INTERSEEDING CEREAL RYE AND WINTER CAMELINA INTO CORN IN NORTH DAKOTA

A Thesis
Submitted to the Graduate Faculty
of the
North Dakota State University
of Agriculture and Applied Science

By

Melissa Marie Geiszler

In Partial Fulfillment of the Requirements
for the Degree of
MASTER OF SCIENCE

Major Department:
Plant Sciences

October 2018

Fargo, North Dakota

North Dakota State University
Graduate School

Title

Interseeding cereal rye and winter camelina into corn in North Dakota

By

Melissa Marie Geiszler

The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

SUPERVISORY COMMITTEE:

Dr. Joel Ransom
Chair

Dr. Marisol Berti

Dr. Hans Kandel

Dr. Abbey Wick

Approved:

November 1, 2018
Date

Dr. Richard Horsley
Department Chair

ABSTRACT

Limited photosynthetically active radiation (PAR) can reduce interseeded cover crop growth in corn (*Zea mays* L.). Two experiments in North Dakota evaluated the effect that hybrid relative maturity (RM), row width, and cover crop planting date have on cereal rye (*Secale cereale* L.) and winter camelina [*Camelina sativa* (L.) Crantz.] establishment when interseeded into 80 and 89 RM hybrids at V7 and R4 growth stages in 56- and 76 cm corn row widths. Cover crop biomass was typically less than 100 kg ha^{-1}. In the following spring larger amounts of PAR beneath the 80 RM hybrid increased cover crop biomass by 20.8 kg ha^{-1}. Cover crop biomass tended to be greater in the 76 cm row width but was not significantly different from the 56 cm width. Cover crops decreased residual soil nitrate by 6.0 kg ha^{-1} in the fall and by 15.6 kg ha^{-1} in the spring.

ACKNOWLEDGEMENTS

I would like to thank my advisor Dr. Joel Ransom for his patience, kindness, and guidance over the past few years. I could not have completed any of this without the help of Chad Deplazes, Darin Eisinger, J Stanley, Matt Rellaford, Nick Schimek, Tracy Hillenbrand, and Lizzy Lovering. I am grateful for what God has taught me in James 1:4 through it all.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDIX TABLES

INTRODUCTION

Cover crops can be used to decrease nitrate (NO_3^--N) leaching and soil erosion, increase soil aggregation and soil organic matter (SOM), manage water, and suppress weeds (Putnam et al., 1983; Nielsen and Vigil, 2005; Basche et al., 2016; Pantoja et al., 2016;). Interest in integrating cover crops into cropping systems in the upper Midwest has spread as awareness has grown about the impacts that agricultural practices can have on the environment (NCR SARE and CTIC, 2016). As cover crop adoption has increased, cover crop establishment appears to be one of the greatest challenges of using cover crops. This is especially true in the upper Midwest where the short growing season and freezing winters discourage the use of most cover crops after corn harvest (NCR SARE and CTIC, 2016).

To remedy this, winter hardy cover crops can be broadcasted or drilled into standing corn to allow more time for cover crop establishment and growth during the growing season (Bich et al., 2014). Cereal rye is the most commonly used cover crop because of its fast growth, N-scavenging and soil-building characteristics, and winter hardiness (Clark, 2007; NCR SARE and CTIC, 2016). Winter camelina has the potential to be used as a cover crop in the upper Midwest because of its extreme cold tolerance, however little research has been done to assess the performance of camelina as an interseeded cover crop (Berti et al., 2016).

Interseeded cover crops can be difficult to establish successfully if there is limited rainfall after cover crop planting, or if there is not enough photosynthetically active radiation (PAR) infiltrating through the canopy of the main crop to sustain the cover crops below (Crusciol et al., 2013; Wilson et al., 2013; Belfry and Van Eerd, 2016; Bich et al., 2014; Curran et al., 2018). The need for increased research regarding cover crop management to improve cover crop establishment and performance when interseeded into standing crops has become increasingly apparent. Just as with cash crops, proper cover crop management will determine whether or not the cover crops deliver the desired outcome or completely fail to establish in a given environment.

This research was conducted to assess how corn hybrid relative maturity (RM), corn row width, and cover crop planting date affect the establishment and persistence of cereal rye and winter camelina interseeded into corn. Understanding these interactions will help to improve cover crop management in North Dakota and the upper Midwest.

OBJECTIVE

The overall goal of this research was to evaluate how corn row width, hybrid relative maturity, and cover crop planting date affect cover crop development in North Dakota. The specific objectives were:

1. Evaluate cover crop establishment and development when interseeded into corn hybrids with differing relative maturities.
2. Evaluate the effect of planting date on cover crop development.
3. Evaluate the development of rye and camelina seeded alone and in a mixture.
4. Evaluate the effect of cover crop growth on corn grain yield.
5. Quantify the amount of photosynthetically active radiation available for cover crop growth under different hybrids and row widths.

LITERATURE REVIEW

Benefits of Cover Crops to Production and the Environment

Reducing Soil Erosion

Cover crops and crop residues left on the soil surface help reduce wind and water erosion. Surface residues slow water erosion by intercepting raindrops before they hit the soil surface to prevent aggregate break down and surface sealing, and by slowing water movement to increase the amount of time the water has to infiltrate into the soil (Frye et al., 1988). Fast growing grass cover crops are particularly helpful with reducing erosion. Kaspar et al. (2001) found that in a corn-soybean [*Glycine max* (L.) Merr.] rotation in Iowa, a rye cover crop interseeded into soybean in mid-August could increase infiltration by 16%, reduce runoff by 10%, and reduce interrill erosion by an average of 55% compared with leaving the soil bare in the spring prior to corn planting. The authors noted that obtaining a large amount of residue was the most important factor affecting runoff and erosion. In years with reduced spring biomass growth the cover crops did not affect soil water movement (Kaspar et al., 2001). A similar notion was also reported by Blanco-Canqui et al. (2017). They found that when baling corn stover after harvest for feed or fuel, interseeded rye biomass accumulation of less than 1 Mg ha^{-1} by the time of spring termination did not reduce soil erodibility. However, they did find that increasing the total amount of residue cover by leaving the stover in the field increased the mean soil aggregate size and reduced the soil erodible fraction after two years of continuous corn (Blanco-Canqui et al., 2017). Cover crops can protect the soil from erosion and runoff by covering the soil surface in the absence of adequate amounts of crop residue, but an adequate amount of biomass is needed first before the expected benefits can be realized (Kaspar et al., 2001; Blanco-Canqui, 2017).

Soil Physical Properties and Organic Matter

In addition to reducing soil erosion, cover crops can also benefit the soil by increasing SOM, improving aggregation, and alleviating symptoms of soil compaction. Excessive tillage not only leaves the soil susceptible to erosion, it also accelerates the oxidation and mineralization of SOM as well (Doran and Smith, 1987). While mineralization is important for making nutrients available to the crop, mineralizing organic matter faster than it can be replaced by crop residue causes a net decline in SOM content, which decreases soil health and fertility (Blanco-Canqui et al., 2014). Soil organic matter affects other important soil qualities such as soil water retention, increasing the soil’s cation exchange capacity, soil aggregation, and decreasing bulk density (Doran and Smith, 1987). Higher SOM contents are associated with healthier soils that are more resistant to weather extremes, which can improve profitability in excessively dry or wet years.

While cover crops can increase soil organic carbon (SOC) content in the long term, the effects are generally not detectable the first few years after establishment (Blanco-Canqui et al., 2014; Blanco-Canqui et al., 2017). Additionally, large amounts of cover crop biomass are needed to accomplish this. Blanco-Canqui et al. (2017) found that an average of 1.47 Mg ha^{-1} of rye biomass accumulated after planting into corn in Nebraska was not enough to increase soil organic carbon or increase the mean diameter of soil aggregates after three years. Likewise, in Maryland rye following corn was able to increase the number of water stable aggregates, but did not affect SOC or soil bulk density after only two years (Steele et al., 2012). However Basche et al. (2016) found that 13 years of using rye as a winter cover crop in a no-till corn-soybean rotation in Iowa increased field capacity water content by 10-11% and plant available water by 21-22%, which they attributed to increased SOM content and soil aggregation.

Tillage is used to decrease the soil's bulk density and increase macroporosity, however these effects are only temporary. Cover crops could potentially be used to decrease bulk density and increase macroporosity without the negative effects of mixing the soil. In a study by Afzalinia and Zabihi (2014) tillage with a moldboard plow followed by a disk harrow before planting decreased soil bulk density compared with no-till, but as the soil settled during the growing season there was no difference in bulk density between the tilled and no-till treatments by the time of corn harvest. In Texas, after 19 years of continuous cotton (*Gossypium hirsutum* L.) production, no-till treatments with a rye cover crop planted in the winter did not decrease bulk density compared with conventional tillage (Lewis et al., 2018). Chen and Weil (2011) found that forage radish (*Raphanus sativus* L.) did not decrease the soil's bulk density, instead the radish roots were able to create channels through a compacted soil layer which increase the amount of roots below the compaction layer in the following corn crop compared to the amount of roots found in corn following both cereal rye and the no-cover crop control. These studies suggest that while it may take many years before cover crops have a significant effect on SOM and bulk density, certain soil benefits such as increased infiltration and rooting depth may be readily attainable in the near term.

Nitrogen Fixation and Uptake

One of the most favored attributes of cover crops is the role they can play in N cycling. Legumes can add more N to the soil, while some grasses and plants in the Brassiceceae family are good at scavenging NO_3^--N before it leaches below the root zone. Legumes have the potential to increase the amount of N in the system by fixing atmospheric N_2 to supply their N needs, which will become available to subsequent crops later as the residues decay and the N is mineralized. Since they are able to supply their own N, interseeding with a legume could also be advantageous if low soil N near the soil surface is limiting cover crop growth. Curran et al. (2018) hypothesized that limited soil N during corn grain fill negatively affected fall annual ryegrass (*Lolium multiflorum* L.) biomass production, and that under low N conditions, interseeding with a legume may improve cover crop biomass accumulation.

Most N losses occur in the spring when soils become saturated from snowmelt and when spring rains are more frequent, stimulating mineralization, nitrification, and water movement through the soil (Herrera and Liedgens, 2009). Cover crops can take up NO_3^--N in latefall or early spring in the absence of the main crop to prevent loss (Appelgate et al., 2017; Berti et al., 2017). Ball-Coelho and Roy (1997) noted that NO_3^--N that leached deeper than 1.5 m was unavailable for corn uptake later in the season, but that total leaching was reduced when using a rye cover crop before corn. The amount of N loss reduced depends on cover crop species, in-season water movement, cover crop growth, and the amount of residual NO_3^--N in the soil (Kaspar and Singer, 2011). In Denmark, a variety of grass and legume cover crops seeded throughout a rotation of spring barley (*Hordeum vulgare* L.), hemp (*Cannabis sativa* L.), an intercrop of pea and barley, spring wheat (*Triticum aestivum* L.) and potato (*Solanum tuberosum* L.) were able to take up an average of 23 kg N ha^{-1} per year (De Notaris et al., 2018). In North Dakota, forage radish planted in early August was able to scavenge an additional 58 kg N ha^{-1} to what was available according to a pre-plant soil NO_3^--N test (Samarappuli et al., 2014). When cover crops are present to take up NO_3^--N in the absence of a main crop, the N stored in the cover crop tissue may be recycled to the following crop as the cover crop residue decays (Ball-Coelho and Roy, 1997; Vaughan and Evanylo, 1998). In Wisconsin, Ruark et al. (2018) found that radish planted after winter wheat harvest was able to take up anywhere from 19.7 to 202 kg N ha^{-1} before the radish was frost-killed, but the timing of subsequent N release to corn the following year was variable as the tissues decayed. While the radish was able to reduce some N loss, the amount of N turnover would not be enough to supply the N needs of the next crop (Ruark et al., 2018).

It is important that biomass decay and N mineralization is synchronous with crop demand; otherwise the N may be lost (Ball-Coelho and Roy, 1997; Doran and Smith, 1987). Using cover crop mixtures could help increase the overall N balance within the soil by fixing N_2 with legumes, scavenging NO_3^--N that could otherwise be lost and by adding organic material to the soil over time (Basche et al., 2016; Lewis et al., 2018; Ruark et al., 2018).

Water Management

Cover crops can help increase water infiltration in a no-till system and reduce runoff by slowing water movement across the soil surface, and reduce soil crusting or sealing by intercepting raindrops before they hit the soil surface (Frye et al., 1998; Ruiz-Colmenero et al., 2011). Residues from cover crops may also help catch snow to increase snow cover during the winter, which reduces wind erosion, increases the survival of overwintering cover crops, and increases soil water in the spring after snowmelt (Qiu et al., 2011). Reduced tillage systems have been known to have wetter, cooler soils in the spring compared with conventionally tilled soils (Doran and Smith, 1987; Munawar et al., 1990). However, a winter-hardy cover crop able to regrow in the spring could potentially transpire some soil water to speed soil warming and allow for earlier field activities. Often times though, the living cover crop acts as mulch instead, reducing evaporation from the soil surface (Barker et al., 2018). Munawar et al., (1990) found that residues from rye killed two to three weeks before corn planting resulted in significantly greater early-season soil water compared with rye killed at corn planting because it acted as a mulch to reduce water evaporation, whereas the later-killed rye transpired more water while it was still growing and tended to remain more erect after termination, and did not reduce soil water evaporation.

Timing cover crop termination before planting the main crop is important, because spring cover crops could potentially take up too much stored soil water and negatively affect the following cash crop (Unger and Vigil, 1998; Pantoja et al., 2016). Nielsen et al. (2015) found cover crop water use to be 1.8 times greater than normal evaporative water loss in Colorado and Nebraska. Legume cover crops grown before winter wheat reduced the available soil water 5.5 to 10.4 cm depending on termination date, reducing winter wheat yield 0.9-1.7 Mg ha^{-1} (Nielsen and Vigil, 2005).

Cover crops that are interseeded into standing crops generally have a negligible effect on soil water content because growth beneath the canopy is limited while the main crop is actively growing. Noland et al. (2018) found that at the time of corn harvest, although rye interseeded into corn at V7 had reduced the volumetric water content by 14% in the top 30 cm of soil, it had no effect on soil water content from 30 to 60 cm below the soil surface and did not reduce corn yield.

Weed Suppression

Cover crops can be used as an alternative method to chemical weed control because they can outcompete weeds for light and water, and with some species such as rye, inhibit weed growth as allelopathic compounds are released from both live plants and decaying residues (Putnam et al., 1983; Schulz et al., 2013). The primary methods of weed suppression by plant residues is through physical impedance and light deprivation, and so the extent to which weeds are suppressed will depend largely on the amount of vegetative soil cover and how quickly the cover crops are able to get the soil covered with their foliage (Teasdale and Mohler 2000). Thus, fast growth and early ground coverage by the cover crop canopy are important characteristics of a cover crop species used for weed control (Baraibar et al., 2018). To this end, grasses excel as weed suppressors over brassicas and legumes because of their rapid growth habits (Clark, 2007; Baraibar et al., 2018).

Overwintering cover crops growing before the main crop is planted could reduce early season weed pressure, but may also reduce the yield of the main crop (Uchino et al., 2009; Bilalis et al., 2017). Cover crops interseeded after the main crop is planted can still offer some in-season weed control while avoiding potential yield reductions. Bilalis et al. (2017) found that corn-dry bean (*Phaseolus vulgaris* L.) intercropping significantly reduced weed growth compared with corn and bean grown alone. Interseeded rye and hairy vetch suppressed weed growth when interseeded into corn and soybean, but the rye did not survive until harvest beneath the soybean and the hairy vetch did not survive until corn harvest (Uchino et al., 2009). Grain yield was greatest and weed biomass the lowest when rye and hairy vetch were interseeded into corn (Uchino et al., 2009).

Cover crops could possibly be used as a way to extend early-season weed control in conjunction with herbicides if the cover crops are tolerant or unaffected by any residual effects of the herbicide used. Cornelius and Bradley (2017) found that rye was the least sensitive out of eight common cover crops exposed to residual herbicide pressure from 27 common corn and soybean residual herbicides. Even so, cover crop use may be limited in fields with severe herbicide-resistant weed problems. Curran et al. (2018) suggested that cover crop sensitivity to residual herbicides may preclude cover crop use in fields with highly competitive, herbicide resistant weed species such as Palmer amaranth [*Amaranthus palmeri* (S.) Wats].

Cover Crop Management

Planting Method

There are several different strategies available for planting a cover crop. Cover crops can be planted into the soil using a drill, broadcasted onto the soil surface, or broadcasted and incorporated into the soil. The method used to seed the cover crops will depend on the available equipment and the desired application timing.

Cover crops can be planted with an ordinary drill before the main crop is planted, with the main crop during as it is planted, or after the main crop is harvested. The advantages of drilling are that it requires up to 50% less seed and results in faster, more uniform emergence compared with broadcast seeding (Bich et al., 2014; Brennan and Leap, 2014). Cover crop stand establishment can also be up to 50% greater when cover crops are drilled into the soil rather than broadcasted, even if some form of incorporation is used afterward (Brennan and Leap, 2014; Noland et al., 2018).

Cover crops can also be drilled in between the rows of a standing crop if using a specialized high-clearance drill up until the crop is about 75 cm tall (Curran et al., 2018). Noland et al. (2018) found that planting with a high clearance-drill or including light incorporation after surface broadcasting into standing corn at V7 resulted in greater biomass the following spring compared with surface broadcasting. Overall, they harvested an average of 61 kg ha^{-1} of biomass by planting with a drill compared with only 21 kg ha^{-1} of cover crop biomass by broadcast seeding (Noland et al., 2018).

When planting with a drill is not feasible, broadcast seeding cover crops is still a viable option (Fisher et al., 2011). The main advantage of broadcast applications over planting with a drill is that it is not restricted by the main crop’s height and can be done at almost any time during the season. This is accomplished either aerially by plane, with high-clearance equipment for in-season establishment, or with spreading equipment after harvest. The main disadvantage of surface broadcasting is that it leaves the seed exposed to the hot, dry environment at the soil surface and predation by insects, birds, and rodents (Fisher et al., 2011; Wilson et al., 2013). Successful germination and seedling establishment depends largely on whether or not the cover crop receives adequate precipitation within about a week of seeding (Wilson et al., 2013). Including some form of light soil incorporation after broadcast seeding can protect the seeds from predators and desiccation, but this is may be difficult to accomplish while the main crop is still standing. Timing the application to occur immediately before leaf drop of the main crop is an alternative way to protect the seeds, and can improve the chances of successful seedling establishment (Frye et al., 1988).

Timing of Interseeding into Corn

In the upper Midwest there is not enough time for cover crops to produce a beneficial amount of biomass between corn harvest and the first killing-frost if seeded after harvest (Berti et al., 2017). Cover crops can be interseeded early in the season before canopy closure or later in the season as the corn approaches maturity and the canopy opens as the corn leaves begin to senesce. Time of cover crop seeding early in the season is important, because it must be late enough not to effect corn yield, while still early enough to allow the cover crops to establish before canopy closure (Noland et al., 2018). In North Dakota, corn yield was significantly reduced when winter camelina was interseeded at the same time as corn planting, but yield was not affected when the camelina was interseeded after V4-5 (Berti et al., 2017). Similarly, in South Dakota, Bich et al. (2014) saw reduced corn yield when cover crops were interseeded at V3, but no yield effect was measured when cover crops were interseeded at V5.

