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Establishing winter annual cover crops by interseeding into Maize and Soybean

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Abstract

The limited time available for cover crop establishment after maize (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] harvest is one of the main reasons for low cover crop adoption in the upper Midwest. Therefore, a 2-yr multilocation study was conducted to evaluate winter annual cover crops establishment, their effect on main crop grain yields, and soil water content when interseeded into standing maize and soybean. Treatments were three interseeding dates (broadcasting at R4, R5, and R6 growth stages for maize, and R6, R7, and R8 for soybean) and three cover crops (winter camelina [WC] [*Camelina sativa* L.], field pennycress [PC] [*Thlaspi arvense* L.], winter rye [*Secale cereale* L.] plus a no cover crop control). Cover crop establishment and growth varied with interseeding date across locations and seasons for both maize and soybean systems. Averaged over the years, rye produced more green cover and biomass than the oilseeds in spring. However, at the northern-most site, the greatest (40%) green cover was recorded from pennycress and indicates its potential as a cover crop. Seeding date and cover crops did not negatively affect maize or soybean grain yields or soil water content. Generally, cover crop establishment and growth were better in the soybean system than maize due to better light penetration. Further research is needed to develop better suited cultivars and/or agronomic management practices for interseeding into maize. The results of this study indicate that producers could integrate these covers to diversify and add ecosystem services to soybean production practices.

1 | INTRODUCTION

Crop diversification is essential to system sustainability. Diversified cropping systems improve agroecosystem performance and increase profit stability with less inputs (Davis, Hill, Chase, Johannes, & Liebman, 2012; Myers & Watts, 2015; Snapp et al., 2005). Cropping system diversity can help build greater agroecosystem resilience by improving soil health, and suppressing insect, weed, and disease pressures (Myers & Watts, 2015; Roesch-McNally, Arbuckle, & Tyndall, 2018). However, in the last few decades, the release and adoption of high-yielding maize and soybean cultivars have resulted in a decline of crop diversification in the upper Midwest (Aguilar et al., 2015; Roesch-McNally et al., 2018). For instance, maize and soybean were planted on 18.2 million ha (85% of cropland) in the upper Midwest in 2016 with a value of more than US$25 billion (Myers & Watts, 2015;

Abbreviations: PAR, photosynthetic active radiation; PC, pennycress; PLS, pure live seeds; PPD, plant population density; WC, winter camelina.

USDA-NASS, 2016). This limited crop diversification contributes to the cause of unintended environmental consequences such as increased prevalence of herbicide resistant weeds, loss of pollinator habitat, and increased nitrate N loading of water sources (Davis et al., 2012; Sindelar et al., 2017; Vetsch & Randall, 2004). Introducing appropriate multipurpose cover crops into the maize–soybean rotation could improve cropping system diversity (Heaton et al., 2013; Sindelar et al., 2017) and thus could contribute to reduce these unintended environmental consequences.

A recent report of CTIC (2017) showed grain yield increases of 3.8% for soybean, 1.3% for maize, and 2.8% for wheat following cover crops. Miguez and Bollero (2005) meta-analysis results indicated a 37% maize grain yield increase in the United States and Canada when maize was seeded following legume winter cover crops. This meta analysis showed that the increase in maize grain yield depends on the cover crop species used. However, producers have described several barriers to increased cover crop adoption. These include lack of enough time to establish cover crops following maize and soybean harvest, limited winter-tolerant crop species, additional input costs, and lack of attractive and measurable short-term economic benefits of growing cover crops (Basche & Roesch-McNally, 2017; CTIC, 2016; Myers & Watts, 2015; Singer, 2008). These limitations should be addressed to enhance cover crop adoption.

Winter rye, the most popular cover crop in the upper Midwest (CTIC, 2016), is either terminated or utilized for livestock feed prior to planting the primary crop (Krueger, Ochsner, Porter, & Baker, 2011). The amount of forage produced may not justify the economic costs associated with winter rye establishment and grazing is not a common practice in the Midwest. Additionally, maize following winter rye can suffer yield losses due to diseases (Acharya et al., 2017, 2018). Winter camelina and PC, both cold-hardy winter annuals, require less inputs (such as fungicides and pesticides) and could serve as alternative cover crops to winter rye with the added benefits of providing nectar and pollen for pollinators during flowering, and can be harvested for use of their seed oil for several industrial and food-use applications (Berti, Gesch, Eynck, Anderson, & Cermak, 2016; Eberle et al., 2015; Fröhlich & Rice, 2005; Gesch & Archer, 2013; Gesch & Cermak, 2011; Johnson, Kantar, Betts, & Wyse, 2015; Keske, Hoag, Brandess, & Johnson, 2013; Mohammed, Chen, & Afshar, 2017; Wysocki, Chastain, Schillinger, Guy, & Karow, 2013; Zaleckas, Makarevičienė, & Sendžikienė, 2012). These oilseed crops also allow double and relay cropping, and thus may incentivize farmers to increase their adoption (Berti et al., 2015; Bishop & Nelson, 2018; Gesch & Archer, 2013; Gesch, Archer, & Berti, 2014; Sindelar et al., 2017). Additionally, Liu, Wells, and Garcia (2019) showed that WC and PCseeded as cover crops in Minnesota increased maize grain yield compared with winter rye.

Core Ideas

- Interseeding cover crops did not affect main crop yields or soil water content.
- Pennycress and camelina did not perform as well as rye when interseeded.
- Cover crop establishment into standing soybean is feasible but challenging in maize.
- Interseeding winter annual cover crops into soybean could increase ecosystem services.

Previous studies showed that direct sowing of WC from September through early October (Gesch & Cermak, 2011) and PC in late August through September (Dose, Eberle, Forcella, & Gesch, 2017) worked well to maximize seed and oil yields in the following season. But the limited time available to establish these oilseed crops after maize and soybean harvest poses a challenge. Interseeding these oilseeds into standing maize and soybean may provide an opportunity for successful establishment before freezing conditions occur.

