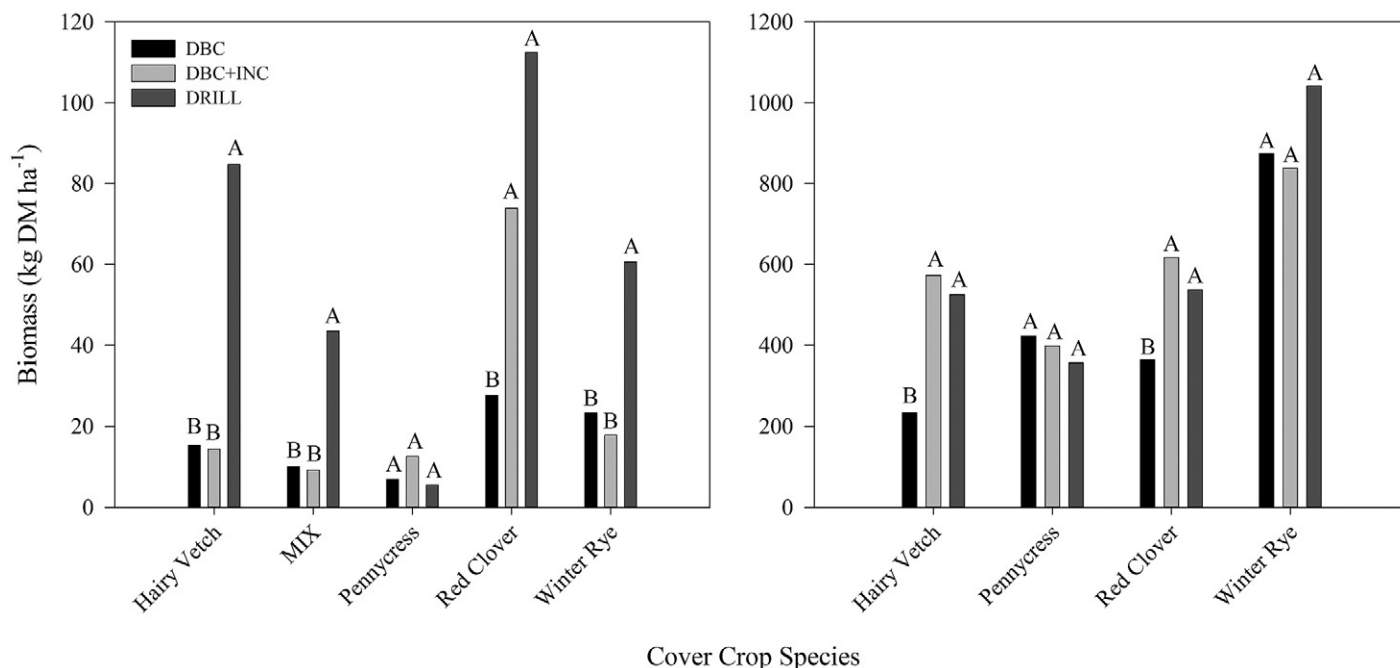
Fig. 2. Cover crop species and planting method effects on cover crop biomass in fall (left) and spring (right) at Lamberton and Waseca, MN. DBC, direct broadcast; DBC+INC, direct broadcast with light incorporation; DRILL, high-clearance no-till drill; MIX, mixture of oat (*Avena sativa* L.), pea (*Pisum sativum* L.), and tillage radish (*Raphanus sativus* L.); DM, dry matter. Means presented are back-transformed from log-transformed model estimates. Within cover crops, means with the same letter are not significantly different at $P \leq$ 0.05 according to Fisher's LSD.

the DRILL and DBC+INC methods (mean = 641 kg DM ha$^{-1}$) compared with DBC (514 kg DM ha$^{-1}$). The DBC method resulted in less spring biomass than other planting methods for hairy vetch and red clover; however, planting method did not affect winter rye or pennycress biomass in the spring (Fig. 2), indicating that compensatory spring growth made up for initial differences in winter rye bio-mass (Boyd et al., 2009). Wilson et al. (2013) concluded that precipitation within 7 d after broadcast planting of cover crops improved establishment and biomass accumu-lation. All experiments received precipitation within 7 d of planting and greater-than-normal precipitation through-out the growing season (Table 1), which likely contributed to the success of broadcast seeding in this study. Under drier conditions, broadcast planting would impose greater risk of poor or failed cover crop establishment.