Seeding cover crops after V4-5 appears to have no effect on corn yield, although delaying cover crop interseeding after V5 can negatively affect cover crop establishment and performance because there may be too little time between interseeding and canopy closure to adequately establish the cover crops before they enter into growing conditions with extremely reduced light availability after canopy closure (Belfry and Van Eerd, 2016; Curran et al., 2018). Limited water and light availability are often cited as reasons for poor establishment when cover crops are interseeded underneath into corn (Wilson et al., 2013; Bich et al., 2014; Belfry and Van Eerd, 2016). In Canada, cover crops interseeded at V4-V6 and at V10-V12 failed to establish due to the reduced water availability at the soil surface during the summer and the reduced light infiltration through the corn canopy after canopy closure (Belfry and Van Eerd, 2016).

Cover crops can also be interseeded during the later reproductive stages in late July or August so that the germinated seedlings will have more light available to them as the corn canopy begins to open as the corn senesces. The biomass of rye and oat (*Avena sativa* L.) broadcasted into soybean as early as late July was maximized when cover crops were planted in mid-August just prior to leaf drop (Johnson et al., 1998). However, late July and August are typically the driest part of the growing season when precipitation is less frequent. Cover crop seeds may not germinate or may sprout and wither if a timely rain is not received after planting (Wilson et al., 2013). In a study in Iowa, oat and rye cover crops interseeded into soybean in mid-August had to be reseeded in September because hot, dry conditions had caused a cover crop failure (Kaspar et al. 2001).

Winter-hardy Cover Crops

Cereal Rye

Cereal rye is able to germinate at low temperatures and is frost-tolerant down to -4˚C, making it a good choice for fall seeding when there is little time between cover crop planting and the first hard-frost (Webb et al., 1994). Because it is winter-hardy, spring re-growth can help to protect the soil from erosion and take-up any nutrients that could potentially leach to groundwater. Rye is commonly used as a cover crop in the upper Midwest for its winter-hardiness, N-scavenging ability, and soil-building qualities (Liu et al., 2005; Clark, 2007). Ball-Coelho and Roy (1997) found that using rye to take up unused NO_3^--N in the soil decreased the amount of NO_3^--N leached below the corn root zone. The NO_3^--N stored in the rye residue was released coinciding with times of high N demand from the following corn crop, which in turn decreased the amount of in-season N needed by about 10 kg ha^{-1} (Ball-Coelho and Roy, 1997). However, this is typically not the case. Corn yield was reduced following rye by 1.6 Mg ha^{-1} caused either by allelopathy or nutrient tie-up when the rye was not terminated until corn planting (Johnson et al., 1998). Rye grown before corn has been known to reduce yield when immobilized N is not released to the corn in a timely manner (Pantoja et al., 2016; Thomas et al., 2017).

Rye can also increase SOM and soil aggregate stability (Steele et al., 2012; Basche et al., 2016). Liu et al. (2005) measured an increase in soil aggregate stability after a rye cover crop, which correlated with an elevated presence of soil organic binding agents that were exuded from the cover crop roots. These organic binding agents ‘glue’ soil particles together to increase soil aggregation (Liu et al., 2005).

Winter Camelina

Camelina has been studied for use as an edible oil or biofuel, but its use as a cover crop has not been explored thoroughly (Berti et al., 2016; Appelgate et al., 2017). Winter camelina is able to germinate at 4˚C (Russo et al., 2010), and is one of the few broadleaf crops able to survive upper Midwestern winters, which greatly increases its usefulness as a cover crop. Camelina also has a high water-use efficiency, which is important for decreasing the risk of competition with the main crop (Gesch and Johnson, 2015). Though it is not currently grown commercially, studies have shown that winter camelina can be integrated into established cropping systems. This was demonstrated by Gesch et al. (2014), who showed that double- and relay-cropping systems with fall-seeded winter camelina followed by an early-maturing soybean could be profitable. As a cover crop in the upper Midwest, winter camelina planted following soybean harvest has the potential to produce up to 20 kg ha^{-1} of biomass in the fall and 308 kg ha^{-1} of biomass in the spring (Appelgate et al., 2017).

Cover Crop Mixes

There are many advantages and several disadvantages to seeding cover crop mixtures rather than just a single species of cover crop. Mixing grasses, legumes, and brassicas can take advantage of differing growth habits and root structures to target multiple environmental benefits at the same time (Clark, 2007). Including a tap-rooted brassica with a fast growing grass can help control erosion, weeds, and conserve soil moisture while also alleviating the effects of soil compaction by creating root channels through compacted layers which the roots of the main crop can follow after the cover crop roots decay (Williams and Weil, 2004). Multiple species of cover crops increases soil biodiversity, benefiting mycorrhizal fungi and other soil microbial communities (Chavarria et al., 2016).

Disadvantages of cover crop mixes can include increased seed cost and fewer herbicide choices safe for all of the cover crops. Several studies have shown that there may be no benefit to cover crop mixtures over a monoculture since the mixes produce no more biomass that what the most productive species produces on its own (Appelgate, 2017; Murrell et al., 2017). In Texas, a monoculture rye cover crop produced 865 kg ha^{-1} more biomass than a cover crop mix that included rye, hairy vetch, winter pea, and radish (Lewis et al., 2018). Conversely, many other studies have shown the benefits of mixes over monocultures (Williams and Weil, 2004; Curran et al., 2018). A recent meta-analysis by Thapa et al. (2018) found that overall, rye-hairy vetch mixtures produced more biomass and accumulated more N than either of the species grown in monoculture. Many farmers seem to feel this way as well, as indicated in a recent survey that found that 51% of cover crop users began by seeding cover crop monocultures, but eventually moved to using cover crop mixes as they become more experienced in cover crop management (NCR SARE and CTIC, 2016). The performance of cover crop monocultures and mixtures varies widely among environments and will depend on individual conditions for any given environment.

Photosynthetically Active Radiation beneath the Corn Canopy

Several studies have cited reduced light conditions beneath the crop canopy as the reason for suppressed cover crop growth or complete cover crop failure (Wilson, 2012; Bich et al., 2014; Belfry and Van Eerd, 2016). The amount of PAR that penetrates the main crop canopy depends on plant spacing and canopy density (Maddonni et al., 2001). As plant-to-plant spacing becomes more equidistant, resources such as light, water, and space are used more efficiently by the main crop (Widdicombe and Thelen, 2002). Optimal canopy density maximizes the amount of light intercepted by the main crop to achieve the highest rate of photosynthesis, resulting in greater yield (Thelen, 2006). Canopy density can be affected by several factors, including plant population, row width, crop hybrid, and crop row orientation (Stewart et al., 2003).

Plant population will affect the intraspecific competition of the individual main crop plants with one another, and also interspecific competition between the main crop and weeds or cover crops (Teasdale, 1995). Optimal plant population results in the greatest number of plants per hectare without causing too much intraspecific competition between plants so that yield begins to decrease.

Crop row widths vary depending on equipment and field activity and the desired plant population. Decreasing row width increases the intra-row plant-to-plant spacing as a way to achieve more equidistant plant spacing to optimize the amount of space that each plant has to grow in order to optimize yield (Maddonni et al., 2001). Available equipment is also a factor determining the row width used. Decreasing row width suppresses weeds by decreasing the amount of time to reach canopy closure, after which weed growth beneath the canopy is greatly suppressed (Tharp and Kells, 2001). However, interseeded cover crops are also suppressed under the canopy as well (Belfry and Van Eerd, 2016; Berti et al., 2017).

Canopy density is also affected by hybrid leaf architecture and RM. Some corn hybrids have a flatter leaf architecture more perpendicular to the ground that will decrease the amount of PAR that reaches the soil surface compared with leaves with a more erect architecture (Stewart et al., 2003). Additionally, corn hybrids with a shorter RM will mature earlier in the fall than a later maturing hybrid, thus allowing more light to infiltrate the corn canopy to reach the cover crops below sooner than with a later maturing hybrid (Crusciol et al., 2013). Senescing corn plants will also begin reducing their water intake, thereby reducing competition for water for the cover crops. Crusciol et al. (2013) found that palisadegrass (*Brachiaria brizantha*) intercropped between corn hybrids of various maturity lengths yielded less and were of lower forage quality under the latest maturing corn hybrid, due to the increased duration of growth suppression by water and light stress. A separate study with soybean also found that greater cover crop biomass could be gained using earlier-maturing cultivars (Crusciol et al., 2012). However, because early-maturity hybrids have less time to grow and accumulate dry matter, they are lower yielding than longer maturing hybrids and should not be used to aid cover crop establishment if it will impact profitability (Hao et al., 2010).

Belfry and Van Eerd (2016) observed that cover crops interseeded at the V4-V6 growth stage had difficulty surviving through the growing season, and as a result did not produce enough biomass to benefit the cropping system. Planting corn at a lower population, choosing an earlier maturing variety, or choosing a variety with a more erect leaf architecture to let more light down into the canopy may increase performance of interseeded cover crops (Curran et al., 2018). However, some suppression of the cover crop growth is still needed so that they do not reduce the yield of the main crop, interfere with mechanical harvesting, or encourage greater weed growth along with the cover crops (Borghi et al., 2013). Fast growing cover crops species like cereal rye should be used to limit the potential for increased weed growth (Baraibar et al., 2018).

Corn production management practices can directly affect cover crop growth and survival. Further investigation is required in order to better understand how management practices such as corn row width and choice of hybrid maturity affect interseeded cover crops.

MATERIALS AND METHODS

Experimental locations in Forman and Prosper, ND, were established from the spring of 2016 to the spring of 2018. Forman was managed with no tillage, while Prosper was managed with conventional tillage. A ‘Hybrid Experiment’ and a ‘Corn Row Width Experiment’ were planted in close proximity to each other at each location in each year. The soil types at each experimental location are listed in Table 1. Daily temperature and precipitation were recorded by the North Dakota Agricultural Weather Network (NDAWN) stations at Prosper and Brampton (near Forman), ND.

Table 1. Soil series description of 2016-2017 experimental locations at Forman and Prosper, ND.†

Location	Series	Texture	Taxonomy	Slope
				- % -
Forman	Aastad-Forman	Loam	Fine-loamy, mixed, superactive, frigid Pachic Argiudolls	0-3
Prosper	Kindred-Bearden	Silty clay loam	Fine-silty, mixed, superactive, frigid Typic Endoaquolls	0-2

†Soil data obtained from Web Soil Survey (Soil Survey Staff, 2016).

The Hybrid Experiment was laid out in a randomized complete block design with four replications. Treatments were a factorial combination of corn hybrid and cover crop. Corn hybrids used were Dekalb brands ‘DKC 30-19’ and ‘DKC 39-27’ with RMs of 80 and 89, respectively. Cover crops used were the rye cultivar ‘ND-Dylan’, interseeded at a rate of 67.0 kg live seeds ha^{-1}, the winter camelina cultivar ‘Joelle’, interseeded at a rate of 4.5 kg live seeds ha^{-1}. In the rye-winter camelina mixed treatment, rye was interseeded at 34.0 kg live seeds ha^{-1} and camelina was interseeded at 4.5 kg live seeds ha^{-1}. Seeding rates were determined using the lowest suggested rate for drilling cereal rye and winter camelina in a pure stand (Clark, 2007; Berti et al., 2016). The rye seeding rate was decreased by half in the mix treatment to reduce the competition of rye with winter camelina.

In the Hybrid Experiment, cover crops were interseeded when the corn reached the V7 growth stage in late June. Corn was planted in 76 cm rows in 3.0 m by 6.1 m plots. The previous crop was wheat at both locations in 2016, and soybean at both locations in 2017.

The Corn Row Width Experiment was laid out as a randomized complete block with a split-plot arrangement with three replications. Corn row widths of 56- or 76 cm were the main plots, and a factorial combination of cover crop and cover crop planting date were the sub-plots. An additional no-cover crop check plot was included within each main plot. Cover crop treatments were the same as described above in the Hybrid experiment. Cover crop planting date was at either the V7 or R4 corn growth stages in late June and late August, respectively. Plots with the 56 cm corn row width were 2.2 m wide and 6.1 m long, while plots with the 76 cm corn row width were 3.0 m wide and 6.1 m long. The hybrid used was Dekalb brand ‘DKC 36-28’ with a RM of 86. The previous crop was soybean at Forman and wheat at Prosper in 2016, and soybean at both locations in 2017.

All corn was planted to a depth of 5.1 cm at a rate of 79,000 live seeds ha^{-1} in four rows per plot on May 4-5, 2016, and May 11, 2017, with an ALMACO row crop plot planter (ALMACO, Nevada, IA). The center two corn rows and the central inter-row were used for collecting corn and cover crop data. Corn rows were orientated east to west in Forman and north to south in Prosper to facilitate field management activities. Nitrogen fertilizer was applied as urea ($CO(NH_2)_2$) in the spring at a rates of 168- and 145 kg ha^{-1} in 2016 and 2017, respectively, at each site. Weeds were controlled with in-season applications of glyphosate [N-(phosphonomethyl)glycine] (Roundup Powermax, Monsanto Co., St. Louis, MO) at the recommended label rate after planting and before cover crop interseeding at V4-V7. Tembotrione (2-[2-chloro-4-(methylsulfonyl)-3-[(2,2,2-trifluoroethoxy) methyl]benzoyl]-1,3-

cyclohexanedione) (Laudis, Bayer Crop Science, Durham, NC) was inadvertently applied to both experiments in Prosper in 2017, three weeks before cover crop interseeding; cover crop emergence did not appear to be affected by any residual effects from the herbicide. Plots were hand weeded as needed after cover crop planting.

A total of 1.5 m of corn stalks were removed from the ends of the corn data rows before corn harvest to reduce error in the grain data from plot edges. The inner two corn rows were harvested and grain weight was recorded with a Zürn 150 plot combine (Zürn Harvesting GmbH & Co, Schöntal-Westernhausen, Germany). Grain moisture was measured with a GAC 2100 moisture tester (Dickey-John Corp., Minneapolis MN), and yield were adjusted to 15.5% moisture.

Cover crops were seeded using a V-hoe with two blades spaced 15 cm apart to make parallel furrows to simulate planting with a high-clearance drill. The furrows were 2 to 2.5 cm deep and centered in each of the corn inter-rows. Cover crop seeds were distributed evenly into the furrows by hand; the furrows were then covered with soil using a hoe. This interseeding method was used for both the early and late cover crop planting dates. While normally the cover crops would be broadcasted into corn at the later planting date, this was done to avoid confounding the cover crop planting dates by using different interseeding methods at each date.

Cover crop performance was evaluated by measuring fractional green canopy cover (FGCC), aboveground biomass, biomass N content, and residual soil NO_3^--N. Fractional green canopy cover was measured biweekly after cover crop emergence using the Canopeo mobile smartphone application (Oklahoma State University Department of Plant and Soil Sciences, www.canopeoapp.com) by taking photographs of the cover crops interseeded in the central corn inter-row of each plot 56 cm above the soil. Photographs were processed with the Canopeo software to determine the FGCC over the soil.

Measurements of PAR were made under a clear sky between 1100 and 1400 h (CDT) using an AccuPAR LP-80 Ceptometer (Decagon Devices, Pullman, WA) at biweekly intervals after cover crop interseeding until corn harvest to quantify the potential amount of light available to cover crops below the corn canopy. In 2016, a light incidence measurement was taken outside of each plot under full sun, followed by three measurements at the soil level and above the cover crop canopy in the central corn inter-row within each plot. In 2017, light incidence was measured above the corn canopy simultaneously with measurements within each plot using the attached incident light sensor either at the soil level, or above the cover crop canopy after cover crops grew large enough to shadow the ceptometer. Measurements were taken by centering the ceptometer between the two cover crop rows, parallel with the direction of planting to measure the amount of the light transmitted to the cover crops.

Cover crop biomass was collected in the fall before the first killing-frost and before chemical termination the following spring. Biomass was sampled by cutting plants from both cover crop rows in one linear m at the soil surface. Separate data were collected for cereal rye and winter camelina for treatments including a cover crop mix. Samples were dried at 60˚C until the sample weight remained constant. Samples were ground finely enough to pass through a 1.0 mm mesh sieve, and then analyzed for N content using near-infrared spectroscopy with an XDS analyzer (Foss, Hillerød, Denmark). Soil was sampled from each plot at depths of 0-15 cm to measure residual soil NO_3^--N following cover crops at the times of cover crop biomass sampling.

Data were subjected to an ANOVA using the general linear models (GLM) procedure in SAS (SAS 9.4, SAS Inst., Cary, NC). Location and year were combined and termed ‘environment’. Environment and replication were considered random effects, while corn hybrid RM, corn row width, cover crop, and cover crop planting date were considered fixed effects. Environments were first analyzed separately to determine homogeneity of variance using Bartlett’s Chi-Square analysis; environments were combined only if variances were homogenous. Means were separated using Fischer’s-protected least significant difference (LSD) at $\alpha=0.05$. For grain yield and nitrate analysis in the Corn Row Width Experiment, cover crop and planting date were combined into a single factor in order to accommodate inclusion of the no-cover crop control. Analyses that did not include the no-cover crop control were analyzed with the factors of row width, cover crop, and planting date.

RESULTS AND DISCUSSION

Weather

Average daily temperature, daily rainfall, and planting and harvest dates are depicted in Figure 1. The monthly average of daily temperatures for each environment were within 1˚C of the 30-year average during each growing season for each year of the study. In 2016 warm temperatures extended late into November followed by an early thaw in the following spring allowed more time for cover crop growth compared with the fall of 2017 where mean daily temperatures fell below freezing in early November, followed by a later thaw in 2018 than in 2017. At Forman, cumulative rainfall was 49.7 cm in 2016 and 39.0 cm in 2017 from April through November compared to the 30-year average of 49.0 cm. At Prosper, cumulative rainfall was 38.6 cm in 2016 and 38.2 cm in 2017 from April through November, much less than the 30-year average of 52.0 cm. In 2018, both Forman and Prosper received 0.7 cm liquid rainfall between 1 April and cover crop termination.

Cover crops were interseeded in late-June and mid-August, and harvested in early November and early May the following spring each year. Unfortunately, the cover crops did not always receive a timely rain within one week after seeding to aid establishment (Wilson, 2013). In 2016, at Prosper the cover crops received 0.7-1.0 cm rain within seven days of planting at both cover crop planting dates, although at Forman it appeared that germination was delayed until 1.6 cm rain was received 14 d after interseeding. In 2017 at Prosper, the cover crops planted at the V7 corn growth stage received 0.7 cm rain within seven days of planting, while the cover crops planted at the R4 corn growth stage in mid-August did not receive any substantial rain until 19 days after planting. Conversely, at Forman cover crops planted at the V7 corn growth stage in late June did not receive rain until 19 days after planting, when 1.1 cm was received. Soil moisture varied within the experiment at the time of cover crop planting, resulting in different times of emergence among experimental units. The cover crops planted at the R4 growth stage in mid-August received 0.5 cm rain the day after planting.

Failure to receive rain soon after planting may have decreased cover crop emergence and survival in some experimental units. Wilson et al. (2012) observed that receiving rain within seven days of cover crop broadcast planting was extremely important for adequate cover crop establishment and growth. In the present experiment, it was observed that cover crops perished soon after emergence if timely rains were not received soon after seeding to sustain the small seedlings and their shallow roots, a problem also observed by Berti et al. (2016) when broadcast seeding camelina into corn. Stand losses were visually observed throughout the season, especially if dry periods occurred before the seedlings could establish an adequate root system to reach sub-surface soil moisture. The delicate camelina seedlings were most affected by these dry periods, most likely due to their small seedling size. While soil moisture was not measured in this study, observational evaluation of the experiments during the course of the season would suggest that timeliness of rains during the season was a critical factor affecting cover crop establishment and survival.