Inconsistent results on the effects of interseeding cover crops on main crop yields and cover crop establishment have been reported. Bich, Reese, Kennedy, Clay, and Clay (2014) and Noland et al. (2018) showed successful cover crop establishment at the vegetative maize growth stage without compromising grain yield. Similarly, Bishop and Nelson (2018) demonstrated that interseeding PC at the vegetative and reproductive growth stages of maize and soybean had no effects on maize and soybean grain yields. Because interseeding cover crops into maize production systems appears to present little risk to maize yield, Belfry and Van Eerd (2016) suggested focusing research on optimizing cover crop interseeding dates. However, in contrast, Uchino, Iwama, Jitsuyama, Yudate, and Nakamura (2009) reported that cover crops interseeded into maize and soybean decreased their grain yields due to competition. Similarly, Berti, Samarappuli, Johnson, and Gesch (2017) also showed that interseeding WC into standing maize and soybean during early vegetative stages (<V4) could result in competition. These studies showed that if cover crops were interseeded at the same time as the crop or during early vegetative stages of main crops, they can act like weeds competing with the main crops and cause yield loss. Conversely, if they are seeded late following maize and soybean harvest, cover crop establishment and their winter survival will be challenged.

Interseeding late in the reproductive development stage of maize and soybean could be an option to eliminate or reduce competition and enhance winter survival. However, information on late interseeding of WC and PC compared with winter rye is limited in the upper Midwest. Identifying an appropriate time to interseed these oilseed crops to achieve successful establishment and winter survival with no yield tradeoff to the main crop is needed. Accordingly, we hypothesized that WC and PC establishment, growth, and winter survival will be improved through interseeding late in the reproductive development stages of maize and soybean without sacrificing main crop yields. Therefore, the objectives of this study were to determine the effects of interseeding date of WC, winter rye, and PC into standing maize and soybean on: (i) autumn and early spring cover crops plant population density (PPD), green cover, biomass yield, and winter survival; (ii) soil water content in autumn and in spring; and (iii) maize and soybean grain yield.

2 | MATERIALS AND METHODS

2.1 | Site description

Field experiments were established at four locations in 2016/2017 and 2017/2018 using recommended management practices (Table 1). The four locations were Ames, IA (42°00′ N, −93°44′ W, and 326 m a.s.l); Morris, MN (45°40′ N, −95°48′ W, and 344 m a.s.l); Waseca, MN (44°42′ N, −93°03′ W, and 347 m a.s.l); and Prosper, ND (46°58′ N, −97°03′ W, and 284 m a.s.l). Data from Waseca in 2016 were not collected due to flooding and in 2017 the experiment was moved to Rosemount, MN (44°42′ N, −93°03′ W, and 284 m a.s.l). The soils at each site were: Clarion loam (fine-loamy, mixed, superactive, mesic Typic Hapludolls) and Webster clay loam (fine-loamy, mixed, superactive, mesic Typic Endoaquolls) in Ames; Hokans (fine-loamy, mixed, superactive, frigid Calcic Hapludolls)-Svea (fine-loamy, mixed, superactive, frigid Pachic Hapludolls) complex in Morris; Kindred silt loam (fine-silty, mixed, superactive, frigid Typic Endoaquolls) and Bearden silt loam (fine-silty, mixed, superactive, frigid Aeric Calciuaquolls) in Prosper; and Waukegon silt loam (fine-silty over sandy or sandy-skeletal, mixed, superactive, mesic Typic Hapludolls) in Rosemount (Soil Science Division Staff, 2017). Monthly mean air temperature and monthly total precipitation for each location are shown in Table 2. Weather data were collected from weather stations located at each experiment site.

2.2 | Experimental design and treatment structure

The experiment was conducted in two separate systems (maize and soybean) with four replicates at each location using a split-plot design at three locations (Ames, Morris, & Rosemount) and a randomized complete block design (RCBD) at one location (Prosper). The main and subplot sizes were 9.1 by 7.6 m and 3.0 by 7.6 m, respectively. The main plots were cover crop seeding dates and the subplots were cover crop species. Seeding dates were R4, R5, and R6 development stages for maize and R6, R7, and R8 development stages for soybean. The cover crop species were WC, PC, and winter rye plus one control to represent the conventional maize–soybean cropping sequence. Factorial combination of these seeding dates and cover crop species plus the control were used as treatments in the RCBD case. The cover and main crop seeding dates varied for each location following recommendation and are shown in Table 1.

2.3 | Seeding, plot management, and data collection

Maize and soybean were planted with 76-cm row spacing at each location. The seeding rates for maize and soybean are shown in Table 1. Each plot contained four rows of maize and soybean. Maize and soybean agronomic management practices differed at each location and followed locally adapted best management practices as shown in Table 1. Prior to seeding both maize and soybean, spring tillage was performed. Pre-plant fertilizer was applied along with pre- and post-emergent herbicides as needed. Weeds and insects were controlled according to need. Winter camelina (cultivar Joelle), PC (cultivar MN106) and winter rye (cultivar Rymin) were broadcasted at 1368, 1064, and 222 pure live seeds (PLS) m^{-2} which translate into 13, 17, and 84 kg ha^{-1}, respectively. Seed rates of WC and PC were increased intentionally to improve germination and emergence under broadcast conditions. In Minnesota, Krueger et al. (2011) planted the same winter rye variety at simillar rate (79–94 kg ha^{-1}). At Ames and Prosper, seeds were hand broadcasted between maize and soybean rows followed by a light raking to aid seed to soil contact and to simulate what was done at the other two sites. At the Morris and Rosemount sites, cover crops were seeded with a Lee Avenger (LeeAgra, Inc., Lubbock, TX) which is a high clearance tractor modified to broadcast seed with shallow incorporation using spring tines to loosen the soil and a chain dragging the soil to cover the seed. Control plots were left untouched (i.e., neither raked nor run through with the Avenger).