Cover crop N content in the fall was not affected by location, cover crop species, or planting method (Table 2), and average N content ranged from only 0.3 to 2.6 kg N ha$^{-1}$, compared with reports of 0.1 to 45 (Wilson et al., 2013) and 15 to 57 kg N ha$^{-1}$ (Belfry and Van Eerd, 2016). The importance of fall N uptake may vary depending on levels of residual soil N after the corn crop, but cover crop benefit will most frequently be associated with successful establishment, winter survival, and spring N uptake, since the greatest risk of N loss occurs in the spring (Randall et al., 2003). Spring N content was affected by location, planting method, and the interaction between cover crop species and planting method (Table 2). Cover crop N

content in the spring was greater at Waseca (26 ± 3.3 kg N ha$^{-1}$) than Lamberton (7 ± 3.4 kg N ha$^{-1}$). The DRILL and DBC+INC planting methods resulted in greater spring cover crop N content than DBC for hairy vetch and red clover, but planting method did not affect spring N for pen-nycress and winter rye (Table 3). These effects coincide with differences in biomass between species and across locations, as cover crop N content was strongly correlated ($R = 0.99$, $P < 0.001$) with aboveground cover crop biomass. Aver-aged by species, spring cover crop N content ranged from 11 to 24 kg N ha$^{-1}$, with an overall average of 17 kg N ha$^{-1}$. Spring N uptake was less in this study than values reported by Belfry and Van Eerd (2016) for other cover crop species (mean = 47 kg N ha$^{-1}$). These differences are likely due to

**Table 3. Cover crop species effects on tissue N content in spring (sampled between 6 and 17 May) at Lamberton and Waseca, MN.**

| Planting method | Tissue N content† | | | |
|---|---|---|---|---|
| | Hairy vetch | Pennycress | Red clover | Winter rye |
| | ——————— kg N ha$^{-1}$ ——————— | | | |
| DBC‡ | 6.7b§ | 11.7a | 11.7b | 21.7a |
| DBC+INC | 14.9a | 11.6a | 19.4a | 25.8a |
| DRILL | 18.9a | 10.8a | 21.1a | 26.0a |

† Means presented for biomass and tissue N content are back-transformed from log-transformed model estimates.

‡ DBC, direct broadcast; DBC+INC, direct broadcast with light incorporation; DRILL, high-clearance no-till drill.

§ Within a column, means with the same letter are not significantly different at $P \leq$ 0.05 according to Fisher's LSD.

greater fall growth, as those cover crops were established in seed corn fields. These findings suggest that interseeded cover crops have potential to sequester excess N that may otherwise be vulnerable to offsite movement, but also that growth and corresponding N uptake are likely limited by the short periods of viable growing conditions in northern climates. Although not an objective of this research, it is implied that even less cover crop growth and N assimilation would be expected if cover crops were integrated into the transition from soybean to corn, as they would likely need to be terminated in time for earlier corn planting. Average C/N ratios of spring cover crop biomass were 18.1, 14.9, 13.4, and 11.5 for the rye, pennycress, red clover, and hairy vetch, respectively. Ranells and Wagger (1996) report similarly low C/N ratios for legume cover crops, but much greater C/N (ranging from 38–42) for rye that was in the late reproductive growth stages. Rye in this study was terminated at earlier maturity, and the resulting lower C/N ratio likely enabled more efficient decomposition of residue and corresponding mineralization and availability of assimilated N (Ranells and Wagger, 1996). Quick mineralization of residues could possibly counter the benefit of the cover crop by risking offsite movement before the main crop is able to use the mineralized N. Soybeans will use available N before using biologic N fixation; however, the timing of cover crop N mineralization in relation to soybean N demands has not been assessed. In regions with suitable markets, one option to ensure N utilization would be to harvest the cover crop as hay or haylage (SARE-CTIC, 2016), removing the aboveground assimilated N from the field.