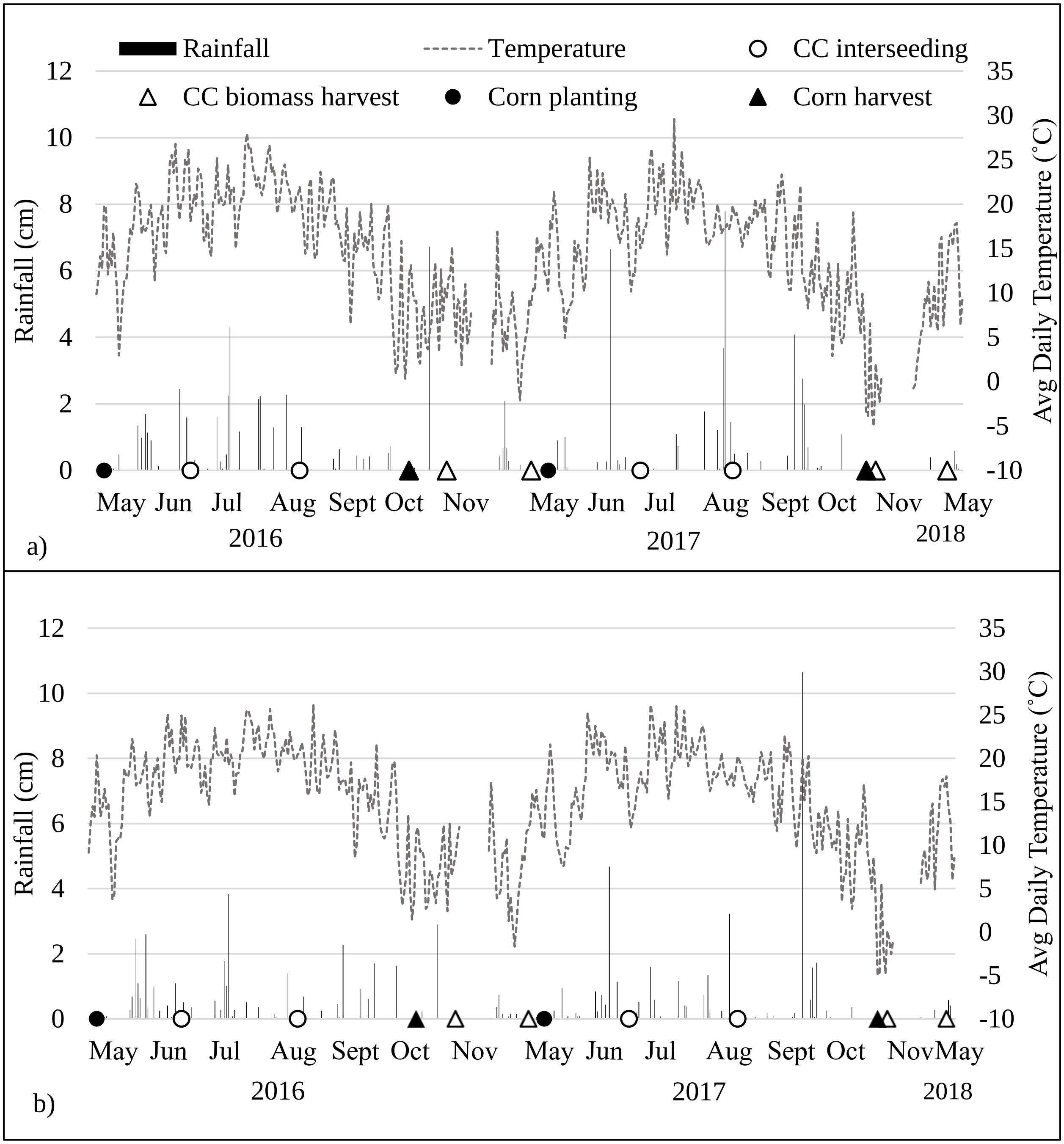

Figure 1. Average daily temperature and daily rainfall at a) Forman and b) Prosper, ND, from May 2016 through May 2018 obtained from automated weather stations located near Brampton and Prosper, ND. Cover crops were interseeded at the V7 and R4 corn growth stages. Biomass was harvested before the first killing frost and before termination the following spring.

Corn Yield

Interseeding cover crops between corn rows did not decrease grain yield in either the Hybrid or the Corn Row Width experiments. The 89 RM hybrid yielded significantly more than the 80 RM hybrid at individual environments (date not shown) and by an average of 2.6 Mg ha^{-1} when combined across environments (Table 2). Later maturing hybrids often yield more than earlier maturing hybrids because they have more time to accumulate photosynthate in the kernels before reaching physiological maturity (Olson and Sander, 1988; Crusciol et al., 2013).

Table 2. Cover crop and hybrid relative maturity (RM) effect on corn yield combined across locations at Forman and Prosper, ND, 2016-2017.

	2016		2017		Combined	
Cover crop	80 RM	89 RM	80 RM	89 RM	80 RM	89 RM
			Mg ha^{-1}			
Camelina	12.6	15.6	10.7	13.1	11.7	14.3
Rye	12.9	15.6	10.4	13.2	11.6	14.4
Mix†	12.7	16.1	10.8	12.6	11.7	14.4
No cover crop	13.0	15.8	10.9	12.8	11.9	14.3
RM Means‡	12.8 b	15.8 a	10.7 b	12.9 a	11.7 b	14.4 a

† Mix is the sum of the rye and camelina biomass in the treatment.

‡ Means within the same row followed by different letters are significantly different at $p \leq 0.05$.

In the Corn Row Width Experiment, yield was significantly different between corn row widths while cover crop treatments did not affect corn yield. Yield in the 56 cm row width was 1.4 Mg ha^{-1} greater than the 76 cm row width in the 2017 growing season and 1.2 Mg ha^{-1} greater when combined across all environments (Table 3). This is likely because corn grown north of latitude 44 N has a limited amount of time to accumulate biomass before critical yield determining growth periods. Narrower corn rows better optimize plant-plant spacing and use light, water, and nutrients more efficiently, enabling corn grown in narrower rows to yield more than traditional 76 cm rows, especially in dry years (Lee, 2006; Thelen, 2006).

Interseeding the cover crops as early as V7 did not affect corn yield in either experiment. Many studies have shown that interseeding cover crops into corn after the V4 to V5 growth stage does not reduce yield (Exner and Cruse, 1993; Baributsa et al., 2008; Bich et al., 2014), but yield may be reduced when cover crops are interseeded at the same time as corn planting up through the V3 corn growth stage as the cover crops begin to compete with the small corn plants for light, water, and nutrients (Exner and Cruse, 1993; Bich et al., 2014).

Table 3. Corn row width (RW), cover crop, and cover crop planting date (PD) effect on corn yield combined across environments at Forman and Prosper, ND, 2016-2017.

		2016		2017		Combined	
Cover crop	PD	56 cm	76 cm	56 cm	76 cm	56 cm	76 cm
				Mg ha^{-1}			
Camelina	V7	17.3	16.0	13.8	11.5	15.5	13.7
	R4	16.8	16.6	13.1	11.5	14.9	14.0
Rye	V7	17.3	16.5	13.3	12.4	15.3	14.4
	R4	17.9	16.2	12.9	12.0	15.4	14.1
Mix†	V7	17.0	15.3	13.4	12.0	15.2	13.6
	R4	17.6	17.0	13.4	12.0	15.5	14.5
No cover crop		17.5	16.0	13.6	12.7	15.6	14.4
RW Mean‡		17.3	16.2	13.4	12.0	15.3 a	14.1 b

† Mix is the sum of the rye and camelina biomass in the treatment.

‡ Means within the same row followed by different letters are significantly different at $p \leq 0.05$.

Cover Crop Biomass Yield

Hybrid Experiment

Hybrid by cover crop by planting date interactions were mostly non-significant for observations taken in the fall at individual environments and in combined environments. However, in the spring either the RM or cover crop main effect was significant in some individual environments, and when combined across environments. Overall, there tended to be more biomass beneath the 80 RM hybrid compared with the 89 RM hybrid, and overall the rye tended to produce a similar amount of biomass to the mixed cover crops and a greater amount of biomass than the camelina. It should be noted though, that biomass yield among treatments across environments was typically less than 100 kg ha^{-1}.

At Forman in the fall of 2016, the rye perished due to apparent insect damage and low rainfall after germination. Three weeks after seeding, few rye plants were found and several blades of rye were observed lying on the ground with what appeared to be damage from chewing insects. Thus, most of the mix biomass consisted of camelina biomass in this environment. Some amount of rye biomass was observed in the spring of 2017 in the mix, which may be why the mix had significantly more biomass than camelina (Table 4). At Forman in the spring of 2018, camelina biomass was 21.0 kg ha^{-1} greater than rye, which was the opposite of what occurred in all other environments where rye biomass was equal to or significantly greater than camelina (Table 5).

At Prosper in the spring of 2017, the rye and cover crop mix biomass was 130.3 kg ha^{-1} and 152.5 kg ha^{-1} greater than camelina biomass, respectively (Table 6). At Prosper in the fall of 2017, the camelina perished due to insect damage in the fall, thus most of the mix treatment consists of rye biomass in this environment (Table 7). Wilson (2013) saw that cover crop losses could be expected to seed predation by birds, rodents, and insects when cover crops are broadcast onto the soil surface, however in this experiment, both instances of insect damage occurred after germination when the small seedlings were eaten by insects.

At Prosper in the spring of 2017, the mean cover crop biomass beneath the 80 RM hybrid was 30.1 kg ha^{-1} greater than with the 89 RM hybrid (Table 7). In the combined analysis, the 80 RM hybrid produced 20.8 kg ha^{-1} more biomass than the 89 RM hybrid (Table 8). This trend existed but was not significantly different in the other individual environments. It was expected that more cover crop biomass would accumulate beneath the earlier maturing hybrid because the 80 RM hybrid is shorter in height and has a less dense canopy that intercepts less light during the season than the taller, leafier 89 RM hybrid. The earlier maturing hybrid also senesces earlier than the later hybrid which allows more light down to the cover crops for photosynthesis earlier than with the 89 RM hybrid (Baributsa et al., 2008). Earlier maturing hybrids will also begin reducing their water intake, thereby reducing competition for water for the cover crops earlier than later maturing hybrids (Crusciol et al., 2013).

Overall, the cover crops tended to grow more beneath the 80 RM hybrid versus the 89 RM hybrid, similar to what was reported by Crusciol et al. (2013), who found that a later maturing hybrid reduced interseeded palisadegrass biomass by as much as 19.8%. The rye treatment tended to produce a similar amount of biomass to the mix treatment and more biomass than the camelina treatment. Even so, there was typically less than 50 kg ha^{-1} biomass produced before the cover crops entered winter dormancy in early November. While early spring growth yielded about 3 times that before spring termination, it is still highly unlikely that the cover crops provided significant environmental benefits from such little growth.

Table 4. Corn hybrid relative maturity (RM) effect on cover crop (CC) biomass at Forman, ND, 2016-2017.

	Fall 2016			Spring 2017		
	RM			RM		
CC	80	89	CC Mean	80	89	CC Mean
			kg ha^{-1}			
Camelina	39.5[†]	23.4	31.5	12.0	5.6	8.8
Rye[‡]	--	--	--	--	--	--
Mix[§]	27.2	5.1	16.2	50.0	20.4	35.2
RM Mean[¶]	33.4	14.3		31.0	13.0	

† *k*=4 for individual treatments in both the fall and the spring.

‡ Rye perished due to apparent chewing insect damage and lack of rain after seeding.

§ Mix is the sum of the rye and camelina biomass in the treatment.

¶ Table means are not significantly different at $p \leq 0.05$.

Table 5. Corn hybrid relative maturity (RM) effect on cover crop (CC) biomass at Forman, ND, 2017-2018.

	Fall 2017			Spring 2018		
	RM			RM		
CC	80	89	CC Mean	80	89	CC Mean[†]
			$kg\ ha^{-1}$			
Camelina	8.4[‡]	10.5	9.5	49.1	14.6	31.9 b
Rye	7.0	21.0	14.0	11.6	10.3	10.9 c
Mix[§]	23.3	18.1	20.7	49.6	42.1	45.8 a
RM Mean	12.9	16.5		36.7	22.3	

[†] Means within the same column followed by a different letter are significantly different at $p \leq 0.05$.

[‡] *k*=4 for individual treatments for both the fall and the spring.

[§] Mix is the sum of the rye and camelina biomass in the treatment.

Table 6. Corn hybrid relative maturity (RM) effect on cover crop (CC) biomass at Prosper, ND, 2016-2017.

	Fall 2016			Spring 2017		
	RM			RM		
CC	80	89	CC Mean	80	89	CC Mean[†]
			$kg\ ha^{-1}$			
Camelina	14.4[‡]	5.8	10.1	11.9	24.3	18.1 b
Rye	14.1	9.1	11.3	153.5	143.3	148.4 a
Mix[§]	26.3	12.3	19.3	206.1	135.2	170.6 a
RM Mean	18.6	9.1		123.8	100.9	

[†] Means within the same column followed by different letters are significantly different at $p \leq 0.05$.

[‡] *k*=3-4 for individual treatments in the fall, and 4 for individual treatments in the spring.

[§] Mix is the sum of the rye and camelina biomass in the treatment.

Table 7. Corn hybrid relative maturity (RM) effect on cover crop (CC) biomass at Prosper, ND, 2017-2018.

	Fall 2017			Spring 2018		
	RM			RM		
CC	80	89	CC Mean	80	89	CC Mean
			kg ha^{-1}			
Camelina[†]	--	--	--	--	--	--
Rye	69.6[‡]	50.4	60.0	71.6	26.3	48.9
Mix[§]	51.5	39.3	45.4	48.2	33.3	40.7
RM Mean[¶]	60.6	44.8		59.9 a	29.8 b	

† Camelina perished due to apparent chewing insect damage in Fall 2017.

‡ *k*=4 for individual treatments in both the fall and the spring.

§ Mix is the sum of the rye and camelina biomass in the treatment.

¶ Means within the same row followed by different letters are significantly different at $p \leq 0.05$.

Table 8. Corn hybrid relative maturity (RM) effect on cover crop (CC) biomass combined across environments at Forman and Prosper, ND, 2016-17.

	Fall			Spring		
	RM			RM		
CC	80	89	CC Mean	80	89	CC Mean
			kg ha^{-1}			
Camelina[†]	20.8[‡]	13.2	--[§]	24.3	14.8	19.6
Rye[§]	31.7	26.8	29.1	78.9	59.9	69.4
Mix[¶]	32.1	18.7	25.4	88.5	57.7	73.1
RM Mean[#]	28.5	19.5		66.3 a	45.5 b	

† Fall camelina perished due to apparent chewing insect damage at Prosper in 2017.

‡ *k*=11-16 for individual treatments.

§ Fall rye perished due to apparent chewing insect damage and drought at Forman in 2016.

¶ Mix is the sum of the rye and camelina biomass in the treatment.

Means within the same row followed by different letters are significantly different at $p \leq 0.05$.

Corn Row Width Experiment

In the Corn Row Width experiment, cover biomass differed significantly between treatments at either $p \leq 0.05$ in both the fall and the spring in most individual environments, and in the spring of 2018 combined across locations. There tended to be differences in biomass between row widths and planting date, however treatments were only significantly different at Prosper in the individual environments.

At Forman in 2016, the rye planted at V7 perished due to apparent chewing insect damage and lack of rainfall following germination. Across row widths, the rye planted at R4 produced significantly more biomass than camelina or mix cover crops in the fall (Table 9). The rye and mix cover crops planted at R4 produced significantly more biomass than each of the other treatments in the spring. A possible reason for the mix producing significantly less biomass than the rye in the fall may be because the rye in the mix treatment was seeded at half the rate of the rye in the rye treatment. However, this behavior was not consistent with what occurred in the other environments, where the mix treatment produced just as much biomass as rye. This suggests that the seeding rate for interseeded rye cover crops may not need to be as high as 67 kg ha^{-1}. Treatments were not different from each other at Forman in the fall of 2017 and spring of 2018 (Table 10).

At Prosper in the fall of 2016, the cover crop and planting data main effects were significant, along with the spacing by planting date and spacing by cover crop by planting date interaction. In the spring of 2017, the cover crop and planting date main effects and their interaction were significant at $p \leq 0.05$ (Table 11). It should be noted here that rye planted at R4 produced a mean of 1,064 kg ha^{-1} biomass in the spring in this environment, considerably more biomass than any of the other environments. Of the four environments, this environment likely had the best growing conditions for the late-planted cover crops. Timely rains, more sunlight during early growth as the corn senesced, and a late frost helped the later planted rye establish and grow more vigorously, which likely increased winter survival to contribute to greater growth the following spring.

At Prosper in the fall of 2017, much of the Camelina perished due to insect damage. The cover crop main effect was significant in the fall and spring, and the planting date main effect was significant in the fall only. In this environment, the V7 planting date produced more biomass overall than the R4 planting date, most likely because the lack of rain following the R4 planting date delayed germination and fall growth (Figure 1). In the fall, rye produced 18.8 kg ha^{-1} and 31.1 kg ha^{-1} more than the mix and camelina, respectively (Table 12). In the spring, the rye produced 23.1 kg ha^{-1} more biomass than the cover crop mix, possibly because the seeding rate for the cover crop mix was half that of rye.

When combined across all environments, fall biomass was not significant (Table 13). Spring biomass could not be combined across all locations due to non-homogenous variances among environments.

Overall, there existed a general trend for greater biomass beneath the 76 cm row spacing compared with the 56 cm row spacing, and for greater biomass at the R4 planting date compared with the V7 planting date. Even though cover crop growth was reduced, that the cover crops did establish in the 56 cm corn rows shows that interseeding cover crops into narrow corn rows could be a viable practice. Cover crops tended to produce more biomass in both the spring and the fall when interseeded later in the season at the R4 corn growth stage, however there was insufficient evidence to confirm a significant planting date effect. The cover crops planted at V7 grew thin and wispy and either died or went dormant as the season progressed, whereas the cover crops planted at R4 often grew more vigorously because of reduced suppression by the corn as the crop senesced. In-season senescence of cover crops planted before corn canopy closure has been documented in other studies in Minnesota and Canada as well (Abdin et al., 1997; Belfry and Van Eerd, 2016).

In both experiments, the corn severely suppressed cover crop growth by decreasing the amount of light available to the cover crops beneath the corn canopy, especially in the 56 cm row width. Cover crop suppression has both advantages and disadvantages. The advantage to suppressed growth is that cover crops did not reduce yield by competing with the corn for water or nutrients during the season, but the disadvantage is that the corn canopy shaded the cover crops making it difficult to survive beneath the corn canopy until the corn senesced. Cover crops in this study behaved similarly to those of Belfry and Van Eerd (2016), who hypothesized that after rye interseeded into corn reached the 2-3 leaf stage underneath the corn canopy, it either entered a dormant state or died primarily due to a lack of light beneath the corn canopy.

Table 9. Corn row width (RW), cover crop (CC), and CC planting date (PD) effect on CC biomass at Forman, ND, 2016-2017.