In autumn, prior to freezing (<0°C) of the soil surface (around first week of November), cover crops were assessed for plant count, green cover, and biomass accumulation. Cover crop stand counts were taken twice from 0.09 m^2 in each plot and averaged. The percentage of area covered by green plants was determined by taking two photos from the center row of each plot at 1 m height between rows of the cash crop. The photos were then evaluated using the Canopeo application developed by Patrignani and Ochsner (2015) with the default settings and the two measurements averaged per plot. Cover crop green cover data from Prosper were not collected

TABLE 1 Field operations, variety used, seeding and harvest dates, winter annual cover crop seeding dates corresponding to maize (R4, R5, and R6), and soybean (R6, R7, and R8) growth stages in Ames, IA; Morris and Rosemount, MN; and Prosper, ND, in 2016 and 2017

Field operations	Ames	Morris	Prosper	Rosemount
Tillage	Autumn disk, spring field cultivation	Autumn disk and chisel, spring field cultivation	Chisel in autumn and spring field cultivation	Spring field cultivation
Fertilizer	Maize: 168–123–112 kg ha^{-1} N–P–K; Soybean: 48–123–112 N–P_2O_5–K kg ha^{-1}	Maize:168–79–34–11 kg ha^{-1} N–P–K–S, and 0.3 kg ha^{-1} Zn	Maize received 124 kg N ha^{-1} from urea with urease and nitrification inhibitors	Maize received 129 kg N ha^{-1} from anhydrous ammonia
Herbicides	3.5 L ha^{-1} pendimethalin, 2.2 kg a.i. ha^{-1} of glyphosate (N-(phosphonomethyl) glycine)	two applications per year of 1.1 kg a.i. ha^{-1} of glyphosate (N-(phosphonomethyl) glycine)	one applications 1.1 kg a.i. ha^{-1} glyphosate (N-(phosphonomethyl) glycine)	2.3 L a.i. ha^{-1} S-metolachlor, 1.1 kg a.i. ha^{-1} of glyphosate (N-(phosphonomethyl) glycine)
Insecticide	None	0.1 L a.i. ha^{-1} Lambda-cyhalothrin	None	None
Maize				
Variety	DeKalb DKC57-75RIB	N31H	P863AM	DKC46-36RIB
Seeding rate,	7.9	8.2	7.9	8.9
PLS m^{-2} Seeding date	17 May 2016; 15 May 2017	2 May 2016; 28 Apr. 2017	5 May 2016; 12 May 2017	10 May 2017
Harvesting date	13 Oct. 2016; 31 Oct. 2017	1 Oct. 2016; 20 Oct. 2017	29 Sept. 2016; 23 Oct. 2017	25, Oct. 2017
Soybean				
Variety	Asgrow 2663	R2C1100	Asgrow 0838	Asgrow 2035
Seeding rate	44.5	43	46	37.6
(PLS m^{-2})[a] Seeding date	17 May 2016; 15 May 2017	17 May 2016; 14 May 2017	18 May 2016; 12 May 2017	20 May 2017
Harvesting date	5 Oct. 2016; 18 Oct. 2017	20 Sept. 2016; 10 Oct. 2017	14 Oct. 2016; 6 Oct. 2017	5 Oct. 2017
Cover crop interseeding date into standing maize				
R4[b]	9 Aug. 2016; 11 Aug. 2017	23 Aug. 2016; 23 Aug. 2017	19 Aug. 2016; 24 Aug. 2017	29 Aug. 2017
R5	1 Sept. 2016; 8 Sept. 2017	2 Sept. 2016; 7 Sept. 2017	6 Sept. 2016; 6 Sept. 2017	12 Sept. 2017
R6	29 Sept. 2016; 25 Sept. 2017	14 Sept. 2016; 22 Sept. 2017	22 Sept. 2016; 19 Sept. 2017	20 Sept. 2017
Cover crop interseeding date into standing soybean				
R6	18 Aug. 2016; 24 Aug. 2017	23 Aug. 2016; 23 Aug. 2017	19 Aug. 2016; 24 Aug. 2017	29 Aug. 2017
R7	12 Sept. 2016; 15 Sept. 2017	2 Sept. 2016; 7 Sept. 2017	6 Sept. 2016; 6 Sept. 2017	12 Sept. 2017
R8	30 Sept. 2016; 25 Sept. 2017	14 Sept. 2016; 22 Sept. 2017	22 Sept. 2016; 19 Sept. 2017	20 Sept. 2017

[a]PLS = pure live seeds.

[b]R4, R5, and R6 are interseeding dates for cover crops into standing maize; similarly, R6, R7, and R8 are interseeding dates for cover crops into standing soybean.

TABLE 2 Monthly mean air temperature (Tmp; °C) and monthly total precipitation (Prec; mm) in 2016, 2017 and long-term average at Ames, IA; Morris and Rosemount, MN; and Prosper, ND

	Ames						Morris						Prosper						Rosemount					
	2016		2017		LTA[a]		2016		2017		LTA		2016		2017		LTA		2016		2017		LTA	
Month	Tmp	Prec	Tmp	Prec	Tmp	Prec	Tmp	Prec	Tmp	Prec	Tmp	Prec	Tmp	Prec	Tmp	Prec	Tmp	Prec	Tmp	Prec	Tmp	Prec	Tmp	Prec
Jan.	−6.6	15	−4.1	47	−6.3	17	−9.7	7	−9.1	13	−12.0	19	−11.1	M[a]	−11.1	M	−13.5	M	−10.0	20	−7.6	52	−10.7	26
Feb.	−1.6	17	2.7	30	−4.0	22	−5.2	22	−3.1	11	−9.8	18	−5.6	M	−5.0	M	−10.7	M	−5.3	14	−1.9	16	−7.7	23
Mar.	7.3	38	3.8	79	3.3	50	3.1	21	−0.9	12	−2.6	35	2.8	M	−2.2	M	−3.1	M	3.8	54	−1.0	16	−0.5	58
Apr.	11.3	104	11.6	78	10.5	100	6.9	52	7.5	65	6.4	61	5.6	43	6.7	17	6.0	26	8.4	56	9.0	116	7.9	74
May	16.6	109	16.6	156	16.7	124	15.3	43	13.4	92	13.9	77	15.0	82	13.3	17	13.4	72	15.6	69	13.5	182	14.3	103
June	24.2	25	23.2	44	22.0	122	20.3	54	20.0	101	19.2	108	19.5	38	18.9	88	18.9	98	21.0	81	20.4	91	19.6	120
July	23.9	149	24.9	25	23.7	117	21.5	184	22.1	23	21.4	96	21.1	88	21.1	50	20.7	76	24.8	121	22.3	139	21.9	114
Aug.	23.1	209	21.2	85	22.6	122	20.7	94	18.4	175	20.0	83	20.6	26	18.3	53	19.7	54	21.3	178	18.9	129	5.6	120
Sept.	21.0	201	20.8	46	18.7	83	16.4	43	16.6	105	15.2	71	16.1	60	15.6	152	15.0	69	17.9	133	17.9	42	16.0	92
Oct.	14.9	15	13.0	154	11.9	61	9.5	87	8.5	69	7.6	60	8.3	49	7.8	7	7.3	50	11.0	62	9.6	99	8.9	73
Nov.	8.2	44	3.7	7	3.5	46	4.3	42	−1.4	12	−1.4	24	4.4	M	−3.3	M	−1.9	M	6.0	45	−0.6	2	0.1	53
Dec.	−4.2	30	−3.8	4	−4.1	29	−8.9	33	−9.0	7	−9.1	18	−10	M	−11.1	M	−9.9	M	−7.0	24	−8.2	8	−8.2	31

