# FACTORS AFFECTING ESTABLISHMENT AND GROWTH OF COVER CROPS IN A CORN-SOYBEAN ROTATION

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**Title**

Factors affecting establishment and growth of cover crops in a corn-soybean rotation

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**MASTER OF SCIENCE**

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## ABSTRACT

In the Midwest, it can be beneficial to interseed cover crops into corn (*Zea mays* L.) since there is a limited time for them to establish and grow after corn harvest. Research conducted in four environments in North Dakota quantified the impacts of planting method and time of planting when grown with or without corn competition on the establishment, and development of three cover crop species. Limited light intensity (less than 20%) under the corn canopy drastically reduced cover crop development. Soil water can also constrain cover crop establishment. Model simulations suggest soil water is more limiting for cover crop establishment in August compared with June or July. Interseeded cover crops had no effect on corn yield or the following soybean (*Glycine max* (L.) *Merr.*] crop due to minimal amounts of biomass produced.

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# INTRODUCTION

Effective cover cropping practices can reduce negative environmental impacts and enhance production for annual cropping systems (Noland et al., 2018). In the Midwest, soil managed with corn (*Zea mays* L.)-soybean [*Glycine max* (L.) *Merr*] rotations are susceptible to nutrient losses through surface runoff, leaching, and subsurface tile drainage (Randall et al., 2003; Strock et al., 2004). Although uncommonly utilized, cover crops following corn can be important soil conservation tools for Midwest cropping systems. Cover crops can benefit the soil by protecting it from soil erosion, increasing soil organic matter, and improving soil aggregate stability and soil water retention (Dabney et al., 2001).

It can be challenging to implement cover crops into a corn-soybean rotation because of a narrow planting and establishment window, short growing season, limited photosynthetically active radiation (PAR), and limited soil water availability (Bich et al., 2014; Belfry and Van Eerd, 2016). Limited use of cover crops in corn-soybean rotations is likely due to the costs of establishment and termination and interferences with the following crop. Benefits of cover crops on corn and soybean production is highly dependent on environmental conditions (Unger and Vigil, 1998).

For environments with narrow planting windows and short growing seasons after cash crop harvest, it can be beneficial to interseed the cover crops into the standing cash crop or warm- and cool-season cover crops can be seeded postharvest as a monoculture or mixture (Wick et al., 2017). Annual cover crops, whether they are grasses or brassica, can be a substitute for fallow to provide important benefits including, but not limited to, erosion control and water management (Kaspar et al., 2001; De Baets et al., 2011; Chen et al., 2014; Lounsbury and Weil, 2014), weed suppression (Lawley et al., 2012), disease control (Chew, 1988; Brown and Morra, 1995), and soil fertility (Thorup-Kristensen, 2001; Weil and Kremen, 2007; Dean and Weil, 2009; Thorup-Kristensen et al., 2009; Parr et al., 2014; Jani et al., 2015).

It is important to consider the cover crop plant material when deciding which cover crops fit in the cash crop rotation. In general, brassicas have a low carbon to nitrogen ration (C:N); whereas grasses have a high C:N ratio so brassica plant material breaks down faster (SARE, 2012). Grass cover crops have rapid growth, can tolerate a range of soil conditions and have fibrous root systems (Wick et al., 2017). Brassicas are used as cover crops due to their deep tap root that can grow up to 2 m deep after 4 months of growth (Thorup-Kristensen et al., 2009) and rapid root growth of 2 mm $day^{-1}$ $°C^{-1}$ (Thorup-Kristensen et al., 2001). Although grasses can be effective at remediating shallow compaction layers, brassicas penetrate compacted layers better than grasses (Materechera et al., 1992; Chen and Weil, 2010).

More research is needed regarding interseeding cover crops into standing corn to improve cover crop establishment and performance. This research was conducted to understand the effects of cover crop planting date and planting method on the establishment of rye (*Secale cereal* L.), camelina [*Camelina sativa* (L.)], and radish (*Raphanus sativus* L.) when interseeded in standing corn and compared with their growth when grown without the competition of corn. Also, to understand the effect of cover crop growth and development on the following cash crop, soybean. To be able to understand these interactions, improvement in interseeded cover crop management within corn in the Midwest is needed.

## OBJECTIVES

The goal of this research was to evaluate the effect of planting date and planting method on establishing viable interseeded cover crops in corn. Secondly, to evaluate the effect of limited available light and soil moisture on cover crop development. This was achieved through the following objectives:

1. To determine the effect of planting date, planting method and species on establishing interseeded cover crops.
2. To determine the effect of limited available light and soil moisture on cover crop development.
3. To quantify the effect of interseeded cover crop growth on corn yield.
4. To evaluate the effect of cover crop growth on the yield of a following soybean crop.
5. To quantify the frequency that extractable soil water is adequate for cover crop establishment in a corn crop using the Agricultural Production Systems Simulator (APSIM) model.

# LITERATURE REVIEW

## Cover Crop Benefits

Cover crops have the potential to benefit the soil and following crops in various ways. Cover crops are known for protecting the soil from erosion, increasing soil organic matter, improving soil aggregate stability and soil water retention, and scavenging and releasing nutrients (Dabney et al., 2001; Kaspar et al., 2001; De Baets et al., 2011; Chen et al., 2014; Lounsbury and Weil, 2014).

### Soil Physical Properties

Including cool-season cover crops in rotation improves soil physical properties in the surface soils by increasing root establishment, soil aggregation, soil organic matter, and microbial stimulation (Wick et al., 2017; Hermawan and Bomke, 1997; Villamil et al., 2006; Steele et al., 2012). Folorunso et al., (1992). Kuo and Sainju (1994), however, suggest that it takes several successful years of cover crop growth when grown in the winter months to improve soil aggregation. A soil that has increased aggregation and plant roots can decrease bulk density and increase total porosity in surface soils (Villamil et al., 2006). In a long-term cover crop study, rye was found to decrease bulk density and increase hydraulic conductivity (Keisling et al., 1994). However, Wagger and Denton (1989) saw no effects of cover crops on soil physical properties (bulk density, soil porosity, and hydraulic conductivity) after a 3-yr study.

### Soil Water Content

Corn and soybean are major crops that are produced throughout the Midwest. Soil and water resources have become a concern due to the changing climate (Basche et al., 2015). Reduced crop yields will result when soil and water resources are compromised. This is currently a major issue for corn and soybean producers, especially in the Midwest (Basche et al., 2015).

With the help of conservation management practices, the negative impacts climate change can have on soil and water resources can be reduced. Increasing water storage and enhancing infiltration of water are conservation management practices that improve soil water dynamics (Basche et al., 2016).

Conservation practices, such as cover crops, may aid in protecting the soil and water resources in the Midwest. An efficient way to assess the suitability of cover crops in the Midwest would be to utilize modeling software that provide accurate predictions of crop productivity under different management scenarios.