				Fall 2016				Spring 2017†		
				RW				RW		
CC	PD	Fall	Spring	56 cm	76 cm	Mean‡	CC Mean§	56 cm	76 cm	Mean‡
							kg ha^{-1}			
Camelina	V7			51.6[¶]	32.5	42.1		43.6	9.1	26.4 d
	R4			23.5	22.6	23.1	32.6 b	99.1	132.8	116.0 c
Rye[#]	V7			--	--	--		--	--	--
	R4			64.8	82.8	73.8	73.8 a	428.8	316.6	372.7 a
Mix[††]	V7			42.3	33.7	38.0		--	44.9	44.9 d
	R4			35.1	42.4	38.8	38.4 b	233.6	289.4	261.5 b
RW Mean				43.4	42.8			201.3	158.6	
PD Mean	V7	40.0	--							
	R4	45.2	--							

† Spring data were analyzed with cover crop and planting date combined as one treatment due to missing treatments.

‡ Mean of the CC by PD interaction.

§ Means within the same column followed by different letters are significantly different at $p \leq 0.05$.

¶ k=3 for individual treatments in both the fall and the spring.

Rye planted at V7 was lost to apparent chewing insect damage and drought.

†† Mix treatments consist mainly of camelina biomass.

Table 10. Corn row width (RW), cover crop (CC), and CC planting date (PD) effect on CC biomass at Forman, ND, 2017-2018.

				Fall 2017				Spring 2018			
				RW				RW			
CC	PD	Fall	Spring	56 cm	76 cm	Mean[†‡]	CC Mean	56 cm	76 cm	Mean[†]	CC Mean
							kg ha^{-1}				
Camelina	V7			15.6[§]	36.1	25.9		29.5	35.4	33.1	
	R4			18.0	27.2	22.6	24.2		38.6	38.6	35.2
Rye	V7			23.1	52.5	37.8		23.8	72.8	48.3	
	R4			75.7	63.6	69.7	53.7	55.4	112.9	84.2	66.2
Mix[¶]	V7			40.7	76.5	58.6		21.3	58.4	39.9	
	R4			30.7	43.5	37.1	47.8	50.0	44.9	47.5	43.7
RW Mean				34.0	49.9			36.5	60.5		
PD Mean	V7	40.8	40.8								
	R4	43.1	60.4								

† Mean of the CC by PD interaction.

‡ Table means are not significantly different from each other at $p \leq 0.05$.

§ k=3 for individual treatments in both the fall and the spring.

¶ Mix is the sum of the rye and camelina biomass in the treatment.

Table 11. Corn row width (RW), cover crop (CC), and CC planting date (PD) effect on CC biomass at Prosper, ND, 2016-2017.

				Fall 2016				Spring 2017			
				RW[†]				RW			
CC	PD	Fall	Spring[‡]	56 cm	76 cm	Mean[§]	CC Mean[‡]	56 cm	76 cm	Mean[‡§]	CC Mean[‡]
							kg ha^{-1}				
Camelina	V7			23.4 d[¶]	39.1 cd	31.3		85.0	58.3	71.7 c	
	R4			11.8 d	32.2 cd	22.0	26.6 b	103.5	96.6	100.1 c	85.9 b
Rye	V7			44.6 cd	64.9 bcd	54.8		368.9	318.5	343.7 b	
	R4			61.0 cd	137.4 b	99.2	77.0 a	791.4	1336.6	1064.0 a	703.9 a
Mix[#]	V7			99.4 bc	63.9 bcd	81.7		420.3	564.5	492.4 b	
	R4			50.8 cd	232.4 a	141.6	111.6 a	977.9	950.7	964.3 a	728.3 a
RW Mean[††]				48.5 y	95.0 z			457.8	554.2		
PD Mean	V7	55.9	302.6 b								
	R4	87.6	709.5 a								

† Means among the RW columns in Fall 2016 followed by different letters are significantly different at $p \leq 0.05$.

‡ Means within the same column followed by different letters are significantly different at $p \leq 0.05$.

§ Means of the CC by PD interaction.

¶ k=3 for individual treatments in both the fall and the spring.

Mix is the sum of the rye and camelina biomass in the treatment.

†† Means within the same row followed by different letters are significantly different at $p \leq 0.05$.

Table 12. Corn row width (RW), cover crop (CC), and CC planting date (PD) effect on CC biomass at Prosper, ND, 2017-2018.

				Fall 2017				Spring 2018			
				RW				RW			
CC	PD	Fall†	Spring	56 cm	76 cm	Mean‡	CC Mean†	56 cm	76 cm	Mean‡	CC Mean†
							kg ha^{-1}				
Camelina	V7			11.3§	4.5	7.9		--	--	--	
	R4			--	--	--	7.9 b	--	--	--	--
Rye	V7			34.9	59.4	47.2		31.0	38.1	34.5	
	R4			19.6	41.9	30.7	39.0 a	24.7	54.0	39.4	36.9 a
Mix¶	V7			35.1	25.4	30.2		10.6	12.9	11.8	
	R4			9.9	10.6	10.2	20.2 b	9.3	22.5	15.9	13.8 b
RW Mean				22.9	30.1			18.9	31.9		
PD Mean	V7	38.7 a	27.6								
	R4	20.5 b	23.1								

† Means within the same column followed by different letters are significantly different at $p \leq 0.05$.

‡ Means of the CC by PD interaction.

§ k=3 for individual treatments in both the fall and the spring.

¶ Mix is the sum of the rye and camelina biomass in the treatment.

Table 13. Corn row width (RW), cover crop (CC), and CC planting date (PD) effect on fall cover crop biomass combined across environments at Forman and Prosper, ND, 2016-2017.

CC	PD	Fall	RW			
			56 cm	76 cm	Mean[†‡]	CC Mean
			kg ha^{-1}			
Camelina[§]	V7		26.8[¶]	30.2	28.5	
	R4		17.8	27.3	22.6	25.8
Rye[#]	V7		34.2	59.0	46.6	
	R4		55.3	81.4	68.3	54.5
Mix[§#††]	V7		54.4	49.9	52.1	
	R4		31.6	82.2	56.9	59.0
RW Mean			37.8	56.5		
PD Mean	V7	42.4				
	R4	51.7				

† Mean of the CC by PD interaction.

‡ Table means are not significantly different from each other at $p \leq 0.05$.

§ Data do not include camelina biomass from Prosper in 2017 due to insect damage.

¶ k= 9-12 for individual treatments.

Data do not include rye biomass from Forman in 2016 due to insect damage.

†† Mix is the sum of the rye and camelina biomass in the treatment.

Cover crop biomass was minimal in this study, however the results were somewhat similar to that of Noland et al. (2018) in southern Minnesota, who harvested 21-61 kg ha^{-1} of dry matter from cereal rye and 20 kg ha^{-1} from field pennycress (*Thalspi arvense* L.) in the fall when interseeded into corn at V7. However, in their study the cover crops were harvested at the R6 corn growth stages instead of before the first killing-frost after the corn is harvested. It is interesting that the cover crops in the current study yielded similar amounts of biomass to Noland et al. (2018), even though the cover crops were not terminated until early November. This may indicate that little cover crop growth may be expected between corn harvest and winter dormancy for rye and winter camelina. This was likely caused by burial of the cover crops in corn residue following harvest, which appeared to stunt growth and smother the plants (Belfry and Van Eerd, 2016). Cool, wet temperatures or an early hard frost will also affect the amount that the cover crops are able to grow in the fall.

The rye and mix had similar amounts of biomass yield in both the fall and the spring, and were not significantly different from each other. Biomass in the cover crop mix consisted mostly of rye, and produced the same amount of biomass as the rye alone. This is consistent with other studies that have found that cover crop mixtures do not produce more total biomass than what the most productive species in the mixture would produce by itself (Appelgate, 2017). In this study, at Forman in 2016 and at Prosper in 2017, including a cover crop mixture proved beneficial because it prevented a cover crop failure when one of the species in the mix failed to establish.

The camelina seedling mortality was high, similar to what has been reported in other studies (Robinson, 1987; Berti et al., 2017). Poor camelina establishment could have been partially due to the seeding rate being too low to achieve an adequate stand density when interseeding into corn (Urbaniak et al., 2008; Gesch et al., 2017). However, in this study the most likely cause of poor camelina establishment was the lack of timely rainfall to sustain the small camelina seedlings at the soil surface.

Cover Crop N Content

Cover crop N content was measured from both locations in the fall of 2016 and 2017, and in the spring of 2017 to measure the amount of N accumulated in the cover crop biomass that could be available to the following crop after N mineralization.

Hybrid Experiment

Cover crop N content was not influenced by corn hybrid RM or by cover crop treatment in the fall or the spring. The RM by cover crop interaction was significant in the spring, however this appeared to be the result of random chance rather than a true interaction. Camelina biomass contained 4.4% N in the fall and 3.8% N in the spring. Rye biomass contained 4.1% N in the fall, and 3.9% N in the spring. This equated to an average of 0.7- and 1.2 kg ha^{-1} total N accumulated by camelina and rye, respectively, in the fall, and an average of 0.5- and 4.6 kg ha^{-1} total N accumulated by camelina and rye, respectively, in the spring of 2017. These results are far lower than other studies that reported averages of 14-57 kg ha^{-1} N from camelina biomass and 21-26 kg ha^{-1} from rye biomass harvested in the spring (Pantoja et al., 2015; Appelgate et al., 2017; Berti et al., 2017). With such limited growth, it can be assumed that in this experiment the cover crops did not reduce NO_3^--N leaching or scavenge a meaningful amount of N to be useful to the following crop.

Corn Row Width Experiment

Corn row width, cover crop treatment, and planting date did not influence the amount of N in the cover crop biomass in the fall. The row width by cover crop by planting date interaction was significant in the spring, likely because there was a trend towards a higher cover crop N content at the V7 planting date, although the planting date main effect was not significant. Total spring N accumulation is presented separately by location because spring biomass could not be combined. The average camelina N content was 4.4% in the fall and 3.7% in the spring, which equated to 1.1 kg ha^{-1} N accumulated in the fall, 2.6 kg ha^{-1} N accumulated in the spring at Forman, and 3.2 kg ha^{-1} N accumulated in the spring at Prosper. The average rye N content was 3.8% in the fall and 3.7% in the spring. This equated to 2.1 kg ha^{-1} N accumulated in the fall, 13.7 kg ha^{-1} N accumulated in the spring at Forman, and 26.0 kg ha^{-1} N accumulated in the spring at Prosper.

Even though little biomass was produced in the fall by both rye and camelina, the rye cover crop produced enough biomass to accumulated up to 26.0 kg ha^{-1} of N in the spring, during the period of highest NO_3^--N leaching, an amount similar to what has been reported in other studies (Pantoja, 2015; Pantoja, 2015; Appelgate, 2017). The rye in the corn row width experiment was able to accumulate more N than the hybrid experiment because the treatments planted at R4 in the previous season had more biomass in following spring.

Cover Crop Nitrogen Uptake

Noland et al. (2018) found that cover crops interseeded at V7 did not influence soil NO_3^--N below 10 cm. Samples from the 15 to 60 cm depth were taken from both locations in the fall of 2016, however residual soil NO_3^--N did not differ among treatments and are not presented here. In the present experiments, it was thought that with such small cover crops, a traditional 0-60 cm NO_3^--N sample may dilute any effects that the cover crops had on soil NO_3^--N in the upper cm of the soil in the cover crop rooting zone, and thus only the means for the top 15 cm of soil are presented here. Spring data are from 2018 only, as there was a mistake in data collection during the spring of 2017.

Hybrid Experiment

Soil NO_3^--N was not significantly different among treatments in the Hybrid Experiment except for at Forman in the fall of 2016. However, this difference seemed more likely to be due to random error from a small sample size than a treatment effect. Noland (2018) found that cover crops did not influence fall soil NO_3^--N due to the small amount of accumulated biomass, but found that rye did reduce spring soil NO_3^--N by as much as 18.8 kg ha^{-1} due to a greater biomass yield before spring cover crop termination. It would appear that in the upper Midwest, it can be expected that cover crops will scavenge very little NO_3^--N in the fall when following full season crops, but that greater amounts of N could be accumulated in the spring, which is preferred because early spring is when potential for N leaching losses are greatest (Herrera and Liedgens, 2009).

Corn Row Width Experiment

In the corn row width experiment, there were significant differences among treatments in the fall at Prosper in 2016 and 2017, and in the 2017 combined analysis. In the 2016 combined analysis, there were no significant differences between treatment means. In 2017, rye at both planting dates and camelina at the early planting date had significantly lower residual soil NO_3^--N compared with the other treatments including the no-cover crop control; however the differences in residual NO_3^--N ranged only by 6 kg ha^{-1} among all treatments. Results should be viewed cautiously with such small sample sizes (Table 14). At Forman in the spring of 2018, all cover crop treatments were significantly less than the no-cover crop control, but there were no significant differences among treatments at Prosper and in the combined analysis (Table 15).

Table 14. Corn row width (RW), cover crop (CC), and CC planting date (PD) effect on fall residual soil NO_3^--N combined across locations at Forman and Prosper, ND, 2016-2017.

CC	PD	Fall 2016		Fall 2017	
		n	kg ha^{-1}	n	kg ha^{-1}
Camelina	V7	12	46.7	10	15.5 bcd†
	R4	12	41.4	6	16.3 abc
Rye	V7	6	74.2	12	15.0 bcd
	R4	12	23.8	12	12.6 d
Mix‡	V7	9	26.8	12	16.5 abc
	R4	6	14.2	12	18.0 ab
No cover crop		12	37.4	12	19.3 a

† Means within the same column followed by different letters are significantly different at $p \leq 0.05$.

‡ Mix is the sum of the rye and camelina biomass in the treatment.

Table 15. Corn row spacing, cover crop, and cover crop planting date effect on spring residual soil NO3^{-}-N at Forman and Prosper, ND, in the spring of 2018.

CC	PD	Forman[†‡]	Prosper[‡]	Combined[§]
			kg ha^{-1}	
Camelina[¶]	V7	14.2 bc[†]	--[‡]	14.2[§]
	R4	15.1 b	--[‡]	15.1
Rye	V7	12.5 bc	11.2	11.9
	R4	7.8 c	13.3	10.6
Mix[#]	V7	12.0 bc	13.3	12.6
	R4	12.0 bc	13.7	12.8
No cover crop		23.4 a	14.8	19.1

† Means within the same column followed by different letters are significantly different at $p \leq 0.05$.

‡ k=6 at the individual location.

§ k=12 for Rye and Mix treatments, and k=6 for Camelina treatments within the same column.

¶ Camelina at Prosper was lost in the previous fall to insect damage.

Mix is the sum of the rye and camelina biomass in the treatment.

Photosynthetically Active Radiation beneath the Corn Canopy

Hybrid Experiment

There was a significant difference in PAR interception between corn hybrids on most dates at each of the individual environments. In the combined analysis, the amount of light intercepted by the corn hybrids was significantly different at either $p \leq 0.05$ at most dates, with the 89 RM hybrid intercepting an average of 5% more PAR than the 80 RM hybrid (Figure 2). This reduction in PAR appeared to be a likely cause of the limited cover crop biomass produced beneath the canopy.

There was an unexpectedly significant cover crop effect in the combined analysis at the measurements dates Early August and Mid-August. The amount of PAR reaching the soil surface was 2% lower beneath the canopies of the rye and cover crop mix compared with the camelina and no-cover crop controls. It is possible that there was some PAR interception by the rye cover crop, even though it was assumed that the plants would not affect PAR because they were small and not overshadowing the measurement area at that time.

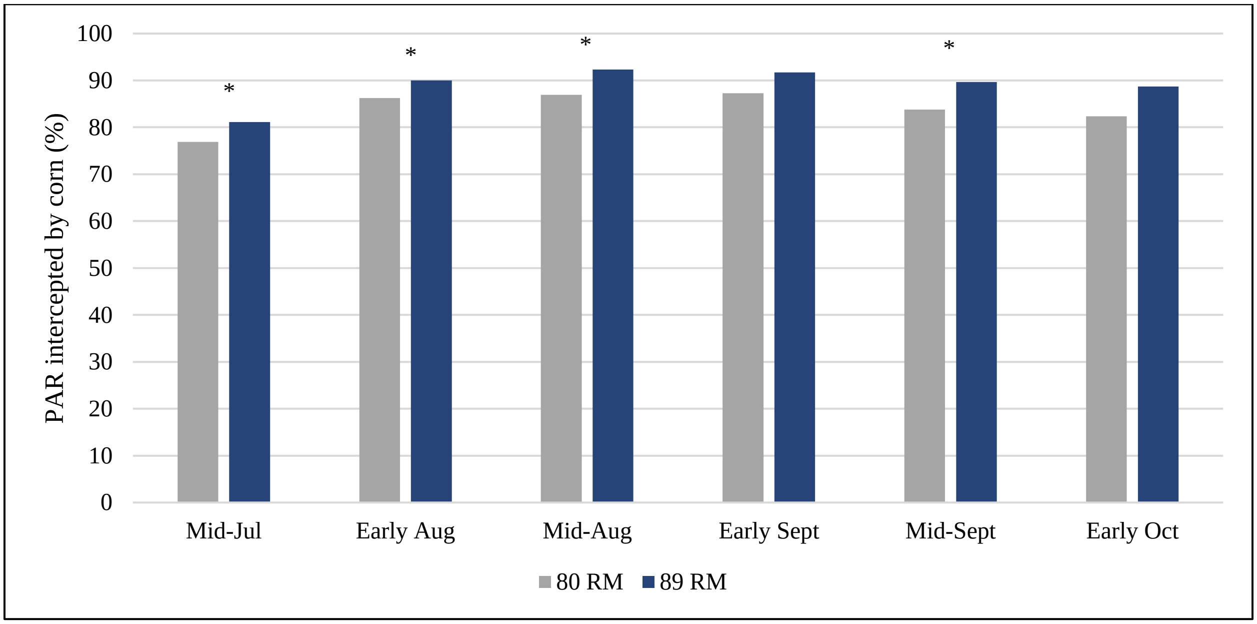

Figure 2. Corn hybrid relative maturity (RM) effect on the amount of photosynthetically active radiation (PAR) intercepted by the corn canopy at bi-weekly intervals throughout the growing seasons at Forman and Prosper, ND, 2016-2017. Mid-Sept does not include data from Prosper in 2016. Early Oct includes only 2017 data. Hybrids means significantly different at the $p \leq 0.05$ level within each date are indicated by *.

Corn Row Width Experiment

Corn row width did not affect the amount of PAR intercepted by the corn canopy when combined across all environments. The 56 cm corn row width tended to intercept a greater amount of PAR than the 76 cm row width at Prosper, but means were not different (Figure 3). The opposite effect tended to happen in Forman, where the 76 cm row width tended to intercept more PAR than the 56 cm row width, however the row width effect was not significant at this location (Figure 4). It is suspected that corn row orientation may have played a role in the differences in canopy light interception between the two locations.