[a]LTA = Long term average, number of years varied by locations.
[b]M = missing data.

in spring 2017. Cover crop biomass was determined by taking representative plant samples from two separate 0.09 m^2 areas from the first and third rows of each plot except in Ames where two 0.76 m^2 areas were used, and the two samples averaged per plot. Biomass samples were harvested with a handheld clippers or scissors at the soil surface and oven-dried at 65°C until constant weight was achieved for biomass determination. These same metrics also were collected in the spring (last week of April to first week of May). Winter survival was calculated as the ratio of spring to autumn counts (counts taken for marked areas). Photosynthetic active radiation (PAR) data were collected from above and below cash crop canopy cover using an AccuPar LP-80 ceptometer (Meter Group Inc., Pullman, WA). The above canopy sensor was placed on a tripod in the alleyway to avoid shading by the cash crop. Ten PAR measurements below the canopy approximately 10 cm apart between rows 2 and 3 were taken and averaged. These data were collected to help explain potential differences in cover crop performance when interseeded into maize and soybean.

2.4 | Maize and soybean harvest

Two center rows of each plot were harvested using a plot combine (make and model varied by location) for maize and soybean grain yield determination. Maize grain moisture was determined either by using a Dickey-John grain moisture tester (Dickey-John Corp., Auburn, IL) or by drying a subsample of grain in an oven at 65°C until constant weight was achieved. Maize and soybean yields were adjusted to 15.5 and 13.0 g kg^{-1} moisture content, respectively, before statistical analysis. Following maize harvest, most of the residue was removed by raking (simulated baling) from the plot area to reduce smothering of the cover crops. However, at Rosemount, maize residue was not sufficiently removed and WC and PC performed very poorly due to smothering and thus, data from maize system for this location were not included in the analysis.

2.5 | Soil sampling

Soil samples were collected following maize and soybean harvest and early the following spring to determine soil moisture from 0–30 and 30–60 cm soil depths within the center row using a composite of two cores per plot. The samples were collected using either a Giddings hydraulic truck mounted probe (Windsor, CO, USA) or a push probe (1.7-cm diameter, JMC Soil Samplers, Newton, IA, USA) from each plot. Soil water content was determined by weighing the soil samples at field moisture and after drying in an oven at 105°C until constant weight was achieved. Soil samples for moisture determination were not collected in autumn 2016 and spring 2017 from Prosper.

2.6 | Statistical analysis

Data from the two systems (maize and soybean) were analyzed separately for each location. Data analysis from the three locations (Ames, Morris, and Rosemount) followed a split-plot design, and a RCBD procedure was followed for the Prosper location. Analysis of variance was performed using Generalized Linear Mixed Model (PROC GLIMMIX) procedure in SAS 9.4 (SAS Institute, 2014). This procedure is widely used and the best tool for analyzing non-normal data that involve random effects (Bolker et al., 2009). Our data includes plant population counts that usually do not follow a normal distribution and contained some missing values as well.

Year, seeding date, cover crop species, and their interaction were fixed effects. Replication and its interaction with seeding date and cover crop species were considered as random effects. Appropriate error terms were used for each design (split-plot and RCBD). Cover crop (plant count, green cover, and biomass) and soil water content data were analyzed by season (autumn and spring) for each location. Treatments' mean effects were separated with LSD at $P = 0.05$ when ANOVA showed significant difference at $P < 0.05$. When interaction is significant, the SLICE option in SAS was used to examine interaction means. A Pearson correlation analysis was used in SAS to determine the association among recorded variables and correlation was significant when $P < 0.05$. The effect of year was apparent (primarily due to climate) and the effects of year for each parameter discussed but means for treatments combined over years for each location presented and discussed.

3 | RESULTS AND DISCUSSION

3.1 | Weather

In 2016 from August to December, air temperatures were slightly warmer at all locations than the 30-yr averages by 1.9, 3.4, and 2.1°C in Prosper, Morris, and Ames, respectively. Precipitation was above average at Morris (by 43 mm) and Ames (by 158 mm) during these months, but below average at Prosper (by 38 mm) (Table 2).

In 2017 from August to December, mean air temperature at all locations was near normal compared with the 30-yr average, but was 3.0°C above the long-term average at Rosemount (Table 2). Precipitation during these months in 2017 was highly variable at all locations. Morris and Prosper received relatively more precipitation than Ames or Rosemount. The precipitation at Ames and Rosemount was less than their long-term averages. The cumulative precipitation from August to December at Rosemount was substantially lower (56 mm) than the long-term average (203 mm).

3.2 | Cover crop plant population

In the maize and soybean systems, cover crop PPD (plants per m^2) was significantly greater in 2017 than in 2016 at all locations. Under the maize system, mean PPD in 2017 autumn were 146, 287, and 464 per m^2 for Ames, Morris, and Prosper, respectively, compared with 103, 199, and 267 per m^2 in 2016 autumn for the corresponding locations. However, mean PPD differences between years were less under the soybean system. The greater PPD in 2017 could be due to better precipitation received following cover crop seeding than in 2016. For instance, Morris was relatively drier and warmer in August and September in 2016 compared with 2017 or the long- term means (Table 1).

At Ames, interseeding date and interseeding date × cover crop interaction, interseeding date at Morris, and cover crop species at Prosper significantly affected PPD in the maize system. At Ames in autumn, the first (R4) and second (R5) interseeding dates decreased PPD by 48 and 38% compared with the third interseeding date (R6), respectively (Table 3) under the maize system. At Ames in spring, the interaction of interseeding date with cover crop species showed that PC had greater PPD (182 plants m^{-2}) at the second seeding date (R5) than either winter rye (83 plants m^{-2}) or WC (25 plants m^{-2}) in the maize system. At Prosper (both autumn and spring), PC PPD was greater than winter rye or WC in the maize system showing that PC has good potential as a cover crop under this system and environment.