Agricultural Production System Simulator is a model that is made up of individual modules of key farming system components (Keating et al., 2003). The individual modules consist of biophysical, management, and data input modules and a simulation engine. With this model, farmers can develop a plant to improve soil and water management of their farms based on their specific operations, utilizing the recommendations from the simulation process. The modeling software provides accurate predictions for crop production since it takes into consideration the climate, genotypes grown, soil and management factors, along with addressing long-term resource management issues in a specific farming system (Keating et al., 2003). With this software, genotypes, soil types, and management factors can be altered, if needed, to simulate a specific crop, cultivar, location, region, or plot.

According to Unger and Vigil (1998), cover crops grown in humid areas with sufficient precipitation, will have negligible effects on available soil water for primary crop production. Cover crops can, however, possibly reduce available soil water for primary crop production, especially in low rainfall areas (Unger and Vigil, 1998; Blanco-Canqui et al., 2015). Even if cover crops negatively impact soil water, they can contribute to other important soil benefits (Blanco-Canqui et al., 2015).

Raimbault et al., (1991) reported that rye can reduce soil moisture enough to reduce yield in the following cash crop. A study conducted by Krueger et al., (2011), found rye treatments to significantly reduce soil moisture by 13% when rye was harvested in the spring for grain compared with the no rye control treatments. In the same study, rye that was killed 3 to 4 weeks prior to harvest did not significantly reduce soil moisture in Minnesota. Waiting until the boot stage to terminate the rye will reduce available soil moisture for the following cash crop (Krueger et al., 2011). To avoid depleting soil moisture, Clark et al. (1997) and Liebl et al. (1992) suggest terminating rye by early May in the Midwest. Krueger et al., (2011) reported that rye utilized available N and ground cover, without reducing available soil water for the following cash crop.

Nitrogen Recovery

In the upper Midwest, spring weather conditions prior to primary crop establishment promotes the greatest risk of N loss in annual cropping systems (Noland et al., 2018). According to Randall et al. (2003), 69% of the annual N loss occurs as runoff in April through June in corn-soybean rotations in the upper Midwest. Winter annual cover crops can be incorporated into a corn-soybean rotation to stabilize N in plant biomass and reduce its loss (Feyereisen et al., 2006; Qi and Helmers, 2010; Blanco-Canqui et al., 2015). Although a cover crop that winterkills will not assimilate and retain as much N as a cover crop that overwinters, it becomes a valuable option if early-spring herbicide applications are undesirable (Noland et al., 2018).

Cover crops can protect water quality and retain N in the field for future mineralization and crop use, which can reduce fertilizer inputs for the following crop (Noland et al., 2018;

Stock et al., 2004; Shipley et al., 1992; Staver and Brinsfield, 1998). A study conducted in Lamberton, MN reported that soil where rye was interseeded into corn had reduced soil N levels compared with no cover crops in both fall and spring (Rusch et al., 2019). To be able to maximize N uptake, cover crops need to be well established to have sufficient fall and spring growth prior to termination (Komatsuzaki and Wagger, 2015).

Due to brassica's deep tap root and rapid growth, they can uptake N from deep within the soil profile, bringing it closer to the soil surface and within the biomass (Wick et al., 2017). Dean and Weil (2009), found N uptake by radish to be greater than or equal to cereal rye. Radish N uptake ranged between 36 and 171 kg N $ha^{-1}$ and cereal rye uptake ranged between 42 and112 kg N $ha^{-1}$ (Dean and Weil, 2009).

## Cover Crop Management

Cover Crop Species

***Rye***

Winter rye is cold-tolerant and has the potential for rapid growth and for accumulating large amounts of biomass in the fall and spring, rapidly scavenging excess N, and suppressing weeds for up to five weeks (Wilson et al., 2013; Martin et al., 1976; Komatsuzaki and Wagger, 2015; SARE, 2016; Crowley et al., 2018). According to SARE (2016), rye is hardier than other cover crops on infertile, sandy, or poorly prepared land in cool, temperate zones. Rye will germinate at temperatures as low as 1°C in soils with minimal soil moisture, and can tolerate waterlogging (SARE, 2016).

Although rye has shallower rooting depths and slower growth than brassicas (Thorup-Kristensen, 2001), Kuhlmann et al. (1989) and Strebel and Duynisveld (1989) found rye was still able to take up significant amounts of N between 0.9 and 1.5-m depths. An 8-yr study conducted by Staver and Brinsfield (1998), reported rye reducing annual N leaching by 80% when used between cash crops. Feyereisen et al. (2006) suggest that winter rye should be planted on or prior to 15 September to be able to produce sufficient biomass in the fall to have the greatest effect on reducing N loss the following spring.

Using rye as a winter cover crop in a corn-soybean rotation has been shown to increase soil structure, improve soil organic matter, fertility, and improve soil physical properties by increasing soil aggregate stability (Rorick and Kladivko, 2017). In a corn-soybean rotation under no-till, rye is known to increase soil organic matter for readily available soil C pools and surface soils (Fae et al., 2009; Sequiera and Alley, 2011; Moore et al., 2014). In contrast, rye can pose a threat of reducing the yields of the succeeding corn due to the depletion of soil water, allelopathy, and the potential of tying up N (Hartzler, 2014). According to Martinez-Feria et al. (2016), the greater the accumulation of rye biomass, the greater the potential to negatively affect soil water and N availability for the succeeding crop.

***Camelina***

Winter camelina is a relatively new option for cover cropping and is not commonly interseeded into a standing cash crop but has potential in a corn-soybean cropping system (Berti et al., 2017). Winter camelina as a cover crop has the potential to increase biodiversity and reduce soil erosion, N leaching, phosphorus run-off, and weed management input costs, while maintaining or improving primary cash crop yields (Berti et al., 2017). Winter camelina is winter hardy and can germinate in soil temperatures as low as 1°C (Gesch et al., 2014; Berti et al., 2015; Gesch and Cermak, 2011). Camelina that is fall-seeded will remain in the rosette stage throughout the winter, with growth resuming in the spring (Berti et al., 2017).

In a study conducted by Berti et al. (2017), corn yield was reduced when camelina was interseeded at the time of corn planting. Camelina did not significantly compete with corn when it was interseeded after the V4-V5 stage (Berti et al., 2017). Camelina plants died after emergence, due to lack of light penetration through the corn canopy. Shading the camelina plants inhibited plant growth, whereas surviving plants remained small. Planting date did not affect fall and spring camelina ground cover as it was minimal for all treatments. The average spring camelina biomass from 21 plots ranged from 966 and 2240 kg $ha^{-1}$ and N accumulation in aboveground plant biomass ranged from 24 and 59 kg N $ha^{-1}$.

***Radish***

Radish can be used as an annual cover crop and is known for its rapid fall growth and suppressing winter annual weeds due to the large amounts of biomass it produces. Interest in radish has increased due to ecological benefits in the fall and not requiring termination in the spring (Noland et al., 2018). Radish has a low C:N ratio, which results in low residue the following spring because it’s capable of decomposing rapidly (Lawley et al., 2011). Since radish winter kills, decomposes rapidly, and suppresses winter annual weeds, it sets up a desirable seed bed the following spring.