In both years of the study, corn at Prosper was oriented north-south, while the corn at Forman was oriented east-west. Because the corn population remained the same between row width treatments, the intra-row spacing between corn plants differed between the two row widths. For the corn rows oriented north-south, the sun shone directly down the inter-row spaces so that the leaves covering the inter-row space influenced the measured PAR the most, while the effect of the intra-row spacing of the corn stalks on the measured PAR was negligible. However, at Forman the corn was oriented east-west, and it was observed that the decrease in intra-row plant spacing in the 76 cm rows had a somewhat greater shading effect on the ceptometer because the corn stalks also shaded the ceptometer and influenced PAR measurements in the east-west rows as the sun shone from the south. This effect became more apparent later in the summer as the sun's zenith slowly decreased as the season progressed. However, this is only a hypothesis formed from personal observations, as this trend is not significant and not fully consistent within the data. The differences in orientation could potentially confound the results when comparing the two locations, however any differences that may have existed due to corn row orientation did not appear to affect the cover crops, as the 76 cm row width generally produced more cover crop biomass than the 56 cm row width regardless of corn row orientation. These findings support the hypotheses offered by other studies that limited PAR significantly inhibited the growth of interseeded cover crops (Belfry and Van Eerd, 2016; Berti et al., 2017; Noland et al., 2018)

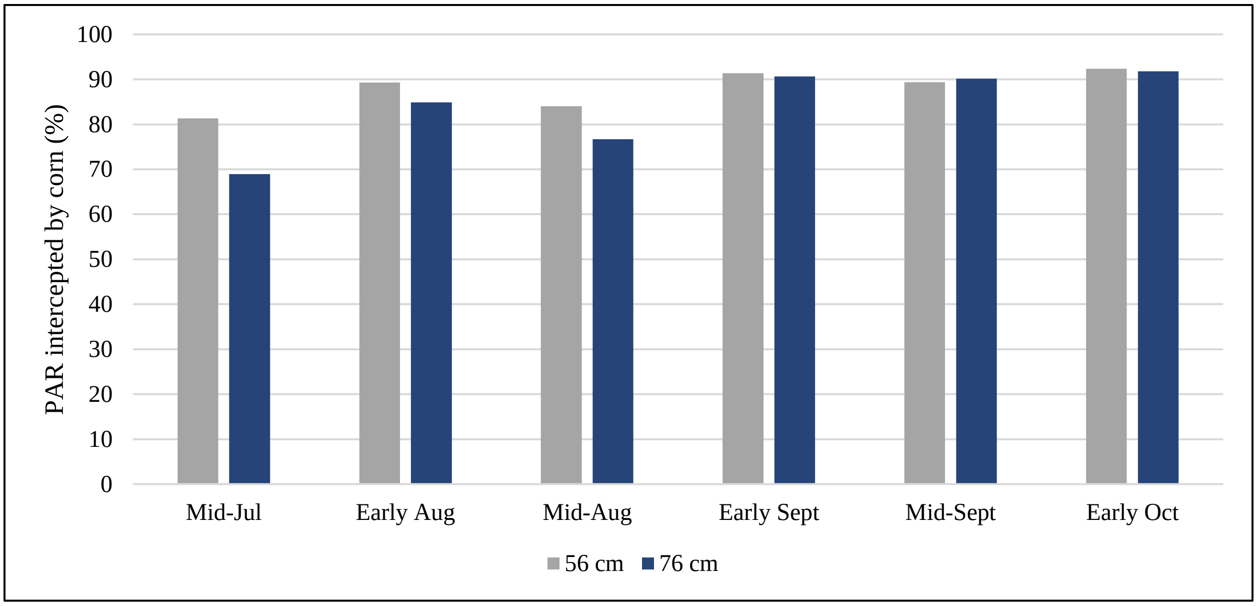

Figure 3. Corn row width effect on intercepted photosynthetically active radiation (PAR) at bi-weekly intervals during the growing seasons at Prosper, ND, 2016-2017. Mid-Sept and Early Oct include only 2017 data. Row width treatments were not significantly different on any date.

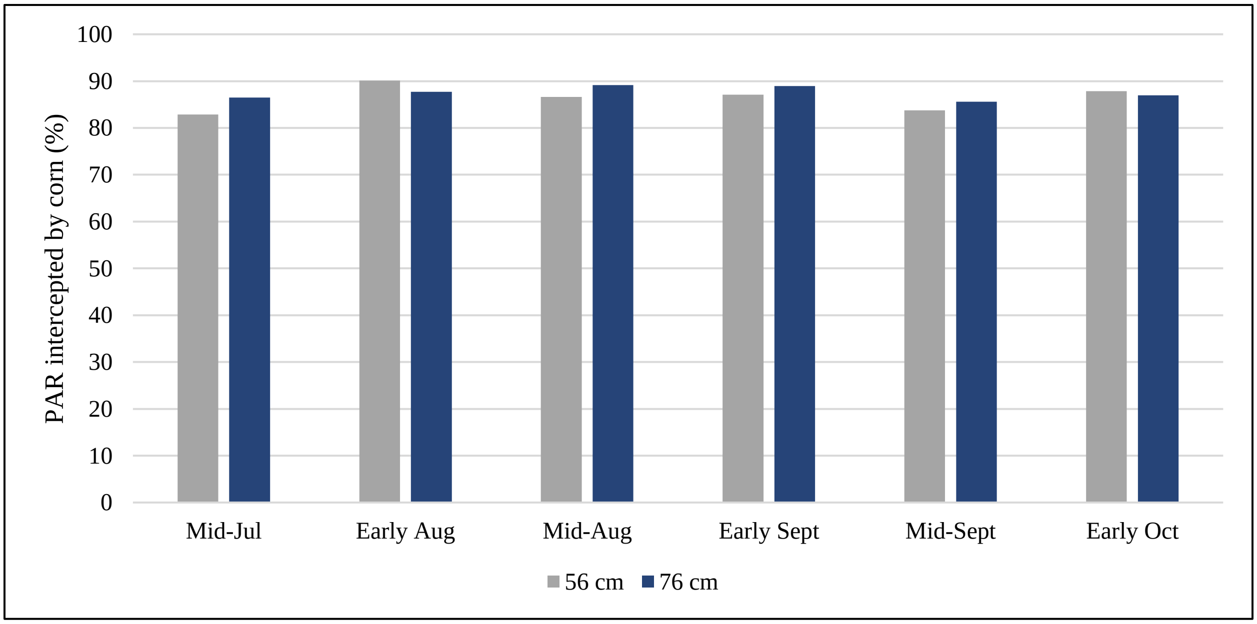

Figure 4. Corn row width effect on intercepted photosynthetically active radiation (PAR) at bi-weekly intervals during the growing seasons at Forman, ND, 2016-2017. Early Oct includes only 2017 data. Row width treatments were not significantly different on any date.

Cover Crop Fractional Green Canopy Cover

The Canopeo mobile application was used to measure FGCC. In this study Canopeo was used in an attempt to relate the amount of FGCC to cover crop biomass and ground coverage (Patrignani and Ochsner, 2015). At individual environments there were often significant differences between cover crop treatments generally related to the amount of cover crop biomass present, however when very little biomass was present the FGCC measurements were influenced by cover crop leaf architecture. Camelina often resulted in higher FGCC readings than rye because the broad, prostrate camelina leaves would result in a higher FGCC compared with the slender, erect rye leaves, even though rye often had the greater amount of biomass (data not shown). There was usually less than 5% FGCC in the fall and less than 10% FGCC in the spring for most treatments, although the rye treatment reached as high as 43% in the spring of 2017. Canopeo's measurements of FGCC were not a good proxy for total residue cover because the application can only measure green biomass, and cannot measure senesced crop tissue that may also be covering the ground. Measuring the total amount of both living and decaying tissue covering the soil as it relates to weed control or soil erosion is more beneficial than just the living tissue because both tissues act as a mulch to suppress weed growth (Teasdale and Mohler, 2000; Blanco-Canqui et al., 2017). Total biomass may be overestimated based on crop species; even though the camelina tissues returned the higher FGCC estimations, the delicate tissues often crumbled and decayed soon after senescence, leaving little tissue behind to protect the soil surface.

CONCLUSION

Receiving adequate rainfall throughout the summer to sustain the interseeded cover crops was a significant factor influencing cover crop establishment and performance. Cover crops need to receive timely rains to aid both germination and seedling establishment while they developed a deeper root system to be more resilient during dry periods.

Interseeding cover crops into corn at V7 and R4 did not affect corn grain yield, showing that the cover crops did not compete with the corn when interseeded at these timings. The 89 RM hybrid yielded significantly more than the 80 RM hybrid, and the 56 cm row width yielded significantly more than the 76 cm row width, as could be expected.

Cover crop growth was also likely limited due to the reduced amount of PAR beneath the corn canopy compared to the growth that may have been obtained in full-sun conditions. However, because soil water content was not monitored in this experiment, it cannot be confirmed if either lack of rainfall or reduced PAR below the canopy was the most influential factor limiting cover crop growth. Overall, cover crops produced less than 100 kg ha^{-1} whether measured in the fall or the spring. The amount of biomass produced depended largely on how long the cover crop was able to grow in the fall before it entered winter dormancy, and how long it was able to grow in the spring after thaw and before termination. Cover crop biomass was significantly greater beneath the earlier maturing hybrid partly because the 80 RM hybrid intercepted an average of 5% less PAR than the 89 RM hybrid, and because of the earlier senescence of the 80 RM hybrid in the fall. Cover crop biomass also appeared to be greater when cover crops were interseeded into the 76 cm corn row width, although the results were not significant in this study. This shows that it is possible to establish cover crops in corn in 56 cm rows, but growth will likely be less than cover crops grown in wider row widths. Cover crops planted at the R4 corn growth stage tended to produce more biomass overall because the cover crops did not endure as much light stress during establishment as did the cover crops planted at V7. However, this also depended on whether or not the cover crops received a timely rain in August for cover crop establishment.

Rye produced the most biomass compared with camelina and the cover crop mix. Oftentimes, the biomass in the mix was usually not different from rye, supporting the idea that cover crop mixes do not produce more biomass than what the most productive crop in the mix will produce by itself (Appelgate, 2017). It also suggests that the seeding rate of interseeded rye could be lowered to 34 kg ha^{-1}. Planting a cover crop mixture can prevent a cover crop failure if one of the species in the mix fails to establish, which occurred twice over the course of this study. Camelina treatments frequently produced less than 20 kg ha^{-1}. Under the management practices used in this study, winter camelina does not seem to be a suitable cover crop choice for interseeding into corn. The cover crops also failed to scavenge enough NO_3^--N to reduce leaching losses by a meaningful amount.

Cereal rye and winter camelina were chosen for their extreme winter hardiness, since the greatest benefit of interseeding cover crops into corn will be in the following spring when the cover crops are able to take up N. However, while the cover crops did overwinter and resume growth the following spring for the most part, the small amount of accumulated biomass likely produced little to no environmental benefit. More research to improve the management of interseeded cover crops is needed in order to achieve greater cover crop biomass production if the practice is to be an environmentally beneficial and economically viable practice in North Dakota.

REFERENCES

Abdin, O.A., B.E. Coulman, D.C. Cloutier, M.A. Faris, and D.L. Smith. 1997. Establishment, development and yield of forage legumes and grasses as cover crops in grain corn in eastern Canada. J. Agron. Crop Sci. 179:19-27.

Afzalinia, S., and J. Zabihi. 2014. Soil compaction variation during corn growing season under conservation tillage. Soil Tillage Res. 137:1-6.

Appelgate, S.R., A.W. Lenssen, M.H. Wiedenhoeft, and T.C. Kaspar. 2017. Cover crop options and mixes for upper Midwest corn-soybean systems. Agron. J. 109:1-17.

Ball-Coelho, B.R., and R.C. Roy. 1997. Overseeding rye into corn reduces NO_3 leaching and increases yields. Can. J. Soil Sci. 77:443-451.

Basche, A.D., T.C. Kaspar, S.V. Archontoulis, D.B. Jaynes, T.J. Sauer, T.B. Parkin, and F.E. Miguez. 2016. Soil water improvements with the long-term use of a winter rye cover crop. Agric. Water Manage. 172:40-50.

Baraibar, B., M.C. Hunter, M.E. Schipanski, A. Hamilton, and D.A. Mortensen. 2018. Weed suppression in cover crop monocultures and mixtures. Weed Sci. 66:121-133.

Baributsa, D.N. E.F. Foster, K.D. Thelen, A.N. Kravchenko, D.R. Mutch, and M. Ngouajio. 2008. Corn and cover crop response to corn density in an interseeding system. Agron. J. 100:981-987.

Barker, J.B., D.M. Heeren, K. Koehler-Cole, C.A. Shapiro, H. Blanco-Canqui, R.W. Elmore, C.A. Proctor, S. Irmak, C.A. Francis, T.M. Shaver, and A.T. Mohammed. 2018. Cover crops have negligible impact on soil water in Nebraska maize-soybean rotation. Agron. J. 110:1718-1730.

Belfry, K.D., and L.L. Van Eerd. 2016. Establishment and impact of cover crops intersown into corn. Crop Sci. 56:1245-1256.

Berti, M., R. Gesch, C. Eynck, J. Anderson, and S. Cermak. 2016. Camelina uses, genetics, genomics, production, and management. Ind. Crops Prod. 94:690-710.

Berti, M., D. Samarappuli, B.L. Johnson, and R.W. Gesch. 2017. Integrating winter camelina into maize and soybean cropping systems. Ind. Crops Prod. 107:595-691.

Bich, A.D., C.L. Reese, A.C. Kennedy, D.E. Clay, and S.A. Clay. 2014. Corn yield is not reduced my mid-season establishment of cover crops in Northern Great Plains environments. Crop Manage. 13(1). doi: 10.2134/CM-2014-0009-RS.

Bilalis, D., P. Papastylianou, A. Konstantas, S. Patsiali, A. Karkanis, and A. Efthimiadou. 2017. Weed-suppessive effects of maize-legume intercropping in organic farming. Int. J. Pest Manage. 56:173-181.

Blanco-Canqui, H., R.B. Ferguson, V.L. Jin, M.R. Schmer, B.J. Wienhold, and J. Tatarko. 2014. Can cover crop and manure maintain soil properties after stover removal from irrigated no-till corn? Soil Sci. Soc. Am. J. 78:1368-1377.

Blanco-Canqui, H., M. Sindelar, C.S. Wortmann, and G. Kreikemeier. 2017. Aerial interseeded cover crop and corn residue harvest: Soil and crop impacts. Agron. J. 109:1344-1351.

Borghi, E., C.A.C. Crusciol, G.P. Mateus, A.S. Nascente, and P.O. Martins. 2013. Intercropping time of corn and palisadegrass or guineagrass affecting grain yield and forage production. Crop Sci. 53:629-636.

Brennan, E.B., and J.E. Leap. 2014. A comparison of drill and broadcast methods for establishing cover crops on beds. HortSci. 49:441-447.

Chavarria, D.N., R.A. Verdenelli, E.J. Munoz, C. Conforto, S.B. Restovich, A.E. Andriulo, J.M. Meriles, and S. Vargas-Gil. 2016. Soil microbial functionality in response to the inclusion of cover crop mixtures in agricultural systems. Spanish J. Agric. Res. 14(*2*):e0304.

Chen, G., and R.R. Weil. 2011. Root growth and yield of maize as affected by soil compaction and cover crops. Soil Tillage Res. 117:17-27.

Clark, A. 2007. Managing cover crops profitably. 3rd ed. Sust. Agric. Network, Beltsville, MD.

Cornelius, C.D., and K.W. Bradley. 2017. Carryover of common corn and soybean herbicides to various cover crop species. Weed Tech. 31:21-31.

Crusciol, C.A.C., G.P. Mateus, A.S. Nascente, P.O. Martins, E. Borghi, and C.M. Pariz. 2012. An innovative crop-forage intercrop system: Early cycle soybean cultivars and palisadegrass. Agron. J. 104:1085-1095.

Crusciol, C.A.C, A.S. Nascente, G.P. Mateus, E. Borghi, E.P. Leles, and N.C.B. Santos. 2013. Effect of intercropping on yields of corn with different relative maturities and palisadegrass. Agron. J. 105:599-606.

Curran W.S., R.J. Hoover, S.B. Mirsky, G.W. Roth, M.R. Ryan, V.J. Ackroyd, J.M. Wallace, M.A. Dempsey, and C.J. Pelzer. 2018. Evaluation of cover crops drill interseeded into corn across the Mid-Atlantic region. Agron. J. 110:435-443.

De Notaris, C., J. Rasmussen, P. Sørensen, and J. Eivind Olesen. 2018. Nitrogen leaching: a crop rotation perspective on the effect of N surplus, field management and use of catch crops. Agric. Ecosyst. Environ. 255:1-11.

Doran, J.W., and M.S. Smith. 1987. Organic matter management and utilization of soil and fertilizer nutrients. *In*: p. 53-72. R.F. Follett, J.W.B. Stewart, C.V. Cole, editors, 1987.

Soil Fertility and Organic Matter as Critical Components of Production Systems. SSSA Spec. Publ. 19. SSSA and ASA, Madison, WI.

Exner, D.N., and R.M. Cruse. 1993. Interseeded forage legume potential as winter ground cover, nitrogen source, and competitor. J. Prod. Agric. 6:226-231.

Fisher, K.A., B. Momen, and R.J. Kratochvil. 2011. Is broadcasting seed an effective winter cover crop planting method? Agron. J. 103:472-478.

Frye, W.W., R.L. Blevins, M.S. Smith, S.J. Corak, and J.J. Varco. 1988. Role of annual legume cover crops in efficient use of water and nitrogen. *In*: p. 129-154. B.G. Ellis, W. L. Hargrove, editors, 1988. Cropping Strategies for Efficient Use of Water and Nitrogen. ASA Spec. Publ. 51. ASA, CSSA, SSSA, Madison, WI.

Gesch, R.W., D.W. Archer, and M.T. Berti. 2014. Dual cropping winter camelina with soybean in the northern Corn Belt. Agron. J. 106:1735-1745.

Gesch, R.W., H.L. Dose, and F. Forcella. 2017. Camelina growth and yield response to sowing depth and rate in the northern Corn Belt USA. Ind. Crops. Prod. 95:416-421.

Gesch, R.W., and M.-F. Johnson. 2015. Water use in camelina-soybean dual cropping systems. Agron. J. 107:1098-1104.

Hao, X., K. Thelen, and J. Gao. 2010. Earlier-maturing hybrids improve corn grain profitability in the northern Corn Belt. Crop Manage. doi: 10.1094/CM-2010- 1203-01-RS

Herrera, J.M., and M. Liedgens. 2009. Leaching and utilization of nitrogen during a spring wheat catch crop succession. J. Environ. Qual. 38:1410-1419.

Johnson, T.J., T.C. Kaspar, K.A. Kohler, S.J. Corak, and S.D. Logsdon. 1998. Oat and rye overseeded into soybean as fall cover crops in the upper Midwest. J. Soil Water Conserv. 53:276-279.

Kaspar, T.C., J.K. Radke, and J.M. Laflen. 2001. Small grain cover crops and wheel traffic effects on infiltration, runoff, and erosion. J. Soil Water Conserv. 56:160-164.

Kaspar, T.C., and J.W. Singer. 2011. The use of cover crops to manage soil. *In*: p. 321–337. J.L. Hatfield and T.J. Sauer, editors, Soil management: Building a stable base for agriculture. SSSA, Madison, WI. doi:10.2136/2011.soilmanagement.c21

Lee, C.D. 2006. Reducing row corn row widths to increase yield: Why it does not always work. Crop Manage. doi: 10.1094/CM-2006-0227-04-RV

Lewis, K.L., J.A. Burke, W.S. Keeling, D.M. McCallister, P.B. DeLaune, and J.W. Keeling. 2018. Soil benefits and yield limitations of cover crop use in Texas high plains cotton. Agron. J. 110:1616-1623.

Liu, A., B.L. Ma, and A.A. Bomke. 2005. Effects of cover crops on soil aggregate stability, total organic carbon, and polysaccharides. Soil. Sci. Col. Am. J. 69:2041-2048.

Maddonni, G.A., M.E. Otegui, and A.G. Cirilo. 2001. Plant population density, row spacing and hybrid effects on maize canopy architecture and light attenuation. Field Crops Res. 71:183-193.