Under the soybean system, the effect of interseeding date on PPD was significant at Ames, Morris, and Rosemount. The earliest interseeding date generally resulted in less PPD under the soybean system (Table 3). At both Ames and Prosper, PPD was greater for PC than WC or rye while at Rosemount, WC PPD was consistently low (Table 3).

Generally, PPD was reduced for early interseeding dates under both systems. This effect could be due to competition between the cover and cash crops because the cash crop is still actively growing during this time. Based on our observation, at the latest interseeding date, maize and soybean had relatively less canopy closure due to leaf shrinkage in maize and soybean leaf dropping that allows increased light penetration between rows. This could enhance seedling growth. Our analysis of PAR data showed that light penetration through the canopy was less than 15% when interseeded at early development stage of the cash crop. Overall, the mean PPD for the three cover crop species was very low compared with the amount of PLS seeded. This could have been due to several factors, namely, poor seed-soil contact due to insufficient incorporation, seedling mortality before autumn counting, competition with cash crops for light and nutrients, and/or winter kill. Based on observations, cover crop seedlings were etiolated due to shading, which likely made them weak and susceptible to winter kill. Selecting and or

TABLE 3 Mean plant count (plants per m^2) for the different locations, seasons, interseeding dates, and cover crop species when cover crops interseeded into standing maize and soybean in 2016 and 2017

	Plant count, no. of plants per m^2							
	Ames		Morris		Prosper		Rosemount	
Factors and levels	Autumn	Spring	Autumn	Spring	Autumn	Spring	Autumn	Spring
Interseeding date[a]	Maize system							
R4	90b[b]	31b	188b	83b	391a	96a	na[c]	na
R5	109b	97a	313a	126a	369a	123a	na	na
R6	176a	135a	228ab	71b	337a	109a	na	na
Cover crop[d]								
PC	146a	127a	221a	98a	653a	227a	na	na
Rye	113a	89b	211a	99a	158b	66b	na	na
WC	116a	47c	297a	82a	286b	35b	na	na
Interseeding date	Soybean system							
R6	138a	47b	142c	110b	312a	239a	64b	44c
R7	133a	102a	380a	205a	365a	263a	139a	113b
R8	185a	141a	253b	158ab	405a	296a	186a	164a
Cover crop								
PC	229a	144a	309a	180a	677a	520a	192a	121a
Rye	98b	80b	208a	135a	121c	113b	155a	149a
WC	129b	65b	258a	158a	284b	165b	42b	51b

[a]R4, R5, and R6 are interseeding dates for cover crops into standing maize; similarly, R6, R7, and R8 are interseeding dates for cover crops into standing soybean.
[b]Means followed by a common letter in a column for a factor levels and same recorded variable within a system and in a season are not statistically significant at $P = 0.05$.
[c]na = Not applicable.
[d]PC = Pennycress; Rye = winter rye; WC = winter camelina.

developing cultivars that can perform better under interseeding conditions could be a solution for this challenge. Brennan and Leap (2014) suggested increasing seeding rate to increase the chance for more seed-to-soil contact to improve germination. However, this may increase seed cost. A previous study on direct seed-drilling indicated that planting WC at 334 PLS m^{-2} was enough to achieve maximum seed and oil yields (Gesch, Matthees, Alvarez, & Gardner, 2018). However, optimum broadcasting rates to achieve agroecosystem goals under interseeding conditions are likely to differ, and thus, deserve further research.

Winter survival, estimated as the ratio of spring to autumn PPD, varied by seeding date and cover crops for each location (results not shown). The difference in winter survival due to interseeding date was too small to discuss. However, substantial differences in winter survival occurred among the cover crop species in the maize system. At Ames, PC had the least winter kill followed by winter rye. But at Morris and Prosper, winter rye had better winter survival followed by PC. In the soybean system, generally, later interseeding improved winter survival at Ames and Rosemount, while at Morris, it was greatest for the first interseeding, and there was no clear response at Prosper. Generally, winter survival of rye was better under the soybean system than the oilseeds.

Camelina and PC winter survival decreased with increased latitude. Ames had warmer mean annual and winter air temperatures than the other locations (Table 2), which might have contributed to increased early root and seedling growth and thus, better winter survival. Winter camelina had the lowest winter survival at all locations under the interseeding conditions studied. For instance, at Prosper, survival was only 12% under the maize system. A previous study showed that the WC variety used in this study (cultivar Joelle) had a survival rate of 64% over three seasons when direct-drilled after spring wheat, which was greater than three other cultivars tested (Gesch et al., 2018). In the present study, the low winter survival reported may be related to additional stress incurred by shading from the cash crop following establishment, and broadcast interseeding compared with direct-drilling. The generally lower winter kill of rye than the oilseed species could be due to more selection efforts given to rye to develop improved winter hardiness. Also, results could indicate that rye is less affected by interplant competition, and thus, functions better under interseeding conditions than the oilseeds.

3.3 | Cover Crop Green Cover

Green cover as reported is the percent of area occupied by living cover crops, which has practical implications in

TABLE 4 Mean percentage of cover crops green cover (%) for the different locations, seasons, interseeding dates, and cover crop species when cover crops interseeded into standing maize and soybean in 2016 and 2017

	Cover crop green cover, %							
	Ames		Morris		Prosper		Rosemount	
Factors and levels	Autumn	Spring	Autumn	Spring	Autumn	Spring	Autumn	Spring
Interseeding date[a]	Maize system							
R4	7a[b]	25a	14a	11b	7a	5a	na[c]	na
R5	11a	31a	18a	16a	8a	5a	na	na
R6	9a	29a	6b	8b	4b	5a	na	na
Cover crop[d]								
PC	8b	20b	6b	8b	6a	9a	na	na
Rye	15a	56a	24a	20a	7a	5a	na	na
WC	5b	9c	9b	6b	5a	1b	na	na
Interseeding date	Soybean system							
R6	3b	18b	23a	16a	17a	23b	4a	6a
R7	9a	33a	27a	21a	19a	31a	5a	8a
R8	4b	33a	18a	15a	10b	36a	7a	12a
Cover crop								
PC	5b	24b	15b	16b	16a	40a	4b	6b
Rye	10a	48a	29a	27a	17a	30b	12a	17a
WC	2b	12c	25a	10c	13a	20c	1b	3b

[a]R4, R5, and R6 are interseeding dates for cover crops into standing maize; similarly, R6, R7, and R8 are interseeding dates for cover crops into standing soybean.
[b]Means followed by a common letter in a column for a factor levels and same recorded variable within a system and in a season are not statistically significant at $P = 0.05$.
[c]na = not applicable.
[d]PC = Pennycress; Rye = winter rye; WC = winter camelina.

protecting soil from erosion. In the maize system, interseeding date affected percent green cover significantly at Morris and Prosper. Similarly, cover crop species significantly affected percent green cover at Ames, Morris, and Prosper in the maize system.