Radish has an advantage of reducing compaction and scavenging for excess nutrients due to its deep tap roots. The fine roots at the tip of the large fleshy tap root of the radish can grow through root-restricting layers when soils are wet (Chen and Weil, 2010). The root channels that are created by the fine roots of the radish continue to act as tunnels for the following crop roots, enabling them to grow through compacted soil layers to reach soil moisture and nutrients (Williams and Weil, 2004).

Also, brassicas are capable of suppressing pathogenic fungi. Brassicas produce glucosinolates which hydrolyze to form isothiocyanates (fungi inhibitor) (Hill, 2006). According to Hill (2006), soybean plants had significantly lower fungal infection where brassicas were growing prior. Although infection levels were reduced, Hill (2006) concluded that it was unknown how much inhibition was caused from the isothiocyanates, soil texture, presence of fungal host, and tillage practices.

Interseeding Cover Crops in Corn

Typically, there is a relatively long period during the winter when cropland can be bare. Producers are interested in exploiting cover crops as a conservation management tool to add coverage, increase snow catch, and improve soil health. In the Midwest it is challenging for cover crops to fully establish in the fall due to the short growth period and limited soil water availability (Berti et al., 2017). The short growing season following corn in the Midwest causes difficulties for establishing cover crops; which is an important factor limiting adoption of cover in the upper Midwest (Singer, 2008; SARE-CTIC, 2016). To mitigate this challenge, cover crops can be interseeded into standing corn to allow them a longer growing season to establish prior to winter. Planting date, planting method, and competition for solar radiation are all limiting factors to successfully establish interseeded cover crops in corn (Humphreys et al., 2003).

Planting Date

Corn has a critical weed-free period and when cover crops are planted within this period, they can potentially act as weeds and reduce corn yield. The critical weed free period in corn needed to prevent yield losses greater than 5% is generally from V1 to V6 stages (Berti et al., 2017). Fortunately, corn has the capability of detecting another plant growing at very early stages, which encourages it to modify its shoot/root ratio, growth, and development (Liu et al., 2009, 2016). According to Curran et al. (2018), reduction in corn yield associated with cover crop competition was minimized and cover crop production was maximized when interseeded between the V4 and V6 corn growth stages.

According to Gallo et al., (1985), the percentage of incoming photosynthetically active radiation (PAR) absorbed by the corn canopy increases rapidly from roughly 20 to 90% between the V5 and V12 corn growth stages. The corn canopy absorbs greater than 80% of incoming PAR from the V12 corn growth stage to the dough stage of grain fill (R4) (Gallo et al., 1985). Since the incoming PAR absorbed by the corn canopy increases rapidly after V5, time of planting is critical for successful establishment for interseeded cover crops (Gallo et al., 1985).

Critical planting windows need to be determined in order to know when cover crops can be interseeded most successfully. Prior to corn canopy closure, cover crops need to be planted early enough to establish roots while PAR is reaching the soil surface, but late enough to avoid competing with the primary crop for water, nutrients, and solar radiation (Abdin et al., 1997). Also, planting date for cover crops is important as it influences the amount of biomass they can produce, and biomass is related to the amount of nutrients captured (Thorup-Kristensen, 2001; Komatsuzaki and Wagger, 2015) and the amount of cover provided.

Planting Method

Cover crops can be interseeded by broadcasting the seed into the corn crop using aerial equipment or by specifically-designed ground equipment. New and old machinery have been adapted (high-clearance implements) to broadcast or place cover crop seed directly in the inter-row to increase seed-to-soil contact when interseeding cover crops (Roth et al., 2015). Improved establishment has been positively associated with methods to increase seed-to-soil contact (Boyd and Van Acker, 2003; Wilson et al., 2013; Curran et al., 2018).

Planting method can be restricted by planting time. Aerial application can be done anytime throughout the growing season but are typically made in August and September; whereas broadcasting or drilling cover crops with high clearance implements occur early in the growing season, typically prior to corn emergence until the V7 corn growth stage. The V7 corn growth stage is the latest stage cover crops could be planted with high clearance implements because any later may result in damage to the corn crop.

Success of cover crop establishment when aerially broadcasted into standing corn in August and September was positively associated with the occurrence and amount of rainfall within 1 week of planting (Wilson et al., 2013). If rain was not received in a timely manner after broadcasting cover crops, the failure of stand establishment increased (Fisher et al., 2011).

## Soybean Following Cover Crop

Winter cover crops can be important to Midwest cropping systems (Unger and Vigil, 1998; Blanco-Canqui et al., 2015). Fertility benefits from cover crops are dependent on their ability to capture and release nutrients, environmental conditions, tillage, cover crop termination, and nutrient demand by the following cash crop (Kamh et al., 1999; Vyn et al., 2000).

Timing and effectiveness of termination is crucial for minimizing interference with soybean growth and development and yield loss (Singer et al., 2007). To produce a successful soybean crop following cover crops, additional management tactics need to be added. Modifying crop spacing and population (Teasdale, 1995) with competitive crop cultivars (So et al., 2009) in high residue systems with intense weed management practices (Teasdale and Rosecrance, 2003; Gallandt, 2006) can benefit soybean production when following cover crops.

Corn yield can be reduced following a rye cover crop. However, growing soybean after rye does not result in the same yield reductions as corn. A study conducted by Davis (2010) reported, although planted late, that total soybean yield was greatest following rye cover crop treatments, ranging from 2200 to 3700 kg $ha^{-1}$ compared with 1300 t0 1900 kg $ha^{-1}$ for soybean not following rye.

In another study conducted by Williams and Weil (2004) that focused on the effects of cover crop roots on compaction layers in comparison to tillage, found that soybean yields following a radish + rye mixture were significantly higher than all other treatments, except radish alone. These results show that radish improved the yield of the following crop, but when mixed with rye, the two cover crops enhanced soybean production further. This study concluded that radish + rye benefited soybean yield by radish providing channels through the subsoil and rye providing a mulch to reduce evaporation from the soil.

## MATERIALS AND METHODS

Experiments were conducted in four environments during the 2018 and 2019 growing seasons. In 2018, the field sites were near Casselton and Hickson, ND and in 2019 near Prosper and Hickson, ND. The soil types for these three locations are listed in Table 1. For three of the sites, corn followed a previous soybean crop; while for Prosper, corn followed a previous wheat (*T. aestivum*) crop. Following the 2018 corn experiments, plots were planted to soybean in the spring of 2019 after cover crop termination. All the sites were managed with conventional tillage prior to corn planting and with zero tillage prior to soybean planting. Daily precipitation and temperature throughout the two growing seasons were recorded by the North Dakota Agricultural Weather Network (NDAWN) with Prosper, ND and Sabin, MN being the weather stations closest to Casselton and Hickson, respectively.