Munawar, A., Blevins, R.L., Frye, W.W., and M.R. Saul. 1990. Tillage and cover crop management for soil water conservation. Agron. J. 82:773-777.

Murrell, E.G., M.E. Schipanski, D.M. Finney, M.C. Hunter, M. Burgess, J.C. LaChance, B. Baraibar, C.M. White, D.A. Mortensen, and J.P. Kaye. 2017. Achieveing diverse cover crop mixtures: Effects of planting date and seeding rate. Agron. J. 109:259-271.

Nielsen, D.C., D.J Lyon, G.W. Hergert, R.K. Higgins, F.J. Calderon, and M.F. Vigil. 2015. Cover crop mixtures do not use water differently than single-species plantings. Agron. J. 107:1025-1038.

Nielsen, D.C., and M.F. Vigil. 2005. Legume green fallow effect on soil water content at wheat planting and wheat yield. Agron. J. 97:684-689.

NCR SARE and CTIC. 2016. 2015-2016 Cover crop survey report. http://www.sare.org/Learning-Center/From-the-Field/NorthCentral-SARE-From-the-Field/2016-Cover-Crop-Survey-Analysis (accessed 14 Sept. 2018).

Noland, R.L., M.S. Wells, C.C. Sheaffer, J.M. Baker, K.L. Martinson, and J.A. Coulter. 2018. Establishment and function of cover crops interseeded into corn. Crop Sci. 58:863-873.

Olson, R.A., and D.H. Sander. 1988. Corn production. *In*: p. 639-686. G. F. Sprague, J. W. Dudley, editors, Corn and corn improvement, Agron. Monogr. 18. ASA, CSSA, SSSA, Madison, WI. doi:10.2134/agronmonogr18.3ed.c11

Pantoja, J.L., K. P. Woli, J.E. Sawyer, and D.W. Barker. 2015. Corn nitrogen fertilization requirement and corn-soybean productivity with a rye cover crop. Soil Sci. Soc. Am. J. 79:1482-1495.

Pantoja, J.L., K.P. Woli, J.E. Sawyer, and D.W. Barker. 2016. Winter rye cover crop biomass production, degradation, and nitrogen recycling. Agron. J. 108:841-853.

Patrignani, A., and T.E. Ochsner. 2015. Canopeo: A powerful new tool for measuring fractional green canopy cover. Agron. J. 107:2312-2320.

Putnam, A.R, J. Defrank, and J.P. Barnes. 1983. Exploitation of allelopathy for weed control in annual and perennial cropping systems. J. Chem. Ecol. 9:1001-1010.

Qiu, H., D.R. Huggins, J.Q. Wu, M.E. Barber, D.K. Mccooll, and S. Dun. 2011. Residue management impacts on field-scale snow distribution and soil water storage. Trans. ASABE. 54(5):1639-1647.

Robinson, R.G. 1987. Camelina: A useful research crop and a potential oilseed crop. Bull. 597-1987. Univ. of Minnesota Agric. Exp. Stn., St. Paul.

Ruark, M.D., M.M. Chawner, R.T. Ballweg, R.T. Proost, F.J. Arriaga, and J.K. Stute. 2018. Does cover crop radish supply nitrogen to corn? Agron. J. 110:1513-1522.

Ruiz-Colmenero, M., R. Bienes, and M.J. Marques. 2011. Soil and water conservation dilemmas associated with the use of green cover in steep vineyards. Soil Tillage Res. 117:211-223.

Russo, V., B. Bruton, and C. Sams. 2010. Classification of temperature response in germination of Brassicas. Ind. Crops. Prod. 31:48-51.

Samarappuli, D.P., B.L. Johnson, H. Kandel, and M.T. Berti. 2014. Biomass yield and nitrogen content of annual energy/forage crops preceded by cover crops. Field Crops Res. 167:31-39.

Schulz, M., A. Marocco, V. Tabaglio, F.A. Macias, and J.M.G. Molinillo. 2013. Benzoxazinoids in rye allelopathy – From discovery to application in sustainable weed control and organic farming. J. Chem. Ecol. 39:154-174.

Soil Survey Staff. 2016. Web Soil Survey. Natural Resources Conservation Service, United States Department of Agriculture. Available online at http://websoilsurvey.nrcs.usda.gov/ (Accessed 31 October 2016).

Steele, M.K., F.J. Coale, and R.L. Hill. 2012. Winter annual cover crop impacts on no-till soil physical properties and organic matter. Soil Sci. Soc. Am. J. 76:2164-2173.

Stewart, D.W., C. Costa, L.M. Dwyer, D.L. Smith, R.I. Hamilton, and B.L. Ma. 2003. Canopy structure, light interception, and photosynthesis in maize. Agron. J. 95:1465-1474.

Teasdale, J.R. 1995. Weed Technol. Influence of narrow row/high population corn (*Zea mays*) on weed control and light transmittance. 9:113-118.

Teasdale, J.R., and C.L. Mohler. 2000. The quantitative relationship between weed emergence and the physical properties of mulches. Weed Sci. 48:385-392.

Thapa, R., H. Poffenbarger, K.L. Tully, V.J. Ackroyd, M. Kramer, and S.B. Mirsky. 2018. Biomass production and nitrogen accumulation by hairy vetch-cereal rye mixtures: A meta-analysis. Agron. J. 110:1197-1208.

Tharp, B.E., and J.J. Kells. 2001. Effect of glufosinate-resistant corn (*Zea mays*) population and row spacing on light interception, corn yield, and common lambsquarters (*Chenopodium album*) growth. Weed Tech. 15:413-418.

Thelen, K.D. 2006. Interaction between row corn row width and yield: Why it works. Online. Crop Manage. doi: 10.1094/CM-2006-0227-03-RV.

Thomas, B.W., F.J. Larney, M.H. Chantigny, C. Goyer, and X. Hao. 2017. Fall rye reduced residual soil nitrate and dryland spring wheat grain yield. Agron. J. 109:718-728.

Uchino, H., K. Iwama, Y. Jitsuyama, T. Yudate, and S. Nakamura. 2009. Yield losses of soybean and maize by competition with interseeded cover crops and weeds in organic-based cropping systems. Field Crops Res. 113:342-351.

Unger, P.W., and M.F. Vigil. 1998. Cover crop effects on soil water relationships. J. Soil Water Conserv. 53:200-207.

Urbaniak, S.D., C.D. Caldwell, V.D. Zheljazkov, R. Lada, and L. Luan. 2008. The effect of seeding rate, seeding date and seeder type on the performance of *Camelina sativa* L. in the Maritime Provinces of Canada. Can. J. Plant Sci. 88:501-508.

Vaughan, J.D., and G.K. Evanylo. 1998. Corn response to cover crop species, spring desiccation time, and residue management. Agron. J. 90:536-544.

Webb, M.S., M. Uemura, and P.L. Steponkus. 1994. A comparison of freezing injury in oat and rye: Two cereals at the extremes of freezing tolerance. Plant Physiol. 104:467-478.

Widdicombe, W.D., and K.D. Thelen. 2002. Row width and plant density effects on corn grain production in the northern Corn Belt. Agron. J. 94:1020-1023.

Williams, S.M., and R.R. Weil. 2004. Crop cover root channels may alleviate soil compaction effects on soybean crop. Soil Sci. Soc. Am. J. 68:1403-1409.

Wilson, M. 2012. Factors affecting the successful establishment of an overseeded winter rye cover crop in northern climates. Ph.D. diss, Univ. of Minnesota, St. Paul.

Wilson, M.L., J.M. Baker, and D.L. Allan. 2013. Factors affecting successful establishment of aerially seeded winter rye. Agron. J. 108:1898-1877.

APPENDIX

Table A1. ANOVA for corn grain yield at Forman and Prosper, ND, 2016.

		Forman		Prosper	
SOV	df	MS	F Value	MS	F Value
Rep	3	1.1	1.0	0.3	0.7*
Relative maturity (RM)	1	60.8	53.4*	81.6	205.4
Cover crop (CC)	3	0.5	0.5	0.2	0.5
RM*CC	3	1.3	1.2	0.2	0.4
Error	21	1.1	-	0.4	-
CV (%)		7.7		4.3	

* Significant at $p \leq 0.05$.

Table A2. ANOVA for corn grain yield at Forman and Prosper, ND, 2017.

		Forman		Prosper	
SOV	df	MS	F Value	MS	F Value
Rep	3	0.4	0.3*	0.6	0.9*
Relative maturity (RM)	1	40.3	23.7	39.6	64.2
Cover crop (CC)	3	0.3	0.2	0.1	0.2
RM*CC	3	1.0	0.6	0.2	0.3
Error	12	1.7	-	0.6	-
CV (%)		11.9		6.2	

* Significant at $p \leq 0.05$.

Table A3. ANOVA for corn grain yield at Forman and Prosper, ND, 2017.

	2016			2017			Combined		
SOV	df	MS	F Value	df	MS	F Value	df	MS	F Value
Location (Loc)	1	12.4	16.2	1	41.8	36.1	3	84.5	87.7
Rep(Loc)	6	0.7	0.9	6	0.5	0.4	12	0.6	0.6
Relative maturity (RM)	1	141.6	185.0*	1	79.9	56802.8*	1	217.1	126.3*
Loc*RM	1	0.8	1.0	1	0.0	0.0	3	1.7	1.8
Cover crop (CC)	3	0.3	0.7	3	0.1	0.3	3	0.1	0.2
Loc*CC	3	0.4	0.6	3	0.3	0.3	9	0.3	0.4
RM*CC	3	0.4	0.4	3	0.8	2.8	3	0.2	0.3
Loc*RM*CC	3	1.1	1.4	3	0.3	0.3	9	0.8	0.8
Error	42	0.8	-	42	1.2	-	84	1.0	
CV (%)		6.1			9.1			7.5	

* Significant at *p*≤0.05.

Table A4. Spacing Experiment corn grain yield ANOVA at Forman and Prosper, ND, 2016.

		Forman		Prosper	
SOV	df	MS	F Value	MS	F Value
Rep	2	8.5	7.3*	9.0	16.3*
Row Width (RW)	1	29.3	7.3	3.0	1.5
Rep*RW	2	4.0	3.5	2.0	3.6
Cover crop (CC)	2	1.3	1.1	1.0	1.8
Planting Date (PD)	1	3.8	3.3	0.4	0.8
RW*CC	2	1.2	1.0	0.5	0.9
RW*PD	1	0.1	0.1	1.0	1.9
CC*PD	2	2.9	2.5	0.8	1.4
RW*CC*PD	2	2.0	1.7	0.5	1.0
Error	24	1.2	-	0.6	-
CV (%)		6.3		4.5	

* Significant at *p*≤0.05.

Table A5. Spacing Experiment corn grain yield ANOVA at Forman and Prosper, ND, 2017.

		Forman		Prosper	
SOV	df	MS	F Value	MS	F Value
Rep	2	12.3	11.4*	0.6	0.5
Row Width (RW)	1	20.3	13.1	12.6	7.3
Rep*RW	2	1.5	1.4	1.7	1.4
Cover crop (CC)	2	0.3	0.3	0.3	0.3
Planting Date (PD)	1	0.0	0.0	2.0	1.6
RW*CC	2	0.9	0.8	1.0	0.8
RW*PD	1	0.0	0.0	0.3	0.2
CC*PD	2	0.0	0.0	0.7	0.6
RW*CC*PD	2	0.2	0.2	0.3	0.3
Error	24	1.1	-	1.2	-
CV (%)		8.4		8.5	

* Significant at *p*≤0.05.

Table A6. Spacing Experiment corn grain yield ANOVA at combined locations at Forman and Prosper, ND, 2017.

	2016			2017			Combined		
SOV	df	MS	F Value	df	MS	F Value	df	MS	F Value
Environment (Env)	1	4.6	1.5*	1	5.2	3.2*	3	209.1	90.0*
Rep(Env)	4	8.7	10.1*	4	6.4	5.6	8	7.6	7.5*
Row Width (RW)	1	25.2	3.8	1	32.4	71.1	1	57.4	23.8*
Env*RW	1	6.6	7.7	1	0.5	0.4	3	2.4	2.4
Rep*RW(Env)	4	3.0	3.5	4	1.6	1.4	8	2.3	2.3
Cover crop (CC)	2	0.8	0.5	2	0.4	1.5	2	0.8	1.1
Env*CC	2	1.5	1.8	2	0.3	0.2	6	0.7	0.7
RW*CC	2	0.4	0.4	2	1.5	4.4	2	0.2	0.2
Env*RW*CC	2	1.2	1.4	2	0.3	0.3	6	1.1	1.1
Planting Date (PD)	1	3.4	4.4	1	1.1	1.3	1	0.3	0.2
Env*PD	1	0.8	0.9	1	0.9	0.8	3	2.0	2.0
RW*PD	1	1.0	4.0	1	0.2	1.5	1	1.0	5.6
CC*PD	2	2.0	1.2	2	0.3	0.9	2	2.0	2.5
Env*RW*PD	1	0.2	0.3	1	0.1	0.1	3	0.2	0.2
Env*CC*PD	2	1.6	1.9	2	0.4	0.3	6	0.8	0.8
RW*CC*PD	2	2.1	4.9	2	0.2	0.8	2	1.4	2.7
Env*RW*CC*PD	2	0.4	0.5	2	0.3	0.2	6	0.5	0.5
Error	47	0.9	-	48	1.2	-	95	1.0	-
CV (%)		5.5			8.5			6.8	

* Significant at *p*≤0.05.

Table A7. ANOVA for cover crop biomass at Forman, ND, 2016-2017.

		Fall 2016		Spring 2017	
SOV	df	MS	F Value	MS	F Value
Rep	3	1102.1	2.1	522.8	0.7*
Relative maturity (RM)	1	1463.1	2.8	1294.2	1.6
Cover crop (CC)	1	939.4	1.8	2785.2	3.5
RM*CC	1	36.6	0.1	537.1	0.7
Error	9	523.4	-	796.3	-
CV (%)		96.1		128.2	

* Significant at *p*≤0.05.

Table A8. Hybrid Experiment cover crop biomass ANOVA at Forman, ND, 2017-2018.

		Fall 2017		Spring 2018	
SOV	df	MS	F Value	MS	F Value
Rep	3	283.7	2.2	820.5	1.5
Relative maturity (RM)	1	79.6	0.6	1244.2	2.3
Cover crop (CC)	2	257.0	2.0	2468.5	4.5*
RM*CC	2	187.8	1.5	622.2	1.1
Error	15	126.7	-	551.9	-
CV (%)		76.5		79.6	

* Significant at *p*≤0.05.

Table A9. Hybrid Experiment cover crop biomass ANOVA at Prosper, ND, 2016-2017.

		Fall 2016			Spring 2017	
SOV	df	MS	F Value	df	MS	F Value
Rep	3	280.9	1.1	3	23506.7	6.9
Relative maturity (RM)	1	516.7	2.1	1	3153.3	0.9
Cover crop (CC)	2	182.4	0.7	2	54309.6	16.0*
RM*CC	2	30.3	0.1	2	3706.1	1.1
Error	14	245.6	-	15	3407.2	
CV (%)		115.0			52.0	

* Significant at *p*≤0.05.

Table A10. Hybrid Experiment cover crop biomass ANOVA at Prosper, ND, 2017-2018.

		Fall 2017		Spring 2018	
SOV	df	MS	F Value	MS	F Value
Rep	3	1462.3	2.7	2138.7	3.2
Relative maturity (RM)	1	993.8	1.8	3636.1	5.4*
Cover crop (CC)	1	851.2	1.6	270.6	0.4
RM*CC	1	48.7	0.1	927.2	1.4
Error	9	547.8	-	669.8	-
CV (%)		44.4		57.7	

* Significant at $p \leq 0.05$.

Table A11. Hybrid Experiment fall cover crop biomass ANOVA at combined locations at Forman and Prosper, ND, 2016-2017.

	Forman			Prosper			Combined		
SOV	df	MS	F Value	df	MS	F Value	df	MS	F Value
Env[‡]	1	608.1	2.2	1	10408.9	28.6*	3	5260.4	16.5*
Rep(Env)	6	692.9	2.5	6	871.6	2.4	12	782.2	2.5
RM[†]	1	294.8	0.5	1	1403.8	22.7	1	1679.0	3.6
Loc*RM	1	618.6	2.3	1	61.8	0.2	3	461.9	1.5
Cover crop (CC)	2	19.8	0.0	2	130.8	0.2	2	50.4	0.1
Env*CC	1	1413.8	5.1	1	892.7	2.5	4	637.7	2.0
RM*CC	2	205.7	253.0*	2	1.6	0.0	2	80.3	0.9
Env*RM*CC	1	0.8	0.0	1	105.0	0.3	4	90.1	0.3
Error	24	275.5	-	23	363.9	-	47	318.7	-
CV (%)		90.4			64.3			74.6	

* Significant at $p \leq 0.05$.

† RM, relative maturity.

‡ Env, environment.

Table A12. Hybrid Experiment spring cover crop biomass ANOVA at combined locations at Forman and Prosper, ND, 2017-2018.

	Forman			Prosper			Combined		
SOV	df	MS	F Value	df	MS	F Value	df	MS	F Value
Env‡	1	2261.3	3.5	1	105179.9	44.2*	3	39226.4	25.9*
Rep(Env)	6	671.6	1.0	6	12822.7	5.4	12	6747.2	4.5
RM†	1	1999.8	113.0	1	4661.7	21.6	1	7901.1	61.4*
Loc*RM	1	17.7	0.0	1	216.3	0.1	3	128.6	0.1
CC§	2	3706.7	12.0	2	53514.6	28.8	2	24820.8	1.5
Env*CC	1	308.8	0.5	1	1860.5	0.8	4	16742.6	11.1
RM*CC	2	262.0	0.2	2	2092.6	0.5	2	652.1	0.3
Env*RM*CC	1	1257.5	2.0	1	4154.2	1.7	4	2204.2	1.5
Error	24	643.5	-	24	2380.7	-	48	1512.1	-
CV (%)		95.6			57.2			69.5	

* Significant at *p*≤0.05.

† RM, relative maturity.

‡ Env, environment.

§ CC, cover crop.

Table A13. Spacing Experiment fall cover crop biomass ANOVA at Forman and Prosper, ND, 2016.

	Forman			Prosper		
SOV	df	MS	F Value	df	MS	F Value
Rep	2	1728.3	2.5	2	8601.3	2.8
Row Width (RW)	1	4.1	0.0	1	19446.3	28.8*
Rep*RW	2	2304.5	3.3	2	676.2	0.2
Cover crop (CC)	2	3775.2	5.4*	2	21916.5	7.2*
Planting Date (PD)	1	498.7	0.7	1	9040.8	3.0
RW*CC	2	175.6	0.3	2	2278.1	0.8
RW*PD	1	431.8	0.6	1	19288.6	6.3*
CC*PD	1	584.1	0.8	2	3948.0	1.3
RW*CC*PD	1	1.9	0.0	2	9214.5	3.0
Error	16	704.6	-	20	3040.0	-
CV (%)		61.5			76.9	

* Significant at *p*≤0.05.

Table A14. Spacing Experiment fall cover crop biomass ANOVA at Forman and Prosper, ND, 2017.