For economic comparison, cover crop seed costs at the rates used in this study were US$81, $54, $58, $120, and $154 ha$^{-1}$ for rye, pennycress, red clover, hairy vetch, and MIX, respectively. Planting costs, based on regional custom rates for interseeding cover crops, were $37 ha$^{-1}$ for the DRILL and $35 ha$^{-1}$ for the DBC and DBC+INC planting methods. A comprehensive survey of farmers (n = 784–1017) reported that 76 to 87% of respondents consider increasing overall soil health, increasing soil organic matter, and reducing soil compaction and erosion as the primary motivations for cover cropping, whereas only 25% indicated increasing economic return as a motivation (SARE-CTIC, 2016). The survey also found that tax credit eligibility, discounted crop insurance premiums, and more information about cover crop species were among the most helpful influences for adopting cover cropping practices, and paid technical assistance was considered the least helpful influence. These motivations, influences, and the costs associated with practices tested in this study further emphasize the need for future economic assessments to include environmental and social impacts (Belfry and Van Eerd, 2016), as well as quantifications of soil health and long-term benefit to the farm system.

## Soil Nitrate-Nitrogen and Water Content

Fall soil $NO_3$–N to a depth of 1.2 m was not affected by location or cover crop species in any of the 30-cm depth increments (P > 0.05). This is explained by minimal cover crop N uptake in the fall (mean = 1.3 kg N ha$^{-1}$). Across locations and cover crop treatments, fall soil $NO_3$–N content averaged 26, 11, 16, and 34 kg $NO_3$–N ha$^{-1}$ at the 0- to 30-, 30- to 60-, 60- to 90-, and 90- to 120-cm depths, respectively. These values agree with findings of Randall et al. (2003), who reported relatively low fall soil $NO_3$–N (<100 kg $NO_3$–N ha$^{-1}$ in the 0- to 1.5-m depth) after wet growing seasons. Under the conditions of this study, fall N uptake by the cover crops was not critical to assimilate excess N, yet early cover crop N uptake would likely be more important in drier conditions when fall soil $NO_3$–N levels can range as high as 200 to 300 kg $NO_3$–N ha$^{-1}$ (Randall et al., 2003). Spring soil $NO_3$–N was affected by the interaction of location and cover crop at the 0- to 30-cm depth (P = 0.006), and by cover crop species at the 30- to 60-cm depth (P = 0.002). Soil $NO_3$–N content was not affected by cover crop or location at the 60- to 90-cm and 90- to 120-cm depths (P > 0.05). At Lamberton, rye resulted in less soil $NO_3$–N at the 0- to 30-cm depth than all other cover crops and the no-cover check, and pennycress reduced soil $NO_3$–N compared with red clover and the no-cover check (Table 4). At Waseca, rye, hairy vetch, red clover, and pennycress all resulted in less soil $NO_3$–N at the 0- to 30-cm depth than MIX and the no-cover check. At the 30- to 60-cm depth, rye resulted in less soil $NO_3$–N than all other treatments, and red clover, hairy vetch, and pennycress resulted in less soil $NO_3$–N than MIX and the no cover check. The lack of significant $NO_3$–N reductions by red clover and hairy vetch in the first soil depth at Lamberton coincided with lower spring biomass production (Fig. 2). In all cases where spring soil $NO_3$–N was reduced at either location, spring cover crop biomass was ≥390 kg DM ha$^{-1}$. A negative correlation (R = −0.70, P = 0.003) occurred between spring cover crop biomass and departures in soil $NO_3$–N from the no-cover CHK, supporting that cover crop biomass can serve as a valid indicator for ecological services in the reduction of excess soil $NO_3$–N. Strock et al. (2004) report losses up to 54 kg $NO_3$–N ha$^{-1}$ through leaching and runoff during years of high precipitation in corn–soybean rotations; however, Feyereisen et al. (2006) predict that the average reduction in $NO_3$–N loss due to a rye cover crop would be only 7 kg $NO_3$–N ha$^{-1}$. In this study, interseeded rye cover crops reduced total spring soil $NO_3$–N in the 0- to 1.2-m depth compared with the no-cover crop check by 53 kg $NO_3$–N ha$^{-1}$ at Waseca and by 39 kg $NO_3$–N ha$^{-1}$ at Lamberton. Nitrogen content in aboveground rye biomass (21 kg N ha$^{-1}$ in DRILL treatments) did not account for this entire difference in soil $NO_3$–N compared with the CHK, which indicates that