Table 1. Soil series description of 2018-2019 experimental locations at Casselton, Hickson, and Prosper, North Dakota. †

| Location | Series | Texture | Taxonomy | Slope |
|---|---|---|---|---|
| | | | | - % - |
| Casselton | Kindred-Bearden | Silty clay loam | Fine-silty, mixed, superactive, frigid Typic Endoaquolls | 0-2 |
| Hickson | Fargo | Silty clay | Fine, smectitic, frigid Typic Epiaquerts | 0-2 |
| 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, 2019).

### Experimental Design

The experimental designs of both the corn and soybean experiments was a randomized complete block with three replicates. Treatments consisted of four factors in a factorial combination. Cover crops (three levels), cover crop planting methods (two levels), planting date relative to corn growth stage (two levels), and the removal of corn (two levels) were the factors (Table 2). The three cover crops used were rye, cultivar 'ND-Dylan'; winter camelina, cultivar

‘Joelle’; and ‘Daikon’ radish. Rye was sown at 44.8 kg pure live seed $ha^{-1}$ and both camelina and radish were sown at 7.8 kg pure live seed $ha^{-1}$. The two cover crop planting dates were relative to the V7 and R4 corn growth stages, which was determined by visual observance and estimating the growth stage by totaling growing degree days using NDAWN. When planting cover crops, a mechanical or broadcast method was used. The final factor was corn removal where specific treatments had corn removed at each cover crop planting date. This was done to determine the potential growth and development of the cover crops when grown without the competition of the corn crop.

Table 2. Complete treatment list consisting of the factorial combination of cover crops, planting date, planting method, and removal of corn.

| Treatment | Cover Crop | Application Timing | Corn Removal | Method |
|---|---|---|---|---|
| 1 | Rye | V7 | No | Mechanical |
| 2 | Rye | V7 | Yes | Mechanical |
| 3 | Rye | V7 | No | Broadcast |
| 4 | Rye | V7 | Yes | Broadcast |
| 5 | Camelina | V7 | No | Mechanical |
| 6 | Camelina | V7 | Yes | Mechanical |
| 7 | Camelina | V7 | No | Broadcast |
| 8 | Camelina | V7 | Yes | Broadcast |
| 9 | Radish | V7 | No | Mechanical |
| 10 | Radish | V7 | Yes | Mechanical |
| 11 | Radish | V7 | No | Broadcast |
| 12 | Radish | V7 | Yes | Broadcast |
| 13 | Rye | R4 | No | Mechanical |
| 14 | Rye | R4 | Yes | Mechanical |
| 15 | Rye | R4 | No | Broadcast |
| 16 | Rye | R4 | Yes | Broadcast |
| 17 | Camelina | R4 | No | Mechanical |
| 18 | Camelina | R4 | Yes | Mechanical |
| 19 | Camelina | R4 | No | Broadcast |
| 20 | Camelina | R4 | Yes | Broadcast |
| 21 | Radish | R4 | No | Mechanical |
| 22 | Radish | R4 | Yes | Mechanical |
| 23 | Radish | R4 | No | Broadcast |
| 24 | Radish | R4 | Yes | Broadcast |

## Field Management

In 2018 field experiments, corn was planted in 7-m long plots that were 4 rows with 76-cm wide row spacings. A 61-cm alley without corn between the front and back of the plots was established. The purpose for establishing a small alley was to reduce the amount of light reaching inside the plots from wider alleys. Since it was difficult to apply herbicide treatments with these smaller alleys, the corn plot dimensions were changed to 6.1 m long, with a 1.5 m alley in 2019. The corn hybrids were 89-d relative maturities consisting of 'DKC 39-27' and 'DKC 39-28' in 2018 and 2019, respectively. For both years the corn seeding rate was 79 000 live seeds $ha^{-1}$, with rows planted north and south in all environments.

Nitrogen fertilizer was applied in the spring prior to or at corn planting at each location. All N applications were based on previous crops and soil test results. In 2018, N was applied at the rate of 188 kg $ha^{-1}$ at Casselton and 135 kg $ha^{-1}$ at Hickson. In 2019, N was applied at the rate of 112 kg $ha^{-1}$ at Hickson and 204 kg $ha^{-1}$ at Prosper. In-season weed control consisted of glyphosate [N-(phosphonomethyl)glycine] (Roundup Powermax, Monsanto Co., St. Louis, MO) at the labeled rates after corn emergence but prior to cover crop seeding. After planting cover crops, plots were hand weeded as needed for the remainder of the season. For a complete list of important dates including planting, herbicide applications, and harvest for the two site years refer to Table 3.

Cover crops were seeded between the corn rows using a v-hoe with two blades to make furrows and surface broadcasting by hand. These methods were used to simulate planting with a high-clearance drill and an aerial application. The furrows were made parallel to the corn rows, 15-cm apart, at various depths in relation to the seed size of the cover crop. Although planting depth could not be accurately set with our planting methods, we tried to plant shallower for the small-seeded cover crops and deeper for the larger-seeded cover crops. Radish and rye were planted roughly at 13 mm and camelina was planted roughly 6 mm deep. Seed was hand-placed in the furrows, then a hoe was used to cover the seed and fill furrows with soil. There were two rows of cover crops sown in between two corn rows, for a total of six cover crop rows per plot. These planting methods were used at both the V7 and R4 growth stages and for the treatments where the corn was removed. In 2018, in the corn removed plots, the above ground corn material was removed by hand at both the V7 and R4 growth stage of corn. Since the corn that was removed at the V7 corn growth stage in 2018 continued to grow back throughout the season, clethodim [(E)-2-[1-[[(3-chloro-2-propenyl)oxy]imino]propyl]- 5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen1-one]was used at 136 g $ha^{-1}$ active ingredient to remove the corn at the V7 corn growth stage in 2019.

Table 3. Complete list of important dates for crop planting, herbicide applications, biomass collection, and crop harvest for 2018 and 2019 growing seasons.

| | 2018 | 2019 |
|---|---|---|
| Corn planting | 3-May | 16-May |
| Herbicide application | 13-Jun | 2-Jul |
| V7 corn removal | 14-Jun | 26-Jun |
| V7 cover crop planting | 15-Jun | 2-Jul |
| V7 cover crop stand count | 3-Jul | 22-Jul |
| R4 corn removal | 14-Aug | 30-Aug |
| R4 cover crop planting | 15-Aug | 30-Aug |
| R4 cover crop stand count | 30-Aug | 18-Sep |
| Fall cover crop stand count | 16-Oct | 25-Oct |
| Fall cover crop biomass | 16-Oct | 29-Oct |
| Corn harvest | 19-Oct | 5-Nov |
| Spring cover crop stand count | - | 9-May |
| Spring cover crop biomass | - | 14-May |
| Cover crop termination | - | 20-May |
| Soybean planting Casselton | - | 21-May |
| Soybean planting Hickson | - | 3-Jun |
| Soybean stand count | - | 15-Jul |
| Soybean harvest | - | 5-Nov |

Cover crop growth and development was evaluated throughout the growing season by measuring green canopy cover, plant density, aboveground biomass, and biomass N content from within the second and third corn rows of the plot. Green canopy cover was measured using Canopeo, a smartphone application developed by Oklahoma State University Department of Plant and Soil Sciences (www.canopeoapp.com). Pictures of the cover crops were taken about 60 cm above ground and were used by the application to calculate percent canopy cover of the soil. The ground cover was measured weekly starting two weeks after cover crop planting until corn harvest and again in the spring towards the end of April until cover crop termination.