In autumn at Morris and Prosper, the third interseeding date (R6) produced the lowest green cover in the maize system (Table 4). This likely resulted from less plant growth in the later interseeding (R6) due to less time before freezing temperatures by late autumn (Table 2). At Morris in spring, R4 and R6 had 31 and 50% lower green cover, respectively, than R5 interseeding. The absence of a significant interseeding date effect on green cover at Ames under maize system indicates that producers in this area could have a wider window for interseeding cover crops without jeopardizing soil coverage to protect from erosion mostly in spring. At Ames and Morris in both autumn and spring, green cover was greater for winter rye than the oilseed species in the maize system. For instance, at Ames in spring, the green cover for winter rye was 56% compared with PC (20%) or WC (9%) (Table 4).

In the soybean system, Ames and Prosper showed a tendency of improved spring percent green cover for late interseeding date in general (Table 4). For instance, interseeding date by cover crop interaction means showed that green cover for winter rye at Prosper in spring was 14, 33, and 42% for R6, R7, and R8, respectively. This greater green cover for the late seeding (R8) could be explained by soybean leaf senescence at R8 compared with earlier seeding dates thus, allowing more light penetration. Cover crops species showed substantial differences in percent green cover (Table 4). Winter rye produced the greatest green cover in spring at Ames, Morris, and Rosemount. But at Prosper, PC had significantly greater green cover (40%) in spring than rye (30%) or WC (20%). This greater green cover from PC particularly in early spring indicates that it has good potential as a cover for more northerly latitudes like Prosper.

Successful establishment of winter annual cover crops is essential for covering the soil particularly in spring when soils are most exposed to erosive rain and wind events in the upper Midwest. Dabney, Delgado, and Reeves (2001) showed that cover crops growing in spring can reduce direct impacts of rain drops thus, reducing soil erosion. Generally, the results from this study indicate that spring green cover due to cover crop species was low. According to Allmaras and Dowdy (1985), at least 30% of the soil surface should be covered to protect soil from water and wind erosion. Erenstein (2002) suggested that higher percentage of soil cover implies even greater reductions of soil erosion. Interseeding could increase plant density per unit area but may also lead to taller, thinner seedlings due to competition. This could result in less soil surface coverage due to less tillers and or branches. A seeding rate study on wheat (*Triticum aestivum* L.) showed that the

TABLE 5 Mean biomass of cover crops (kg ha^{-1}) for the different locations, seasons, interseeding dates, and cover crop species when cover crops interseeded into standing maize and soybean in 2016 and 2017

	Biomass of cover crops, kg ha^{-1}							
	Ames		Morris		Prosper		Rosemount	
Factors and levels	Autumn	Spring	Autumn	Spring	Autumn	Spring	Autumn	Spring
Interseeding date[a]	Maize system							
R4	91a[b]	867a	165ab	490a	104a	348a	na[c]	na
R5	108a	1165a	249a	468a	110a	335a	na	na
R6	65a	902a	82b	302b	42b	286a	na	na
Cover crop[d]								
PC	75b	461b	78b	308b	76a	271a	na	na
Rye	147a	2314a	302a	665a	114a	464a	na	na
WC	41b	159b	116b	287b	66a	234a	na	na
Interseeding date	Soybean system							
R6	63a	480a	223ab	600a	345a	764a	199a	136b
R7	118a	1007a	333a	541a	326a	789a	149a	270a
R8	49a	826a	115b	419a	144b	790a	145a	286a
Cover crop								
PC	55b	599b	96b	422b	263a	774b	171b	78b
Rye	137a	1414a	402a	783a	359a	1107a	298a	574a
WC	37b	299b	173b	356b	193a	463c	23c	40b

[a]R4, R5, and R6 are interseeding dates for cover crops into standing maize; similarly, R6, R7, and R8 are interseeding dates for cover crops into standing soybean.
[b]Means followed by a common letter in a column for a factor levels and same recorded variable within a system and in a season are not statistically significant at $P = 0.05$.
[c]na = Not applicable.
[d]PC = Pennycress; Rye = winter rye; WC = winter camelina.

number of tillers reduced with increasing seeding rates (Carr, Horsley, & Poland, 2003). Selecting and or developing cultivars that can produce strong seedlings when interseeded into standing maize and soybean are essential to provide improved soil coverage in early spring.

3.4 | Cover Crop Biomass

In the maize system, the effect of interseeding date at Morris and Prosper significantly affected cover crop biomass. Similarly, the variations in biomass due to cover crops were significant at Ames and Morris. The first two interseeding dates (R4 and R5) produced more cover crop biomass than R6 in autumn at Morris and Prosper (Table 5). Similar results were recorded at Morris in spring. Under the maize system, biomass correlation with percent green cover ($r = 0.89$) was significant ($P < 0.05$). This indicates that green cover may be used as an indirect and nondestructive measure for biomass yield estimation if properly calibrated. Under the maize system, winter rye biomass was greater than that of the oilseeds at Ames and Morris in both autumn and spring and agrees with previous finding (Noland et al., 2018). At Ames, winter rye biomass in spring was greater (2314 kg ha^{-1}) than the oilseed covers and even when compared with the other locations which likely was due to a longer growing season.

In the soybean system, the interaction effect of interseeding date by cover crop species on cover crop biomass was significant at Morris in spring. These interaction means showed that PC produced more biomass than WC in the spring when interseeded at R6. At Morris and Prosper, interseeding at R6 or R7 generally produced more biomass in autumn than at R8 but these differences disappeared in spring. At Rosemount in spring, early interseeding resulted in lower biomass compared with R7 or R8. At Ames, Morris, and Rosemount in both autumn and spring, winter rye consistently produced more biomass than PC or WC (Table 5).