**Table 4. Effects of interseeded cover crops on spring soil $NO_3$–N at four depth intervals within the upper 0 to 120 cm of soil at Lamberton and Waseca, MN.**

| Cover crop | 0–30 cm | | 30–60 cm | 60–90 cm | 90–120 cm |
| --- | --- | --- | --- | --- | --- |
| | Lamberton† | Waseca | | | |
| | | | kg N-$NO_3$ $ha^{-1}$ | | |
| No cover | 28.7 a§ | 27.6 a | 19.5 a | 17.4 a | 27.0 a |
| Hairy vetch | 25.1 ab | 11.1 b | 13.1 b | 13.8 a | 24.7 a |
| MIX‡ | 22.0 ab | 31.7 a | 19.0 a | 15.7 a | 23.2 a |
| Pennycress | 20.1 b | 14.1 b | 13.5 b | 16.1 a | 25.5 a |
| Red clover | 28.8 a | 12.4 b | 12.4 b | 14.1 a | 27.1 a |
| Winter rye | 9.7 c | 8.8 b | 6.8 c | 9.3 a | 21.2 a |

† Means only differed by location at the 0- to 30-cm depth.

‡ MIX, mixture of oat (*Avena sativa* L.) (48%), pea (*Pisum sativum* L.) (48%), and tillage radish (*Raphanus sativus* L.) (4%).

§ Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.

soil $NO_3$–N was also assimilated in the cover crop roots (Kavdir and Smucker, 2005). These findings agree with reports of cover crops reducing potential for $NO_3$ leaching (Meisinger and Ricigliano, 2017) and imply that interseeded cover crops can provide a direct benefit to water quality in the upper Midwest.

At the time of cover crop termination, rye treatments reduced volumetric soil water at the 30-cm depth (0.25 $cm^3$ $cm^{-3}$) compared with the no-cover-crop control (0.29 $cm^3$ $cm^{-3}$) at Waseca in 2015 (Fig. 3). Volumetric water content was not different at the 30- or 60-cm depths between treatments in other experiments throughout the study. The effect observed at Waseca in 2015 aligns with differences in rye biomass and spring precipitation between experiments. Rye biomass averaged 1.6 Mg DM $ha^{-1}$ in the spring of 2015 at Waseca, but only 0.4 Mg DM $ha^{-1}$ at Lamberton. Cumulative precipitation from 3 wk prior to cover crop termination was greater at Waseca in 2016 (74 mm) than in 2015 (32 mm). Therefore, the Waseca 2015 site-year had both sufficient rye growing and low enough precipitation to result in measureable differences in soil water at the 30-cm depth. Although rooting depth was not measured, the greatest direct effect of cover crop roots was in the 0- to 30-cm depth, as indicated by the soil $NO_3$–N results; therefore, sensors placed at shallower depths may have provided greater insight to cover crop effects on soil water content. Aside from water use, cover crops have been reported to increase infiltration and water-holding capacity (Reicosky and Forcella, 1998; Dabney et al., 2001), which may have contributed to the lack of differences observed, particularly in periods of greater-than-normal precipitation. In addition to differences between treatments, the wide fluctuations in soil water content at Lamberton can be explained by slightly lower field capacity compared with the clay loam at Waseca (Fig. 3).