After the cover crops were planted, measurements of PAR were taken every two weeks between the period of 1000 and 1400 h (CDT) until corn harvest. Measurements were taken by placing the AccuPAR LP -80 Ceptometer (Decagon Devices, Pullman, WA) parallel to the corn rows, under the corn canopy about 15-cm above the soil while the attached incident light sensor was above the corn in full sunlight; both sensors collected three measurements per plot. This method of measurement makes it possible to determine the percentage of available light that was accessible to the interseeded cover crops.

Cover crop stand counts were taken at various times throughout the growing season. At both the V7 and R4 planting dates, there was a count conducted roughly one week after the first plants had emerged. There was a complete stand count conducted on all the plots just prior to corn harvest, then again in the spring of 2019 prior to termination of the 2018 cover crops. The counts were conducted in the data row, for a length of 1-m and the width of the corn rows.

Cover crop biomass was collected in the fall prior to corn harvest and again before termination the following spring (excluding radish, as it winter killed). Biomass samples were collected by cutting the plants at the soil surface for one meter in length between two corn rows.

All samples were placed into paper bags and dried until the weight remained constant. After determining biomass dry weights, a Cyclone Sample mill was used to finely grind the biomass to pass through a 1.0 mm mesh which was subsequently analyzed for N content using a Near-Infrared Analyzer (NIR-XDS analyzer, Foss, Inc., Denmark). In the spring prior to soybean planting, soil samples were collected at 0-15 cm and 15-61 cm to determine residual soil N following the cover crop treatments.

Throughout the growing season, soil water content was measured to estimate the available moisture for the cover crops in the top portion of the soil. In the spring, prior to termination, samples were also taken to determine how much moisture the cover crops had removed. The samples were collected by taking a 7.5 cm deep soil core regularly during the growing season and a 15 cm deep core in the spring, placing it in a tin can, weighing the wet soil, drying it for 48 h then weighing the dry soil. Gravimetric water content was calculated by subtracting the dry soil weight from the wet soil weight then dividing by dry soil weight and multiplying by 100 to obtain percent soil water content by mass.

Following the 2018 corn experiments with the interseeded cover crops, soybean was planted in the spring of 2019. An Asgrow 08x8 cultivar was planted at 432 000 seeds $ha^{-1}$ with 76-cm row widths. After emergence, plant density was measured by counting emerged plants for the entire row length from rows two and three. Soybean yield was measured in order to determine the effects the previous crops had on the crop growth and development. A combined mounted weighing system was used to obtain grain weight and moisture values. Final yield was adjusted to 14% moisture content.

## Modeling Soil Water Availability

The APSIM was used to model if there was adequate extractable soil water content for cover crop development. To simulate the frequency of adequacy of available water for cover crop development during a corn crop the water use and productivity of a corn crop system, 30 years of weather data compiled from NDAWN for the Fargo, ND weather station was used as the weather input in the model.

Table 4. Physical and water soil properties for a Fargo silt clay with 0-2% slope, used in the Agricultural Production Systems Simulator (APSIM).

| | Initial soil properties | | | | | | |
|---|---|---|---|---|---|---|---|
| | Soil properties | | | | Water holding capacity | | |
| Soil layer | pH | OC† | $NO_{3-}$ | $NH_{4+}$ | Unavailable | Available | Drainable |
| cm | | % | kg ha$^{-1}$ | | - - - - - - - - - - mm - - - - - - - - - - | | |
| 20 | 7.1 | 2.3 | 10 | 5 | 60.2 | 9.4 | 31.8 |
| 33 | 7.4 | 1.2 | 7 | 4 | 38.9 | 6.2 | 13.5 |
| 53 | 7.4 | 1.2 | 5 | 3 | 61.8 | 8.6 | 19.8 |
| 81 | 8.1 | 0.6 | 4 | 2 | 80.6 | 15.1 | 30.5 |
| 200 | 7.9 | 0.6 | 2 | 1 | 330.8 | 70.2 | 135.7 |

† OC – organic carbon

All the parameters used for the model were set based on the environments that were representative of the field experiments previously described. The soil used was a Fargo silty clay with 0-2% slope, which is a very deep, poorly drained soil (Soil Survey Staff, 2019). Soil tests conducted at Hickson in 2019 and Web Soil Survey were used for the soil profile parameters (Soil Survey Staff, 2019) (Table 4). The previous crop was soybean and the model estimated 1250 kg ha$^{-1}$ of dry matter, 500 kg ha$^{-1}$ C, 18.5 kg ha$^{-1}$ N. Initial water was set at field capacity at the start of the year. Phenological variables for the corn cultivar consisted of 315 °C days from emergence to flowering, 170 °C days from flowering to grain fill and 900 °C from flowering to maturity. This specific cultivar was used as it was the most representable cultivar available in the model to cultivars used in North Dakota. In the simulation, corn was planted on 1 May every year with a seeding rate of 79 000 plants $ha^{-1}$, 50.8 mm deep, and a row spacing of 762 mm. If the N in the topsoil was less than 1000 kg $ha^{-1}$, then 150 kg N $ha^{-1}$ of urea was applied at the time of corn planting. The corn crop was harvested at the time of physiological maturity.

Simulation of daily extractable soil water was run for the period June 1 to September 15, starting in 1990 and ending in 2019. Each year was run individually, and all 30 years of data were averaged across months to determine the average extractable soil water each month. The average, standard deviation, median, minimum, maximum, and range was calculated for the number of days in each month over the 30 years where extractable soil water was less than 40, 20 and 10 mm.

**Data Analysis**

Data were analyzed using estimation and statistical inference for generalized linear mixed models (Proc GLM) in SAS 9.3 (SAS Institute, Cary, NC). Replicate and environment combinations were considered random effects, while cover crops, application method, sowing timing, and corn removal were fixed effects when combined across environments. The protected *F*-test at $\alpha$=0.05 was used to determine significance. If there were significant interactions, the Least Significant Difference (LSD) method was used to separate means at the same level of probability.

# RESULTS AND DISCUSSION

## Weather Data

Spring snow melt, precipitation, and temperature were determinates for when corn, soybeans and cover crops could be planted. In 2018, corn was planted the beginning of May; whereas in 2019 wet spring conditions delayed corn planting until mid-May. Since cover crops were planted in relation to corn growth stages, cover crops were planted in mid-June and mid-August in 2018 and early-July and late-August in 2019.

Casselton and Hickson, 2018

In 2018, the growing season for Casselton, ND started out warmer and drier than normal in May and June but was cooler than normal in July, August, and September. Corn planting and emergence at Casselton occurred during a dry period. The weather conditions early in the growing season caused reduced corn emergence of 72 600 plants $ha^{-1}$ since the site only received a total of 10 mm one week after planting (Figure 1). Casselton received a total of 415 mm of rainfall throughout the entire corn growing season, which was 45 mm below normal. (Figure 1).