	Forman			Prosper		
SOV	df	MS	F Value	df	MS	F Value
Rep	2	2759.5	1.9	2	291.3	0.7
Row Width (RW)	1	2286.4	0.5	1	537.7	0.6
Rep*RW	2	4295.0	2.9	2	963.8	2.3
Cover crop (CC)	2	2922.3	2.0	1	2101.9	4.9*
Planting Date (PD)	1	50.2	0.0	1	1991.1	4.7
RW*CC	2	186.9	0.1	1	1170.4	2.7
RW*PD	1	1437.7	1.0	1	24.8	0.1
CC*PD	2	2204.2	1.5	1	19.1	0.0
RW*CC*PD	2	174.3	0.1	1	58.9	0.1
Error	20	1493.3	-	12	428.0	-
CV (%)		92.1			69.9	

* Significant at $p \leq 0.05$.

Table A15. Spacing Experiment spring cover crop biomass ANOVA at Forman, ND, 2016.

SOV	df	MS	F Value
Rep	2	14020.0	3.9*
Rep*RW	2	794.6	0.2
Row Width (RW)	1	1224.1	1.5
Treatment (Trt)	4	118152.4	33.1*
RW*Trt	3	8605.4	2.4
Error	14	3571.1	-
CV (%)		33.7	

* Significant at $p \leq 0.05$.

Table A16. Spacing Experiment spring cover crop biomass ANOVA at Prosper, ND, 2016.

SOV	df	MS	F Value
Rep	2	83674.1	1.4
Row Width (RW)	1	83617.4	2.3
Rep*RW	2	37174.7	0.6
Cover crop (CC)	2	1590594.3	26.4*
Planting Date (PD)	1	1489945.7	24.7*
RW*CC	2	55575.6	0.9
RW*PD	1	49269.2	0.8
CC*PD	2	368626.2	6.1*
RW*CC*PD	2	119541.0	2.0
Error	20	60331.1	-
CV (%)		48.5	

* Significant at *p*≤0.05.

Table A17. Spacing Experiment spring cover crop biomass ANOVA at Forman and Prosper, ND, 2017.

		Forman		Prosper	
SOV	df	MS	F Value	MS	F Value
Rep	2	858.6	0.6	929.8	5.3*
Row Width (RW)	1	4771.9	1.2	1007.5	1.5
Rep*RW	2	3984.8	2.9	654.5	3.8
Cover crop (CC)	2	2610.1	1.9	3208.6	18.4*
Planting Date (PD)	1	2405.4	1.7	120.2	0.7
RW*CC	2	1455.4	1.0	161.7	0.9
RW*PD	1	426.7	0.3	410.9	2.4
CC*PD	2	651.7	0.5	0.7	0.0
RW*CC*PD	1	960.1	0.7	47.3	0.3
Error	17	1393.2	-	174.6	-
CV (%)		74.7		52.1	

* Significant at *p*≤0.05.

Table A18. Hybrid Experiment cover crop N content at Forman and Prosper, ND, 2016-2017.

	Fall			Spring		
SOV	df	MS	F Value	df	MS	F Value
Env	1	0.9	8.9*	1	0.1	0.6
Rep(Env)	6	0.0	0.4	5	0.1	0.7
RM	1	0.0	0.2	1	0.2	24.0
Env*RM	1	0.2	1.9	1	0.0	0.1
CC	1	2.3	1.4	1	0.1	0.3
Env*CC	1	1.6	15.9	1	0.4	2.7
RM*CC	1	0.2	51.2	1	0.0	943.4*
Env*RM*CC	1	0.0	0.0	1	0.0	0.0
Error	13	0.1	-	7	0.2	-
CV (%)		7.5			10.1	

* Significant at *p*≤0.05.

Table A19. Spacing Experiment cover crop N content at Forman and Prosper, ND, 2016-2017.

	Fall			Spring		
SOV	df	MS	F Value	df	MS	F Value
Environment (Env)	1	0.4	2.8	1	4.3	43.8*
Rep(Env)	4	0.3	2.4	4	0.2	3.2
Row Width (RW)	1	0.2	8.0	1	0.0	0.7
Env*RW	1	0.0	0.2	1	0.0	0.2
Rep*RW(Env)	4	0.1	1.0	4	0.1	1.9
Cover crop (CC)	1	5.1	0.5	1	0.0	0.0
Env*CC	1	9.8	72.5	1	0.8	14.4
RW*CC	1	0.0	0.1	1	0.1	2.6
Env*RW*CC	1	0.3	2.6	1	0.0	0.8
Planting Date (PD)	1	1.3	2.0	1	0.7	0.7
Env*PD	1	0.6	4.8	1	1.1	21.0
RW*PD	1	0.0	0.1	1	0.1	0.5
CC*PD	1	0.0	0.3	1	0.7	5.7
Env*RW*PD	1	0.0	0.2	1	0.2	3.5
Env*CC*PD	1	0.1	0.8	1	0.1	2.4
RW*CC*PD	1	0.0	3.3	1	0.3	165.8*
Env*RW*CC*PD	1	0.0	0.1	1	0.0	0.0
Error	21	0.1	-	19	0.1	-
CV (%)		9.2			6.2	

* Significant at *p*≤0.05.

Table A20. Hybrid Experiment fall residual soil NO_3^--N ANOVA at Forman and Prosper, ND, 2016.

	Forman			Prosper		
SOV	df	MS	F Value	df	MS	F Value
Rep	3	1.2	1.2	3	906.5	1.5
Cover crop (CC)	3	10.9	10.5*	2	540.1	0.9
Error	6	1.0	-	6	587.0	-
CV (%)		12.1			41.5	

* Significant at *p*≤0.05.

Table A21. Hybrid Experiment fall residual soil NO_3^--N ANOVA at Forman and Prosper, ND, 2017.

	Forman			Prosper		
SOV	df	MS	F Value	df	MS	F Value
Rep	3	35.0	0.7	3	12.0	4.0
Cover crop (CC)	3	69.7	1.5	2	21.6	10.8
Error	9	47.5	-	6	3.4	-
CV (%)		41.0			13.6	

* Significant at *p*≤0.05.

Table A22. Hybrid Experiment spring residual soil NO_3^--N ANOVA at Forman and Prosper, ND, 2018.

	Forman			Prosper		
SOV	df	MS	F Value	df	MS	F Value
Rep	3	103.2	1.5	3	7.1	0.7
Relative maturity (RM)	1	1.9	0.0	1	1.9	0.2
Cover crop (CC)	3	102.7	1.5	2	16.4	1.6
RM*CC	3	21.0	0.3	2	0.2	0.0
Error	21	68.5	-	15	10.0	-
CV (%)		38.3			21.0	

* Significant at *p*≤0.05.

Table A23. Hybrid Experiment combined spring residual soil NO_3^--N ANOVA at Forman and Prosper, ND, 2018.

	Combined		
SOV	df	MS	F Value
Environment (Env)	1	738.9	16.7*
Rep(Env)	6	55.1	1.3
Relative maturity (RM)	1	0.6	0.1
Env*RM	1	10.5	0.2
Cover crop (CC)	3	84.9	2.0
Env*CC	2	43.0	1.0
RM*CC	3	14.1	1.3
Env*RM*CC	2	10.6	0.2
Error	36	44.1	
CV (%)		35.3	

* Significant at $p \leq 0.05$.

Table A24. Spacing Experiment fall residual soil NO_3^--N ANOVA at Forman and Prosper, ND, 2016.

	Forman			Prosper		
SOV	df	MS	F Value	df	MS	F Value
Rep	2	370.1	2.1	2	689.2	1.0
Rep*RW	1	526.4	4.5	1	213.9	0.3
Row Width (RW)	2	254.5	2.2	2	348.3	0.6
Treatment (Trt)	5	86.2	0.7	5	1560.2	2.3
RW*Trt	5	135.5	1.2	5	380.7	0.6
Error	19	117.8	-	18	690.8	-
CV (%)		79.8			42.8	

* Significant at $p \leq 0.05$.

Table A25. Spacing Experiment fall residual soil NO_3^--N ANOVA at Forman and Prosper, ND, 2017.

	Forman			Prosper		
SOV	df	MS	F Value	df	MS	F Value
Rep	2	203.8	9.2	2	5.4	0.6
Rep*RW	1	68.9	3.1	1	24.0	2.5
Row Width (RW)	2	97.0	0.7	2	3.4	0.4
Treatment (Trt)	6	26.2	1.2	5	42.6	4.4*
RW*Trt	6	25.8	1.2	5	15.5	1.6
Error	24	22.2	-	18	9.7	-
CV (%)		27.6			20.7	

* Significant at $p \leq 0.05$.

Table A26. Spacing Experiment fall residual soil NO_3^--N ANOVA at Forman and Prosper, ND, 2016-2017.

	2016			2017		
SOV	df	MS	F Value	df	MS	F Value
Environment (Env)	1	28041.5	70.7	1	80.2	4.8
Rep(Env)	4	529.7	1.3	4	104.6	6.2
Row Width (RW)	1	54.4	0.2	1	74.0	1.5
Env*Rep*RW	4	301.4	0.8	4	50.2	3.0
Env*RW	1	561.9	1.4	1	7.7	0.5
Treatment (Trt)	6	816.7	1.0	6	56.0	8.5*
Env*Trt	4	836.3	2.1	5	6.6	0.4
RW*Trt	6	259.6	1.0	6	14.3	0.5
Env*RW*Trt	4	256.7	0.7	5	27.0	1.6
Error	37	396.6	-	42	16.8	-
CV (%)		53.6			25.4	

* Significant at $p \leq 0.05$.

Table A27. Spacing Experiment spring residual soil NO_3^--N ANOVA at Forman and Prosper, ND, 2018.

	Forman			Prosper		
SOV	df	MS	F Value	df	MS	F Value
Rep	2	92.4	2.8	2	18.7	2.9
Rep*RW	1	176.5	5.4	1	19.8	3.1
Row Width (RW)	2	46.2	3.8	2	2.1	0.3
Treatment (Trt)	6	137.5	4.2*	4	10.0	1.5
RW*Trt	6	11.4	0.4	4	11.0	1.7
Error	24	32.6	-	16	6.5	-
CV (%)		41.2			19.2	

* Significant at $p \leq 0.05$.

Table A28. Spacing Experiment fall residual soil NO_3^--N ANOVA combined across locations at Forman and Prosper, ND, 2018.

SOV	df	MS	F Value
Environment (Env)	1	1.2	0.1
Rep(Env)	4	55.6	2.5
Row Width (RW)	1	39.1	1.6
Env*Rep*RW	4	24.1	1.1
Env*RW	1	90.3	4.1
Treatment (Trt)	6	89.5	1.1
Env*Trt	4	81.9	3.7
RW*Trt	6	11.6	1.1
Env*RW*Trt	4	10.8	0.5
Error	40	22.1	-
CV (%)		34.6	

* Significant at $p \leq 0.05$.

Table A29. Hybrid Experiment PAR[†] ANOVA at Forman, ND, 2016.

		Date 1		Date 2		Date 3		Date 4		Date 5		Date 6	
SOV	df	MS	F Value	MS	F Value	MS	F Value	MS	F Value	MS	F Value	MS	F Value
Rep	3	25.1	1.1	8.0	0.9	23.8	3.3	9.5	0.9	4.7	0.3	49.8	3.6
RM[‡]	1	49.2	2.2	193.1	22.8*	341.7	47.3*	536.5	51.0*	221.9	15.2*	714.1	52.1*
CC[§]	3	14.5	0.6	6.1	0.7	13.9	1.9	45.1	4.3*	35.0	2.4	69.4	5.1*
RM*CC	3	4.8	0.2	5.3	0.6	36.2	5.0*	9.3	0.9	58.7	4.0*	68.8	5.0*
Error	17	22.6	-	8.5	-	7.2	-	1007.2	-	14.6	-	13.7	-
CV (%)		5.5		3.2		3.1		3.9		4.7		4.7	

* Significant at $p \leq 0.05$.

† PAR, photosynthetically active radiation.

‡ RM, relative maturity.

§ CC, cover crop.

Table A30. Hybrid Experiment PAR† ANOVA at Forman, ND, 2017.

		Date 1		Date 2		Date 3		Date 4		Date 5		Date 6	
SOV	df	MS	F Value	MS	F Value	MS	F Value	MS	F Value	MS	F Value	MS	F Value
Rep	3	22.7	2.4	16.5	1.3	23.3	2.6	22.5	1.8	9.9	0.4	3.5	0.2
RM‡	1	36.9	3.9	113.3	9.1*	75.7	8.6*	0.9	0.1	341.1	14.6*	4.4	0.2
CC§	3	4.0	0.4	6.6	0.5	4.1	0.5	8.4	0.7	10.8	0.5	14.1	0.7
RM*CC	3	10.0	1.1	35.3	2.8	0.5	0.1	15.7	1.3	2.0	0.1	6.3	0.3
Error	21	9.5	-	12.5	-	8.8	-	12.4	-	23.4	-	19.8	-
CV (%)		3.6		4.0		3.3		3.9		5.4		5.0	

* Significant at $p \leq 0.05$.

† PAR, photosynthetically active radiation.

‡ RM, relative maturity.

§ CC, cover crop.

Table A31. Hybrid Experiment PAR† ANOVA at Prosper, ND, 2016.

		Date 1		Date 2		Date 3		Date 4		Date 5		Date 6	
SOV	df	MS	F Value	MS	F Value	MS	F Value	MS	F Value	MS	F Value	MS	F Value
Rep	3	460.7	13.7	253.3	10.2	757.9	13.4	26.5	2.4	-	-	138.8	3.1
RM‡	1	171.1	5.1*	119.4	4.8*	258.8	4.6*	48.0	4.34*	-	-	623.9	13.8*
CC§	3	18.2	0.5	14.5	0.6	33.0	0.6	8.4	0.8	-	-	19.7	0.4
RM*CC	3	17.2	0.5	9.5	0.4	16.9	0.3	6.3	0.6	-	-	31.2	0.7
Error	21	33.6	-	24.8	-	56.6	-	11.0	-	-	-	45.2	-
CV (%)		6.4		5.4		8.4		3.6		-		7.9	

* Significant at *p*≤0.05.

† PAR, photosynthetically active radiation.

‡ RM, relative maturity.

§ CC, cover crop.

Table A32. Hybrid Experiment PAR[†] ANOVA at Prosper, ND, 2017.

SOV	df	Date 1		Date 2		Date 3		Date 4		Date 5		Date 6	
		MS	F Value	MS	F Value	MS	F Value	MS	F Value	MS	F Value	MS	F Value
Rep	3	201.4	3.7*	875.0	75.6	194.1	8.9	18.0	2.2	13.0	1.5	30.6	2.8
RM[‡]	1	401.8	7.4*	32.9	2.8	161.7	7.5*	307.7	37.6*	135.0	15.6*	195.3	17.7*
CC[§]	3	46.0	0.9	28.1	2.4	34.1	1.6	2.8	0.3	7.3	0.8	15.5	1.4
RM*CC	3	21.4	0.4	73.0	6.3*	59.3	2.7	1.0	0.1	14.3	1.7	8.7	0.8
Error	21	54.0	-	11.6	-	21.7	-	8.2	-	8.6	-	11.0	-
CV (%)		13.8		4.2		5.1		3.1		3.3		3.7	

* Significant at $p \leq 0.05$.

[†] PAR, photosynthetically active radiation.

[‡] RM, relative maturity.

[§] CC, cover crop.

Table A33. Hybrid Experiment PAR† ANOVA combined across years at Forman, ND, 2016-2017.

		Date 1		Date 2		Date 3		Date 4		Date 5		Date 6	
SOV	df	MS	F Value	MS	F Value	MS	F Value	MS	F Value	MS	F Value	MS	F Value
Y‡	1	64.2	4.2	14.5	1.4	118.0	14.5*	796.2	68.8*	751.0	38.6*	1111.4	65.1*
Rep(Y)	6	23.9	1.6	12.3	1.2	23.5	2.9	16.0	1.4	7.3	0.4	26.7	1.6
RM§	1	86.1	55.1	304.9	26.5	385.0	5.8	324.0	1.2	546.9	514.2*	459.4	1.3
Y*RM	1	1.6	0.1	11.5	1.1	65.9	8.1	280.9	24.3	1.1	0.1	348.5	20.4
CC¶	3	14.6	3.3	8.6	2.5	16.3	4.5	27.7	1.1	23.3	1.1	65.6	3.7
Y*CC	3	4.5	0.3	3.4	0.3	3.6	0.5	25.1	2.2	22.2	1.1	17.9	1.1
RM*CC	3	8.4	1.3	4.4	0.2	23.9	1.3	11.3	0.9	42.7	1.7	59.0	2.9
Y*RM*CC	3	6.3	0.4	30.1	2.8	18.1	2.2	12.6	1.1	24.8	1.3	20.7	1.2
Error	38	15.4	-	10.7	-	8.1	-	11.6	-	19.5	-	17.1	-
CV (%)		4.5		3.7		3.2		3.9		5.1		4.9	

* Significant at *p*≤0.05.

† PAR, photosynthetically active radiation.

‡ Y, year.

§ RM, relative maturity.

¶ CC, cover crop.

Table A34. Hybrid Experiment PAR† ANOVA combined across years at Prosper, ND, 2016-2017.

		Date 1		Date 2		Date 3		Date 4		Date 5		Date 6	
SOV	df	MS	F Value	MS	F Value	MS	F Value	MS	F Value	MS	F Value	MS	F Value
Y‡	1	22564.2	515.0*	1917.5	105.4*	19.8	0.5	7.3	0.8	-	-	312.6	11.1*
Rep(Y)	6	331.1	7.6	564.2	31.0	476.0	12.2	22.3	2.3	-	-	84.7	3.0
RM§	1	548.7	22.6	138.8	10.3	414.8	73.1	299.4	5.3	-	-	758.7	12.5
Y*RM	1	24.2	0.6	13.5	0.7	5.7	0.1	56.3	5.9	-	-	60.5	2.2
CC¶	3	59.9	13.9*	27.7	1.9	63.2	16.7*	7.8	2.3	-	-	10.3	0.4
Y*CC	3	4.3	0.1	14.9	0.8	3.8	0.1	3.4	0.4	-	-	24.9	0.9
RM*CC	3	20.8	1.2	45.5	1.2	58.0	3.2	3.7	1.0	-	-	10.3	0.4
Y*RM*CC	3	17.8	0.4	37.0	2.0	18.3	0.5	3.6	0.4	-	-	29.6	1.1
Error	42	43.8	-	18.2	-	39.2	-	9.6	-	-	-	28.1	-
CV (%)		9.2		4.9		6.9		3.4		-		6.1	

* Significant at *p*≤0.05.

† PAR, photosynthetically active radiation.

‡ Y, year.

§ RM, relative maturity.

¶ CC, cover crop.

Table A35. Hybrid Experiment PAR[†] ANOVA combined across all environments at Forman and Prosper, ND, 2016-2017.

		Date 1		Date 2		Date 3		Date 4		Date 5		Date 6	
SOV	df	MS	F Value	MS	F Value	MS	F Value	MS	F Value	MS	F Value	MS	F Value
Env[‡]	3	9558.4	315.4*	700.9	47.9*	67.4	2.8*	527.1	50.1*	409.3	26.2*	529.9	23.5*
Rep(Env)	12	177.5	5.9	288.2	19.7	249.8	10.2	19.1	1.8	9.2	0.6	55.7	2.4
RM[§]	1	518.7	13.7*	432.7	29.2*	797.6	33.4*	623.2	5.5	671.7	52.9*	1188.1	8.2
Env*RM	3	37.9	1.3	14.8	1.0	23.9	1.0	112.4	10.7	12.7	0.8	144.3	6.3
CC[¶]	3	48.5	4.9*	23.9	2.4	57.0	5.7*	15.0	0.9	16.2	0.9	16.6	0.5
Env*CC	9	9.8	0.3	10.0	0.7	10.1	0.4	16.4	1.6	18.9	1.2	34.3	1.5
RM*CC	3	26.8	3.1	25.6	0.8	50.5	2.3	9.4	1.3	16.3	0.5	41.8	1.6
Env*RM *CC	9	8.7	0.3	30.7	2.1	22.4	0.9	7.6	0.7	31.9	2.0	25.9	1.1
Error[#]	80	30.3	-	14.6	-	24.4	-	10.5	-	15.6	-	22.9	-
CV (%)		7.0		4.3		5.5		3.6		4.6		5.6	

* Significant at $p \leq 0.05$.