## Corn Yield and Nitrogen Uptake

Corn grain and silage yields were not affected by location, cover crop species, or planting method (Table 2) and averaged 9.9 and 48.4 Mg $ha^{-1}$, respectively. These results are consistent with reports for cover crops interseeded into corn at the four- and seven-leaf collar stages in Michigan and in southwestern Ontario, Canada (Baributsa et al., 2008; Belfry and Van Eerd, 2016). The critical period of weed control in corn can extend to the 14-leaf stage (Hall et al., 1992); however, the yield response to weed control has been optimized at the 10-leaf-tip stage (Page et al., 2012), which coincides with the seven-leaf collar stage and aligns with the lack of cover crop effects on corn yield in this study. Earlier planting of cover crops may enable direct competition and yield reductions (Jones et al., 1998). Considering that precipitation during the growing season was above average in all experiments in this study (Table 1), more experiments with a range of precipitation and soil water status will be necessary to inform farm practices.

Corn grain and silage N uptake were influenced by the main effects of location and cover crop species (Table 2). Both silage N uptake and grain N uptake were greater at Lamberton (184 and 128 kg N $ha^{-1}$, respectively) than at Waseca (150 and 109 kg N $ha^{-1}$). Lower corn N uptake at Waseca aligns with the excessive in-season precipitation at this site (Table 1), as well as greater soil water-holding capacity. Nitrogen availability was likely decreased via both $NO_3$–N leaching and denitrification under saturated conditions. Winter rye resulted in less corn N uptake (160 kg N $ha^{-1}$) than hairy vetch and CHK (mean = 174 kg N $ha^{-1}$), and less grain N uptake (112 kg N $ha^{-1}$) than CHK, MIX, and hairy vetch (mean = 121 kg N $ha^{-1}$), providing evidence that assimilation of N by rye may have reduced N availability for corn. Similarly, Belfry and Van Eerd (2016) found that interseeded cover crops sequestered 42 kg N $ha^{-1}$ at corn harvest without affecting corn yield, although they did not report corn N uptake. The observed differences in corn N uptake without differences in corn yield suggest that N was not limiting in this study and excess uptake can be attributed to luxury consumption (Macy, 1936). These results support that interseeding cover crops into corn at the seven-leaf collar stage introduces little to no risk of corn yield reduction, at least in years with above-normal precipitation (Table 1).
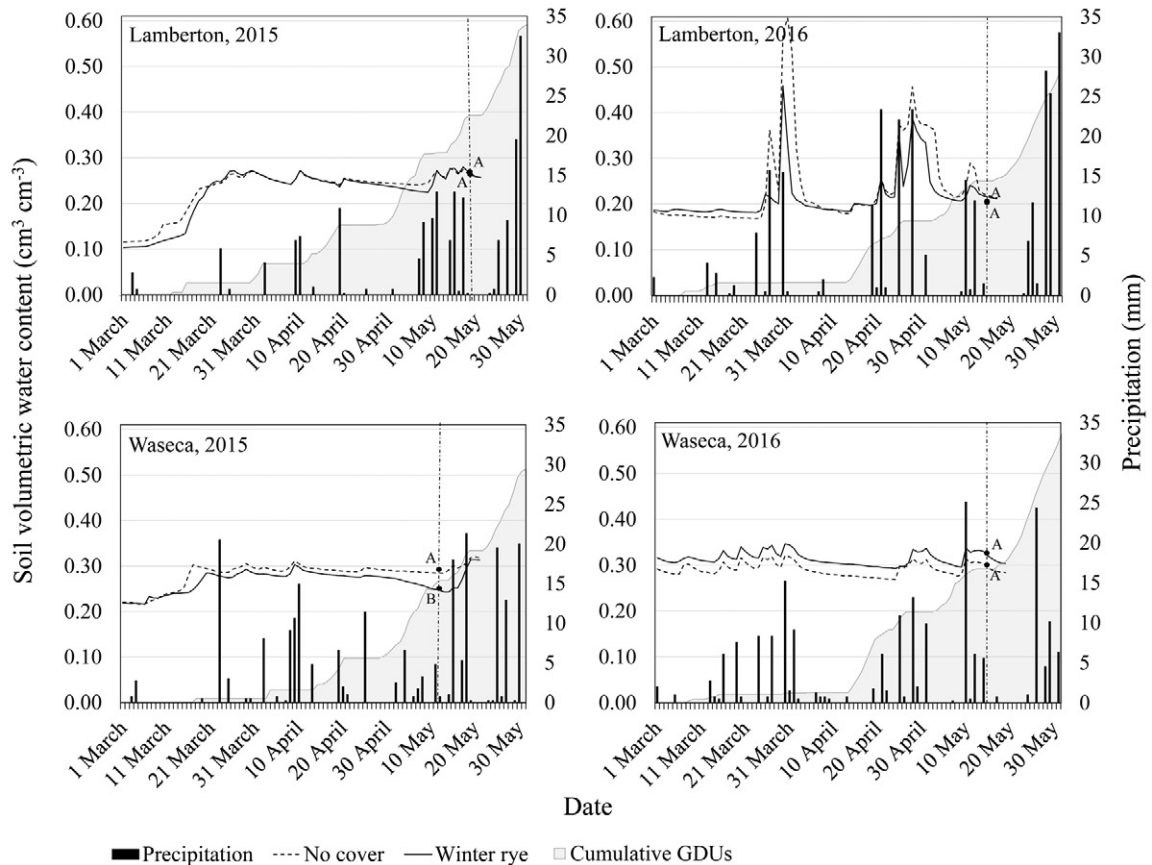
Fig. 3. Volumetric soil moisture at 30 cm under a rye cover crop and a no-cover crop check, shown with precipitation and cumulative growing degree units (GDUs) in spring 2015 and 2016 at Lamberton and Waseca, MN. Units not shown for GDUs. Vertical dashed lines indicate the day that cover crops were terminated in each experiment. Within panels, means with the same letter are not significantly different according to Fisher's LSD at $P \leq 0.05$.