Hickson, ND also started out warmer and drier than normal in May but in June temperatures were above normal with above normal precipitate (Figure 1). July, August, September, and October were cooler than normal. Rainfall was above normal for the majority of the growing season except for May and September at Hickson. Similar to Casselton, this site received 9 mm one week after planting, resulting in poor corn emergence (66 000 plants $ha^{-1}$) (Figure 1). One month after corn planting Hickson received only 29 mm and a total of 505 mm of rainfall throughout the entire growing season, which was 30 mm above normal (Figure 1).

Cover crops were planted at the V7 corn growth stage on 15 June and the R4 corn growth stage on 15 August, 2018. Timely rains are critical for cover crop emergence for both early and late plantings. In North Dakota, August and September tend to be drier months so it is critical to receive timely rains for the late planting. Both early and late planting dates received timely rains within one week of cover crop planting at both locations, so soil moisture did not negatively impact cover crop germination.

Cover crops established in 2018, except for the area harvested in the fall, were allowed to grow until they were terminated in the spring on May 14. Throughout the winter, the coldest months were January and February with an average temperature of -15 and -19˚C, respectively. Since it remained cold in January and February, we did not lose snow cover, which help reduce winter-kill of the cover crops. Camelina that was planted early or grew out of the rosette stage did not overwinter. It was not until the middle of April, when the average daily temperature remained above 0˚C, breaking the cover crop dormancy.

Hickson and Prosper, 2019

In 2019, planting was delayed for roughly two weeks compared with normal due to wet field conditions in the spring. Although minimal amounts of rainfall occurred prior to corn planting, there was excess moisture due to the late and rapid snow melt at both locations. The corn crop at both locations received timely rains after planting as there were five rain events within a 7-d period following corn planting. Corn at Prosper received wind or hail damage on or around 8 July, reducing total leaf area.

Rainfall was below normal in May and June and above normal from July through October at Hickson. This site had the greatest amount of rainfall in July (136 mm) and a total of 515 mm throughout the entire season, which was 40 mm above normal (Figure 1). The early cover crop planting (2 July) received timely rains within 3 days after planting (Figure 1). Within one week after planting the site had already received 98 mm of rainfall. There were noticeable stand losses in the camelina plots at Hickson resulting in a plant population of 166 plants $m^{-2}$. The early planted cover crops received a total of 377 mm of rainfall throughout their growing season (Figure 1). The cover crops planted at the R4 corn growth stage on 30 August, also received timely rains (13 mm) within a week after planting. The cover crops planted later at Hickson received a total of 171 mm of rainfall throughout their growing season (Figure 1).

For Prosper, the months of June, July, and September were warmer than normal (Figure 1). Except for May, the rest of the growing season at Prosper had above normal precipitation. July and September received the largest amount of rainfall, 156 and 148 mm, respectivley (Figure 1). Prosper received a total of 665 mm of precipitation from May through October which was 206 mm above normal (Figure 1). Prosper had multiple days throughout the growing season where the soil was saturated. Although not significantly different, corn yield at Prosper was 12.6 Mg $ha^{-1}$ compared with 14.0 Mg $ha^{-1}$ at Hickson in 2019 (Table 5). The saturated soils did negatively affect initial camelina plant populations for both planting times, but rye and radish had similar populations compared with the other three environments (Table 7).

Prosper received 128 mm of precipitation within one week after the V7 cover crop planting. This amount of rain in a short period of time affected cover crop emergence and initial populations for plots where camelina was planted (56 plants $m^{-2}$). The earlier planted cover crops at Prosper received a total of 483 mm of precipitation and the later-planted cover crops received 225 mm (Figure 1). Around 10 October, there were roughly five days in a row where temperatures were at or below freezing, eventually terminating the season.

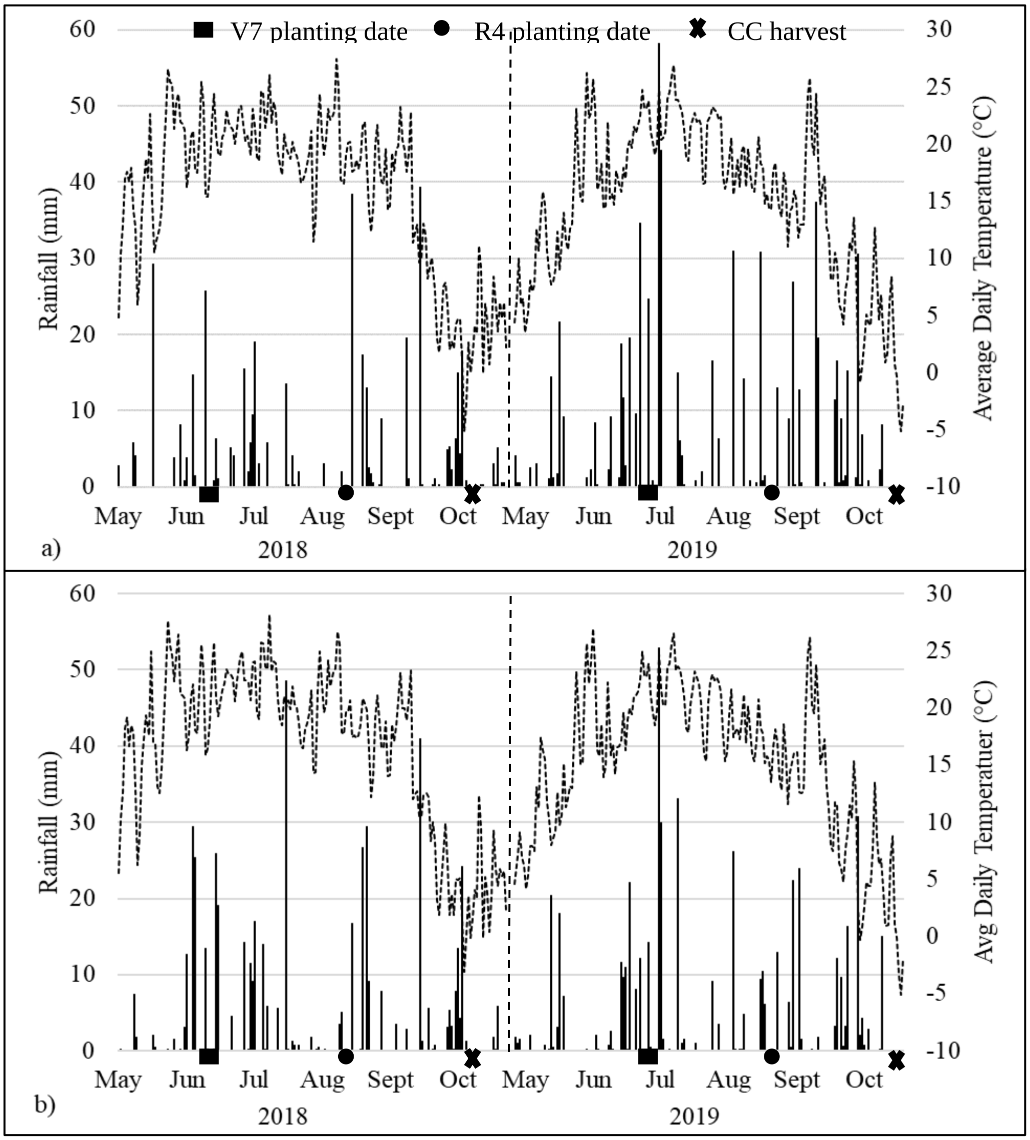


Figure 1. Average daily temperature and daily rainfall at a) Prosper, ND and b) Sabin, MN weather stations from 1 May to 31 October, 2018 and 1 May to 31 October, 2019.