When compared with direct seeding of cover crops, biomasses recorded in this study were generally low, except at Ames, but agree with previous findings by Bich et al. (2014) for a maize system experiment conducted in South Dakota. In addition, PC and WC biomass were lower than previous findings where these oilseeds were direct seeded after spring wheat (Weyers et al., 2019).

3.5 | Soil Water Content

Under both maize and soybean systems, soil water content for the 0 to 30 and 30 to 60 cm was dependent more on weather than applied treatments. Although soil sampling for moisture determination in this study was limited to two sampling times, it was done at critical time periods and differences were not found. At all locations, and for maize and soybean systems, the effect of interseeding date and cover crops on soil water content (for 0–30- and 30–60-cm soil depths) was not significant (Figure 1a,b). But the interaction effect of interseeding date by cover crop species on soil water content was significant in autumn for 0–30-cm soil depth at Prosper under maize system. However, this mean difference was very low and thus, biologically insignificant. Under both maize and soybean systems, generally, soil water content in autumn tended to be greater than spring (Figure 1). In the soybean system, at Ames and Morris, there was more soil water at the 0- to 30-cm depth in 2018 and in 2017 during the spring. The soil water content at 30- to 60-cm soil depth was greater in 2017 than in 2016 at all locations in both autumn and spring except at Ames in autumn.

One of the major reservations of growers establishing cover crops in the off-season is whether there will be enough soil moisture for their cash crop, especially under dryland farming conditions where precipitation is limiting crop growth. However, this study demonstrated that there was no difference in soil moisture content between the control and the treatments in early spring when it is time to seed the next crop. A similar study showed that cover crops had no effect on soil water content particularly at lower soil depths (20–40 and 40–60-cm soil depth) (Odhiambo & Bomke, 2007). Long-term and consecutive use of a rye cover crop contributed to improved soil water content and soil water storage in a maize–soybean cropping system (Basche et al., 2016). This suggests that long-term use of cover crops could contribute to improve system sustainability in maize–soybean dominated cropping systems.

3.6 | Maize and Soybean Grain Yield

Maize grain yield in 2016 was greater than in 2017 at all locations. The mean grain yields in 2016 at Ames, Morris, and Prosper were 13.7, 13.2, and 12.3 Mg ha^{-1}, respectively, compared with 12.1, 10.8, and 12.0 Mg ha^{-1}, respectively, for the corresponding locations in 2017. The greater grain yields in 2016 were mainly associated with better distribution and total rainfall received particularly in the month of July (Table 2). There was no maize grain yield difference due to cover crop interseeding dates, cover crop species or their interaction, but grain yield did vary by location (Figure 2a).

At Ames and Morris, soybean grain yield was greater in 2016 than 2017 but it was greater at Prosper in 2017 than in 2016. Prosper received more cumulative (May–October) precipitation in 2017 than in 2016 and this could partly explain this yield difference. Soybean grain yield was not affected by either interseeding date or cover crops at all locations except at Rosemount. At Rosemount, soybean grain yield in PC and winter rye treatments was significantly greater than the control treatment. This grain yield increase was 10 and 6% over the control for PC and winter rye, respectively (Figure 2b). However, this result was only from one location and one season. Therefore, further research is needed to justify this increase. A similar study showed that interseeding PC into standing soybean increased soybean yield particularly when soybean yields were low during a dry season (Bishop & Nelson, 2018). This suggests that PC biomass in the interrow may have had a mulching effect to conserve soil moisture, but further research would be needed for verification. A different study showed that soybean grain yield following a PC was greater than the control (over winter fallow) (Phippen & Phippen, 2012) indicating the potential compatibility of PC with a soybean double-crop.

Although interseeding disturbs the soil and to some extent the main crop, which presumably could cause yield loss, no such effects were recorded in this study, which agrees with previous findings (Belfry & Van Eerd, 2016; Bich et al., 2014; Bishop & Nelson, 2018; Noland et al., 2018). The absence of maize or soybean grain yield loss due to interseeding cover crops could help to facilitate outreach activities for better adoption of these covers.

3.7 | Cover Crop Establishment Comparison under Maize and Soybean Systems

Overall, winter survival was better under the soybean system compared with maize. This largely may have been attributed to less shading stress under the soybean system due to its smaller leaf canopy area compared with maize. At Morris, above and below canopy light was measured to determine the amount of PAR received by cover crops in both maize and soybean after interseeding. Under maize, for all three seeding dates, the ratio of below to above PAR was relatively constant averaging 0.11. However, under the soybean system, it was 0.34 for the first seeding date and increased to 0.59 by the last seeding date (data not shown), which was primarily due to leaf drop as soybean reached full maturity. This greater light penetration through the soybean canopy in the later seeding dates as compared with maize probably led to improved cover crop seedling growth and winter survival. Additionally, soybean fix N and the residual N left in the soil after its harvest could increase soil available N compared with maize, which may have improved vigor and seedling growth and consequently contributed to greater winter survival. Moreover, soybean stubble interferes less with solar energy warming soil so soil temperatures likely are greater under soybean stubble than for maize, another factor that allows for greater accumulation of nitrate following crop harvest. Uchino et al. (2009) showed that there was more competition for N between maize