† PAR, photosynthetically active radiation.

‡ Env, environment.

§ RM, relative maturity.

¶ CC, cover crop.

\# Error df are 59 for Date 5 because of a missing environment.

Table A36. Spacing Experiment PAR† ANOVA for dates 1-3 at Forman, ND, 2016.

		1-Mid-Jul		2-Earl Aug		3-Mid-Aug	
SOV	df	MS	F Value	MS	F Value	MS	F Value
Rep	2	14.2	1.4	21.8	3.1	18.1	0.6
Row Width (RW)	1	27.1	0.4	23.4	0.4	86.6	2.0
Rep*RW	2	67.4	6.6	64.3	9.1	43.1	1.5
Cover crop (CC)	3	31.9	3.1	20.9	3.0	13.3	0.5
RW*CC	3	16.9	1.7	7.2	1.0	34.6	1.2
Error	12	10.3	-	7.0	-	28.8	-
CV (%)		3.7		2.9		6.0	

* Significant at *p*≤0.05.

† PAR, photosynthetically active radiation.

Table A37. Spacing Experiment PAR† ANOVA for dates 1-3 at Forman, ND, 2017.

	1-Mid-Jul			2-Earl Aug			3-Mid-Aug		
SOV	df	MS	F Value	df	MS	F Value	df	MS	F Value
Rep	2	50.6	4.0	2	197.7	5.1	2	75.8	3.5
Row Width (RW)	1	161.4	9.1	1	47.4	0.6	1	10.2	0.3
Rep*RW	2	17.8	1.4	2	74.4	1.9	2	38.7	1.8
Cover crop (CC)	3	29.0	2.3	3	6.5	0.2	3	14.0	0.7
RW*CC	3	67.4	5.3*	3	7.6	0.2	3	3.5	0.2
Error	12	12.7	-	11	38.7	-	12	21.4	-
CV (%)		4.3			7.1			5.4	

* Significant at *p*≤0.05.

† PAR, photosynthetically active radiation.

Table A38. Spacing Experiment PAR† ANOVA for dates 1-3 at Prosper, ND, 2016.

	1-Mid-Jul			2-Earl Aug			3-Mid-Aug		
SOV	df	MS	F Value	df	MS	F Value	df	MS	F Value
Rep	2	83.0	1.7	2	57.7	1.2	2	153.2	5.9
Row Width (RW)	1	1077.4	200.3*	1	441.2	3.9	1	116.2	1.2
Rep*RW	2	5.4	0.1	2	112.9	2.3	2	99.4	3.8
Cover crop (CC)	3	83.5	1.7	3	16.7	0.3	3	110.5	4.3*
RW*CC	3	5.8	0.1	3	5.6	0.1	3	11.1	0.4
Error	12	49.5	-	12	48.4	-	10	25.9	-
CV (%)		9.3			8.7			6.5	

* Significant at *p*≤0.05.

† PAR, photosynthetically active radiation.

Table A39. Spacing Experiment PAR† ANOVA for dates 1-3 at Prosper, ND, 2017.

	1-Mid-Jul			2-Earl Aug			3-Mid-Aug		
SOV	df	MS	F Value	df	MS	F Value	df	MS	F Value
Rep	2	339.9	12.6*	2	6.3	0.8	2	437.3	22.2*
Row Width (RW)	1	600.9	5.2	1	0.2	0.0	1	445.2	13.7
Rep*RW	2	116.6	4.3	2	7.7	1.0	2	32.4	1.6
Cover crop (CC)	3	98.0	3.6*	3	11.4	1.4	3	49.7	2.5
RW*CC	3	272.0	10.1*	3	8.1	1.0	3	58.2	3.0
Error	11	26.9	-	12	8.0	-	11	19.7	-
CV (%)		7.0			3.0			5.4	

* Significant at $p \leq 0.05$.

† PAR, photosynthetically active radiation.

Table A40. Spacing Experiment PAR† ANOVA for dates 1-3 combined across years at Forman, ND, 2016-2017.

	1-Mid-Jul			2-Earl Aug			3-Mid-Aug		
SOV	df	MS	F Value	df	MS	F Value	df	MS	F Value
Year	1	84.4	7.4*	1	119.2	5.4*	1	187.3	7.47
Rep(Year)	4	32.4	2.8	4	109.8	5.0	4	47.0	1.9
Row Width (RW)	1	160.4	5.7	1	69.2	26.5	1	78.2	4.2
Year*RW	1	28.1	2.5	1	2.6	0.1	1	18.6	0.7
Rep*RW*Year	4	42.6	3.7	4	69.4	3.1	4	40.9	1.6
Cover crop (CC)	3	58.0	19.6*	3	10.4	0.6	3	2.3	0.1
Year*CC	3	3.0	0.3	3	17.0	0.8	3	24.9	1.0
RW*CC	3	25.1	0.4	3	9.1	1.6	3	24.2	1.8
Year*RW*CC	3	59.1	5.2	3	5.7	0.3	3	13.9	0.6
Error	24	11.5	-	23	22.2	-	24	25.1	-
CV (%)		4.0			5.3			5.7	

* Significant at $p \leq 0.05$.

† PAR, photosynthetically active radiation.

Table A41. Spacing Experiment PAR† ANOVA for dates 1-3 combined across years at Prosper, ND, 2016-2017.

	1-Mid-Jul			2-Earl Aug			3-Mid-Aug		
SOV	df	MS	F Value	df	MS	F Value	df	MS	F Value
Year	1	36.2	0.9	1	2250.2	79.7*	1	255.6	11.3*
Rep(Year)	4	211.4	5.5	4	32.0	1.1	4	295.2	13.0
Row Width (RW)	1	1633.5	63.7	1	229.3	1.1	1	489.8	13.1
Year*RW	1	25.6	0.7	1	212.0	7.5	1	37.5	1.7
Rep*RW*Year	4	61.0	1.6	4	60.3	2.1	4	65.9	2.9
Cover crop (CC)	3	56.4	0.5	3	25.0	8.2	3	79.7	0.8
Year*CC	3	117.3	3.0	3	3.0	0.1	3	102.4	4.5
RW*CC	3	142.3	1.0	3	8.9	1.8	3	9.1	0.2
Year*RW*CC	3	137.0	3.5	3	4.8	0.2	3	58.9	2.6
Error	23	38.7	-	24	28.2	-	21	22.7	-
CV (%)		8.3			6.1			5.9	

* Significant at *p*≤0.05.

† PAR, photosynthetically active radiation.

Table A42. Spacing Experiment PAR† ANOVA for dates 4-6 at Forman, ND, 2016.

	4-Early Sept			5-Mid-Sept			6-Early Oct		
SOV	df	MS	F Value	df	MS	F Value	df	MS	F Value
Rep	2	3.7	0.4	2	7.3	0.5	2	7.9	0.45
Row Width (RW)	1	107.2	13.0	1	190.1	13.1	1	5.2	0.3
Rep*RW	2	84.2	1.3	2	37.7	5.0	2	5.1	1.0
Cover crop (CC)	2	5.2	0.6	2	1.6	0.1	2	8.5	0.5
Planting Date (PD)	1	0.1	0.0	1	2.3	0.2	1	16.3	0.9
RW*CC	2	9.5	1.2	2	43.3	3.0	2	0.5	0.0
RW*PD	1	0.1	0.0	1	10.0	0.7	1	43.1	2.4
CC*PD	2	2.8	0.3	2	11.9	0.8	2	23.0	1.3
RW*CC*PD	2	11.2	1.4	2	34.0	2.3	2	2.9	0.2
Error	24	8.3	-	24	14.5	-	24	17.7	-
CV (%)		3.3			4.7			4.7	

* Significant at *p*≤0.05.

† PAR, photosynthetically active radiation.

Table A43. Spacing Experiment PAR† ANOVA for dates 4-6 at Forman, ND, 2017.

		4-Early Sept		5-Mid-Sept		6-Early Oct	
SOV	df	MS	F Value	MS	F Value	MS	F Value
Rep	2	7.9	0.5	162.6	19.4*	70.3	10.0*
Row Width (RW)	1	5.2	1.0	1.4	0.0	11.8	0.1
Rep*RW	2	5.1	0.3	94.4	11.3	225.6	32.0
Cover crop (CC)	2	8.5	0.5	14.0	1.7	3.3	0.5
Planting Date (PD)	1	16.3	0.9	0.8	0.1	2.5	0.4
RW*CC	2	0.5	0.0	9.2	1.1	1.3	0.2
RW*PD	1	43.1	2.4	17.5	2.1	0.0	0.0
CC*PD	2	23.0	1.3	0.9	0.1	33.1	4.7*
RW*CC*PD	2	2.9	0.2	16.5	2.0	3.4	0.5
Error	24	17.7	-	8.4	-	7.0	-
CV (%)		4.7		3.3		3.0	

* Significant at *p*≤0.05.

† PAR, photosynthetically active radiation.

Table A44. Spacing Experiment PAR† ANOVA for date 4 at Prosper, ND, 2016.

	4-Early Sept		
SOV	df	MS	F Value
Rep	2	456.8	21.0*
Row Width (RW)	1	13.8	0.4
Rep*RW	2	36.2	1.7
Cover crop (CC)	2	123.5	5.7*
Planting Date (PD)	1	6.4	0.3
RW*CC	2	8.9	0.4
RW*PD	1	92.8	4.3*
CC*PD	2	6.4	0.3
RW*CC*PD	2	47.2	2.2
Error	24	21.7	-
CV (%)		5.2	

* Significant at *p*≤0.05.

† PAR, photosynthetically active radiation.

Table A45. Spacing Experiment PAR† ANOVA for dates 4-6 at Prosper, ND, 2017.

		4-Early Sept		5-Mid-Sept		6-Early Oct	
SOV	df	MS	F Value	MS	F Value	MS	F Value
Rep	2	24.1	2.87	5.2	0.71	14.8	6.99
Row Width (RW)	1	0.1	0.0	4.1	4.5	2.7	1.4
Rep*RW	2	11.9	1.4	0.9	0.1	1.9	0.9
Cover crop (CC)	2	1.9	0.2	4.8	0.7	0.3	0.2
Planting Date (PD)	1	16.0	1.9	4.0	0.5	0.4	0.2
RW*CC	2	0.3	0.0	3.1	0.4	2.6	1.2
RW*PD	1	10.9	1.3	2.1	0.3	1.8	0.9
CC*PD	2	6.6	0.8	8.0	1.1	2.6	1.2
RW*CC*PD	2	1.0	0.1	1.5	0.2	0.9	0.4
Error	24	8.4	-	7.3	-	2.1	-
CV (%)		3.1		3.0		1.6	

* Significant at *p*≤0.05.

† PAR, photosynthetically active radiation.

Table A46. Spacing Experiment PAR† ANOVA for dates 4-5 combined across years at Forman, ND, 2016-2017.

		4-Early Sept		5-Mid-Sept	
SOV	df	MS	F Value	MS	F Value
Year	1	38.5	3.0	613.1	53.6*
Rep(Year)	4	5.8	0.5	84.9	7.4
Row Width (RW)	1	79.7	2.4	112.1	1.4
Year*RW	1	32.6	2.5	79.4	7.0
Rep*RW*Year	4	44.7	3.4	66.0	5.8
Cover crop (CC)	2	0.8	0.1	12.5	4.0
Year*CC	2	12.9	1.0	3.1	0.3
RW*CC	2	3.3	0.5	13.1	0.3
Year*RW*CC	2	6.6	0.5	39.3	3.4
Planting Date (PD)	1	7.0	0.7	2.9	17.3
Year*PD	1	9.4	0.7	0.2	0.0
RW*PD	1	23.8	1.2	0.5	0.0
CC*PD	2	16.5	1.8	6.1	0.9
Year*RW*PD	1	19.4	1.5	27.0	2.4
Year*CC*PD	2	9.4	0.7	6.7	0.6
RW*CC*PD	2	12.8	9.4	36.9	2.7
Year*RW*CC*PD	2	1.4	0.1	13.6	1.2
Error	48	13.0	-	11.4	-
CV (%)		4.1		4.0	

* Significant at $p \leq 0.05$.

† PAR, photosynthetically active radiation.

Table A47. Spacing Experiment PAR† ANOVA for dates 4-5 combined across years at Prosper, ND, 2016-2017.

	4-Early Sept		
SOV	df	MS	F Value
Year	1	355.6	23.6*
Rep(Year)	4	240.4	16.0
Row Width (RW)	1	8.2	1.4
Year*RW	1	5.7	0.4
Rep*RW*Year	4	24.0	1.6
Cover crop (CC)	2	60.2	0.9
Year*CC	2	65.2	4.3
RW*CC	2	6.0	1.9
Year*RW*CC	2	3.2	0.2
Planting Date (PD)	1	21.4	19.8
Year*PD	1	1.1	0.1
RW*PD	1	83.7	4.2
CC*PD	2	1.1	0.1
Year*RW*PD	1	20.0	1.3
Year*CC*PD	2	11.9	0.8
RW*CC*PD	2	18.9	0.6
Year*RW*CC*PD	2	29.3	1.9
Error	48	15.1	-
CV (%)		4.3	

* Significant at *p*≤0.05.

† PAR, photosynthetically active radiation.

Table A48. Hybrid Experiment Canopeo ANOVA at three dates at Forman, ND, 2016.

		Corn Harvest		Frost		Spring	
SOV	df	MS	F Value	MS	F Value	MS	F Value
Rep	3	32.1	1.7	14.7	9.5*	0.2	1.6
Relative maturity (RM)	1	2.6	0.1	6.9	4.4	0.0	0.1
Cover crop (CC)	2	1.6	0.1	1.0	0.7	0.5	3.3
RM*CC	1	3.7	0.2	1.1	0.7	0.0	0.1
Error	9	19.1	-	1.6	-	0.1	-
CV (%)		100.1		62.8		180.1	

* Significant at *p*≤0.05.

Table A49. Hybrid Experiment Canopeo ANOVA at three dates at Forman, ND, 2017.

		Corn Harvest		Frost		Spring	
SOV	df	MS	F Value	MS	F Value	MS	F Value
Rep	3	27.7	2.7	30.4	2.3	16.5	2.3
Relative maturity (RM)	1	6.2	0.6	1.5	0.1	0.4	0.1
Cover crop (CC)	2	35.2	3.5	52.7	3.9*	25.8	3.6
RM*CC	2	8.5	0.8	5.2	0.4	6.3	0.9
Error	15	10.2	-	13.4	-	7.2	-
CV (%)		74.9		74.4		85.0	

* Significant at $p \leq 0.05$.

Table A50. Hybrid Experiment Canopeo ANOVA at three dates at Prosper, ND, 2016.

		Corn Harvest		Frost		Spring	
SOV	df	MS	F Value	MS	F Value	MS	F Value
Rep	3	4.8	1.4	5.4	2.9	135.7	2.3
Relative maturity (RM)	1	0.0	0.0	0.2	0.1	295.8	5.0
Cover crop (CC)	2	5.6	1.6	2.1	1.1	297.3	5.0
RM*CC	2	1.0	0.3	0.0	0.0	61.9	1.0
Error	15	3.4	-	1.8	-	59.5	-
CV (%)		83.0		72.0		104.9	

* Significant at $p \leq 0.05$.

Table A51. Hybrid Experiment Canopeo ANOVA at three dates at Prosper, ND, 2017.

		Corn Harvest		Frost		Spring	
SOV	df	MS	F Value	MS	F Value	MS	F Value
Rep	3	10.4	1.3	15.3	1.6	35.5	3.2
Relative maturity (RM)	1	4.5	0.6	1.1	0.1	57.6	5.2*
Cover crop (CC)	2	35.8	4.6*	33.2	3.5	4.5	0.4
RM*CC	2	2.3	0.3	2.9	0.3	8.2	0.7
Error	9	7.9	-	9.4	-	11.2	-
CV (%)		50.1		63.4		66.2	

* Significant at $p \leq 0.05$.

Table A52. Hybrid Experiment Canopeo ANOVA at three dates at Forman, ND, 2016.

		Corn Harvest		Frost		Spring	
SOV	df	MS	F Value	MS	F Value	MS	F Value
Rep	2	63.0	3.1	1.9	0.3	30.4	1.4
Row Width (RW)	1	67.1	2.9	0.2	0.0	37.8	0.9
Rep*RW	2	22.9	1.1	7.2	1.3	43.0	1.9
Treatment (Trt)	4	55.3	2.7	16.1	2.9	937.7	42.3*
RW*Trt	4	15.0	0.7	9.7	1.7	7.6	0.3
Error	16	20.3	-	5.6	-	22.2	-
CV (%)		54.8		57.4		42.8	

* Significant at $p \leq 0.05$.

Table A53. Hybrid Experiment Canopeo ANOVA at three dates at Forman, ND, 2017.

		Corn Harvest		Frost		Spring	
SOV	df	MS	F Value	MS	F Value	MS	F Value
Rep	2	33.9	0.7	35.5	1.0	3.4	0.2
Row Width (RW)	1	352.4	6.6	330.6	9.0	45.4	0.6
Rep*RW	2	53.1	1.1	101.1	2.8	76.4	5.2
Treatment (Trt)	5	67.9	1.4	45.2	1.2	36.8	2.5
RW*Trt	5	13.9	0.3	6.0	0.2	7.7	0.5
Error	20	50.3	-	36.7	-	14.8	-
CV (%)		74.6		73.0		81.4	

* Significant at $p \leq 0.05$.

Table A54. Hybrid Experiment Canopeo ANOVA at three dates at Prosper, ND, 2016.

		Corn Harvest		Spring	
SOV	df	MS	F Value	MS	F Value
Rep	2	19.5	3.0	352.2	1.6
Row Width (RW)	1	68.4	4.4	827.4	4.0
Rep*RW	2	15.5	2.4	205.1	0.9
Treatment (Trt)	5	58.4	8.9*	4115.4	18.1*
RW*Trt	5	19.9	3.0*	240.4	1.1
Error	20	6.6	-	227.3	-
CV (%)		46.8		42.6	

* Significant at $p \leq 0.05$.

Table A55. Hybrid Experiment Canopeo ANOVA at three dates at Prosper, ND, 2017.

	Corn Harvest			Frost			Spring		
SOV	df	MS	F Value	df	MS	F Value	df	MS	F Value
Rep	2	14.1	3.6	2	13.5	3.9	2	45.0	6.1*
Row Width (RW)	1	4.6	2.5	1	33.9	31.5*	1	39.3	2.5
Rep*RW	2	1.9	0.5	2	1.1	0.3	2	15.6	2.1
Treatment (Trt)	4	47.5	12.2*	4	29.3	8.6*	4	26.2	3.6*
RW*Trt	4	3.9	1.0	4	3.7	1.1	4	9.3	1.3
Error	15	3.9	-	16	3.4	-	16	7.4	-
CV (%)		51.2			55.5			95.1	

* Significant at $p \leq 0.05$.