## Available In-Season Soil Water Content

Throughout the season, soil water content (SWC) was determined in the top 7.6-cm of the soil, the zone considered critical for cover crop establishment. These measurements were taken every two weeks, unless the soils were saturated due to a recent rain event. The frequency of rain events and amount of rain received determined responses in SWC values, especially in the top 7.6-cm of the soil.

In 2018, the SWC showed greater differences due to the time between rain events and the amount of precipitation received. Soil water content throughout the growing season ranged from 110 to 270 g $kg^{-1}$ for the early planted cover crops and 140 to 270 g $kg^{-1}$ for the later planted cover crops (Figure 2). Alternatively, 2019 had more rain events producing greater amounts of precipitation so the SWC trend showed a gradual increase. The SWC in 2019 for the earlier planted cover crops ranged from 230 to 290 g $kg^{-1}$. The SWC for the later planted cover crops had a shorter sampling period compared with 2018 due to saturated field conditions, but it was evident that SWC was highest in 2019, ranging from 270 to 300 g $kg^{-1}$ (Figure 2).

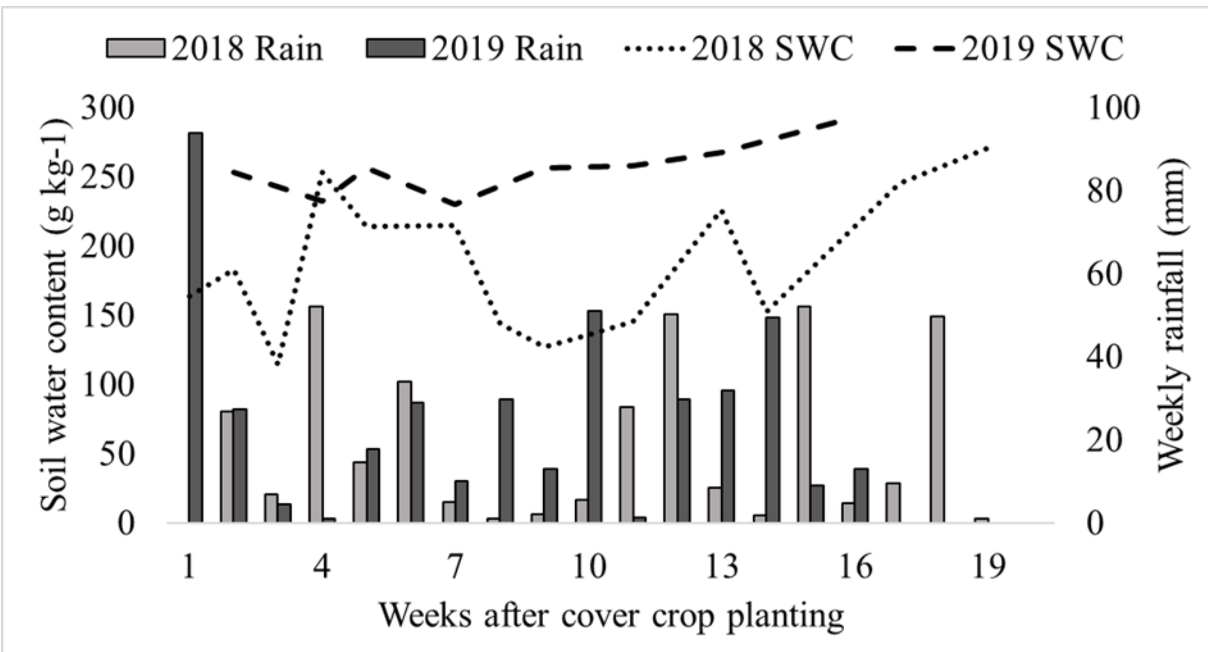


Figure 2. Soil water content (SWC) for interseeded cover crops interseeded at the V7 and R4 (week 8) corn growth stage throughout the 2018 and 2019 growing seasons. Soil cores were taken at a depth of 7.6 cm to measure gravimetric soil water content. Cover crops were planted on 15 June and 2 July for the V7 corn growth stage in 2018 and 2019, respectively. Cover crops were planted on 15 August and 30 August for the R4 (week 8) corn growth stage in 2018 and 2019, respectively.

Comparing the SWC and photosynthetically active radiation on cover crop growth, it is evident that available light had a greater impact on cover crop growth than soil moisture. The 2018 growing season had less precipitation than 2019, but both growing seasons had similar percent ground cover when cover crops were interseeded into corn at the V7 growth stage (Figure 2 and 3). Although light reaching the cover crops may be the limiting factor, adequate SWC was important for carrying the cover crops through the rest of the growing season, especially under the corn canopy.

## Cover Crop Plant Density

### Initial Cover Crop Plant Density

Cover crop seed size impacted the amount of seeds planted at the desired seeding rates. Since camelina is a smaller-seeded cover crop, 1.2 million seeds $ha^{-1}$ were planted at the 7.8 kg $ha^{-1}$ seeding rate compared to 450 000 and 250 000 seeds $ha^{-1}$ for rye and radish planted at 40 and 7.8 kg $ha^{-1}$, respectively. The amount of seeds planted for camelina can be attributed to the differences in initial plant density compared to rye and radish (Table 5). Rye mechanically planted at the early planting date was the only treatment that had similar initial plant density to camelina (Table 5). Other than that, camelina had higher plant densities compared with the other treatments, due to the higher amount of seeds planted.

Planting method did impact initial plant densities for the early planting of rye and radish cover crops. Both rye and radish had higher plant densities when mechanically planted at the V7 corn growth stage (Table 5). For all cover crop treatments, there was no difference in planting method for the later planting date (Table 5). Rye was the only cover crop that had different initial plant densities when comparing planting date for each cover crop species when broadcasted (Table 5). Whereas, mechanically planted camelina was the only cover crop that had different initial plant densities when comparing planting dates (Table 5).