## Soybean Grain Yield

Soybean yield was influenced by the interaction between location and cover crop species (Table 2). Hairy vetch resulted in lower soybean yield (3.8 Mg ha$^{-1}$) than pennycress and MIX (mean = 4.2 Mg ha$^{-1}$) at Lamberton, but similar yield to that with the other cover crop species and the no-cover CHK (mean = 4.1 Mg ha$^{-1}$). Soybean yield at Waseca was not affected by cover crop species (mean = 4.3 Mg ha$^{-1}$). Despite planting 9 to 18 d late for optimum yield in this region (Severson, 2013), all soybean yields were greater than the corresponding county averages during the study (3.7 and 4.1 Mg ha$^{-1}$ for Lamberton and Waseca, respectively) (USDA-NASS, 2017). Lower soybean yields after hairy vetch at Lamberton were likely due to poor termination of hairy vetch prior to soybean planting and subsequent competition with the soybean crop for both water and PAR. Inadequate termination of hairy vetch with glyphosate has also been reported by Palhano et al. (2015). With the exception of hairy vetch at Lamberton, the lack of cover crop effects on subsequent soybean yield is consistent with previous reports (Reddy, 2003; Wells et al., 2013). These findings highlight the importance of complete cover crop termination and support that

soybean can be no-till planted into terminated cover crops without a yield penalty.

## CONCLUSIONS

Cover crops were successfully established via interseeding into corn at the seven-leaf collar stage without affecting corn yield. Subsequent soybean yield was also not affected by the previous cover crop species or planting methods, with the exception of hairy vetch at Lamberton. Winter rye was consistently among the highest in spring cover crop biomass and N uptake, which consequently resulted in generally lower spring soil $NO_3$–N. The DRILL planting method, which achieved the greatest seed-soil contact, resulted in greater cover crop biomass in the fall compared with DBC for all species except pennycress, and spring cover crop biomass was increased with DRILL and DBC+INC for hairy vetch and red clover. Spring soil water content was reduced by the interseeded rye cover crop in only one of four site-years, when sufficient rye biomass was present and spring precipitation was less. Cover crops that produced ≥390 kg DM ha$^{-1}$ in the spring reduced soil $NO_3$–N compared with the no-cover crop check, providing a direct improvement to water quality downstream.

## Conflict of Interest

## Acknowledgments

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