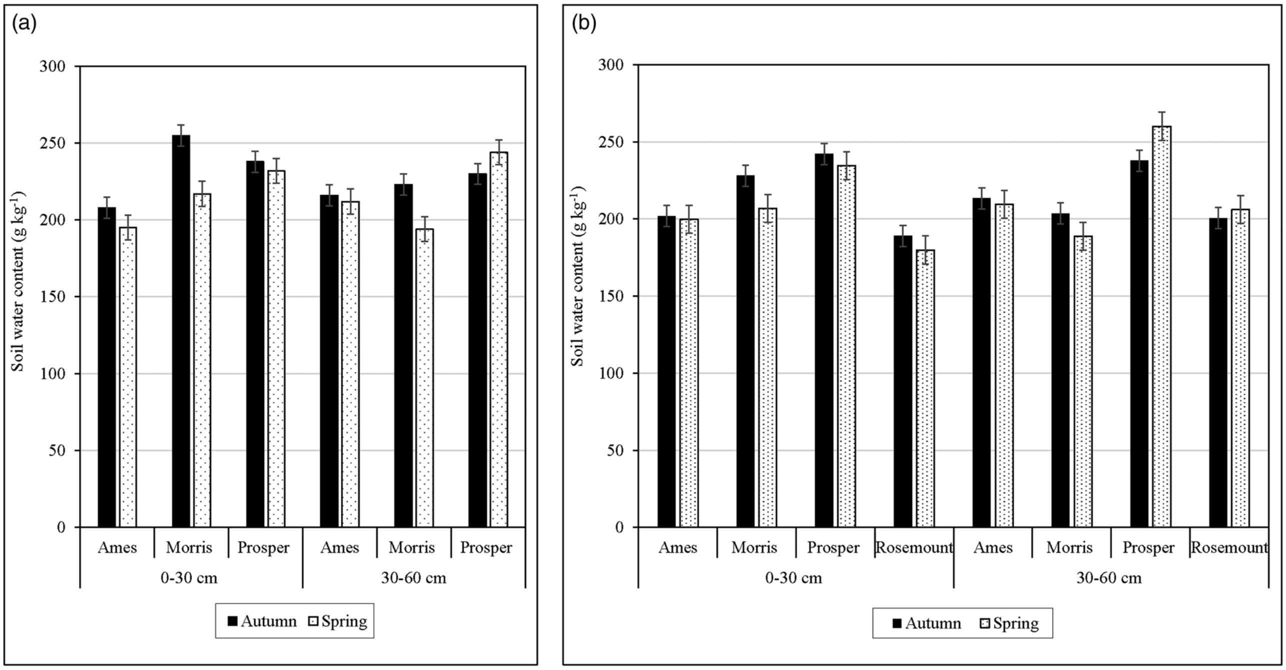

FIGURE 1 Mean soil water content (g kg^{-1}) at 0- to 30- and 30- to 60-cm soil depths for (a) maize (b) soybean systems by seasons at different locations when averaged over interseeding dates and cover crop species in 2016 and 2017. Error bars are standard error of the means

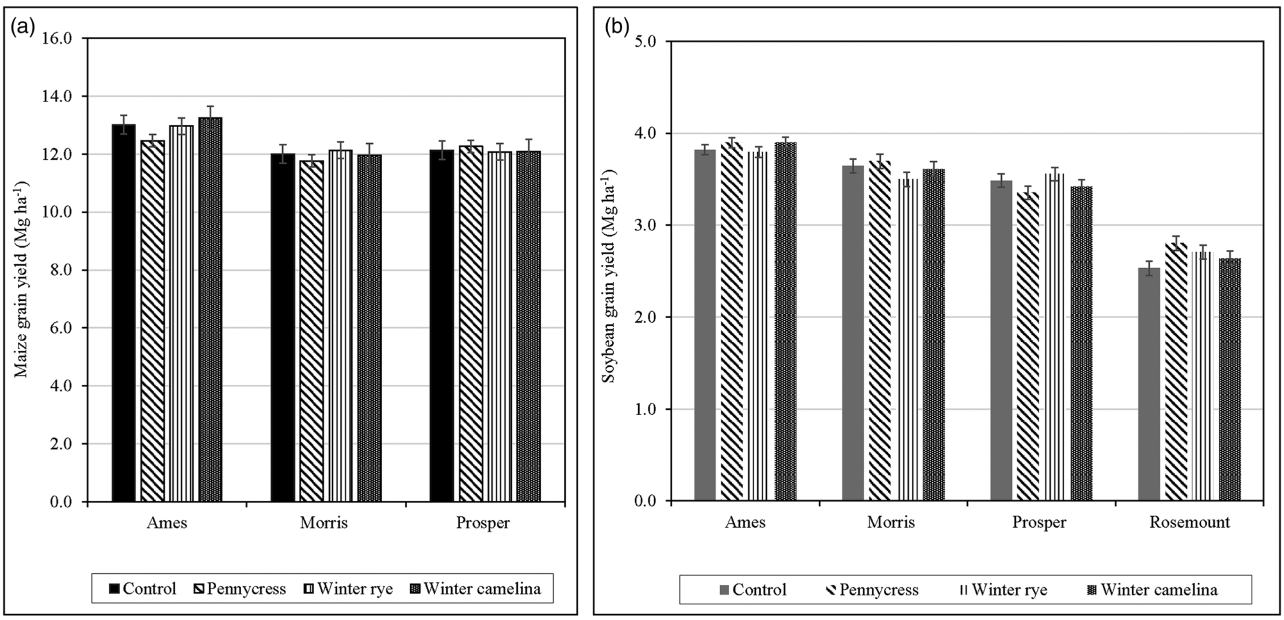

FIGURE 2 Mean grain yield for (a) maize (Mg ha^{-1}) and (b) soybean (Mg ha^{-1}) at different locations showing effects of cover crop species when interseeded into standing maize and soybean in 2016 and 2017 averaged over interseeding dates. Error bars are standard error of the means. Significant effects of cover crop species on mean soybean grain yield was recorded only at Rosemount at $P = 0.05$

and cover crops than between soybean and cover crops. Moreover, Ruffo, Bullock, and Bollero (2004) demonstrated that winter rye (planted as a cover crop following maize harvest) biomass in spring increased when N fertilizer application for the previous maize crop was increased to 270 kg ha^{-1} N, possibly indicating that residual N offers better cover crop growth. Factors such as nutrient availability, light penetration, and soil warming differences between maize and soybean systems can influence fall cover crop growth and winter survival but require further research to verify.

4 | CONCLUSIONS

Neither interseeding date nor cover crop species negatively impacted maize or soybean grain yields. Furthermore, there was generally no significant effect of interseeding cover crops on soil water content. Green cover, biomass, and winter survival of WC and PC were lower than that for winter rye in general. This could be partly due to poor seed-soil contact during broadcast interseeding and perhaps more likely due to canopy shading affecting the small seed size oilseed crops. Shading could have stunted and weakened plants making them more susceptible to winter kill.

Generally, establishment, growth and survival of cover crops were greater in the soybean than the maize system. Results indicate that cover crop establishment, particularly into standing maize, is challenging. Therefore, research should focus on developing cultivars tolerant to shading, and agronomic management practices that improve seed-soil contact to improve establishment and winter survival, while enhancing ecosystem services. Cover crops could be integrated into soybean systems to increase off-season plant cover and crop diversification.

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