Table 5. Planting method and cover crop species effect on initial cover crop density and cover crop density at harvest for the V7 and R4 planting dates combined across Casselton and Hickson in 2018 and Hickson and Prosper in 2019.

| | | Cover crop plant density | | | |
|---|---|---|---|---|---|
| | | Broadcast | | Mechanical | |
| Plant density | Cover crop | V7 | R4 | V7 | R4 |
| | | - - - - - - - - - - - - plants $m^{-2}$ - - - - - - - - - - - - | | | |
| Initial | Rye | 43 | 125 | 114 | 137 |
| | Camelina | 199 | 264 | 198 | 291 |
| | Radish | 24 | 57 | 63 | 78 |
| $LSD_1$† | 37 | | | | |
| $LSD_2$‡ | 106 | | | | |
| $LSD_3$§ | 70 | | | | |
| Harvest | Rye | 26 | 95 | 51 | 90 |
| | Camelina | 43 | 198 | 38 | 219 |
| | Radish | 8 | 39 | 18 | 55 |
| $LSD_1$† | 22 | | | | |
| $LSD_2$‡ | 65 | | | | |
| $LSD_3$§ | 57 | | | | |

† $LSD_1$ compares planting methods within cover crop species and planting date at $p \leq 0.05$.
‡ $LSD_2$ compares cover crop species within planting method and planting date at $p \leq 0.05$.
§ $LSD_3$ compares planting date within cover crop species and planting method at $p \leq 0.05$.

It is important to mention that environmental conditions did impact initial plant densities for both planting dates. The reduced plant density for the early planting could be attributed to a dry period during cover crop emergence in Hickson in 2018 and excessive rainfall in a short amount of time in the 2019 environments. Excess moisture in the seedling stage, like was observed at the V7 planting date, can result in fast imbibition, which can damage the membranes of the small camelina seedlings planted at the V7 planting date (Pereira, et al., 2013). Towards the end of the growing season the surviving plant density were reduced due to waterlogging in 2019, especially at Prosper (data not shown). Reductions in plant populations at Prosper for the later planted cover crops, can be attributed to saturated soils most of the time following planting.

The interaction of cover crop species and whether they were interseeded or grown without corn on plant density was significantly different at $p \leq 0.05$. Camelina that was interseeded and grown without corn had a higher plant density compared with rye and radish for both interseeded and corn removed treatments (Table 6). Again, camelina had a higher initial plant density due to the higher amount of seeds planted compared with rye and radish. Also, camelina was the only cover crop species that had different initial densities when comparing interseeded and corn removed treatments (Table 6). It is possible that the lower initial plant density for camelina when grown without corn was attributed to the lack of protection. For example, in 2019 heavy rains occurred shortly after planting which could have caused fast imbibition, which can damage the membranes of the small camelina seedlings (Pereira, et al., 2013), especially when there is no corn to assist in water uptake.

Table 6. Removal of corn at the time of planting effect on initial cover crop plant combined across Casselton and Hickson in 2018 and Hickson and Prosper in 2019.

| | Initial plant density | |
|---|---|---|
| Cover crop | Interseeded | Corn removed |
| | plants $m^{-2}$ | |
| Rye | 109 | 100 |
| Camelina | 259 | 217 |
| Radish | 61 | 50 |
| | | |
| $LSD_1$† | 92 | |
| $LSD_2$‡ | 18 | |

† $LSD_1$ compares cover crop species within interseeded or corn removed treatments at $p \leq 0.05$.
‡ $LSD_2$ compares interseeded and corn removed treatments within cover crop species at $p \leq 0.05$.

Cover Crop Plant Density at Harvest

It is important to note that there were no differences in plant density when comparing interseeded and corn removed treatments. However, cover crop plant density at the time of harvest differed from one another depending on planting date and planting method. Camelina had higher initial plant densities when planted early compared with the other cover crops; however, at the time of harvest all the early planted cover crops had similar plant densities (Table 5). Specifically, the reduced plant densities for the early planted camelina can be attributed to hot temperatures throughout the summer months. Again, due to the amount of seeds planted and the length of the growing season, the later planted rye and radish had lower plant densities at harvest compared to the later planted camelina for both planting methods (Table 5).

Plant densities at harvest were impacted by planting method depending on cover crop species and planting date. The early planted rye had lower plant densities when broadcasted compared with mechanically seeding at the time of harvest (Table 5). This reduction in plant density at harvest could be due to the fact mechanically seeded rye at the early planting had higher initial plant density compared to the broadcast treatments.

Cover crop plant density at harvest did differ between planting dates within planting methods for rye and camelina. Radish was the only cover crop to have similar plant densities for both planting dates within each planting method. Camelina densities were lowest when planted early for both planting methods. Rye had similar plant densities for both planting dates when mechanically seeded; whereas the early planted treatments had lower plant densities when broadcasted (Table 5).

## Fall Cover Crop Biomass

Although it is essential to know the potential cover crops have when not interseeded in North Dakota, the focus of this research was to understand how well cover crops establish and grow when interseeded into a corn crop, using different planting methods, cover crop species, and planting dates. The method that is used to plant cover crop is important as it can improve seed to soil contact (Boyd and Van Acker, 2003; Wilson et al., 2013; Curran et al., 2018).

The length of the growing season and competition for light, moisture, and nutrients all played a role in cover crop growth and development. There was a significant interaction between the removal of corn plants at planting and planting date, planting method and planting date, and the removal of corn plants at planting and planting method for fall biomass at $p \leq 0.05$. The amount of cover crop N uptake measured in the fall was significantly different at $p \leq 0.05$ when comparing planting methods and the interaction between planting date and removal of corn plants at the time of planting.

Cover crops that were planted at the V7 corn growth stage without corn produced larger amounts of fall biomass compared with the early interseeded treatments (Table 7). However, there was no difference between corn removed and interseeded fall cover crop biomass for the later planting date (Table 7). Also, planting date did not impact interseeded fall cover crop biomass (Table 7). When corn was removed early in the season, the cover crops produced larger amounts of biomass compared to the later planting (Table 7). The cover crop treatments planted early without corn had an advantage of producing more biomass because of no corn competition and longer growing season, compared with the interseeded and later planted treatments.

Plant N uptake was measured in the above ground biomass in the fall. The analysis determined that plant N uptake corresponded with the amount of cover crop biomass produced. Like fall biomass, plant N uptake was highest for cover crops planted at the V7 corn growth stage without corn (Table 7). The early planted treatments had different amounts of N uptake when cover crops were interseeded or grown without corn (Table 7). The later planted cover crop treatments didn’t see any difference in the amount of N uptake when interseeded and grown without corn (Table 7). Within the interseeded cover crop treatments, planting date did not impact the amount of N uptake; whereas the early planted cover crop treatments had greater biomass and plant uptake compared with the later planted cover crops (Table 6 and 7).

Table 7. Removal of corn at the time of planting and planting date effect on fall cover crop biomass combined across Casselton and Hickson in 2018 and Hickson and Prosper in 2019.

| | | Fall cover crop biomass and N uptake | |
|---|---|---|---|
| | | Interseeded | Corn Removed |
| | | - - - - - - - - - - - - kg ha$^{-1}$ - - - - - - - - - - - - | |
| Fall Biomass | V7 | 76 | 3005 |
| | R4 | 85 | 603 |
| | $LSD_1$† | 1302 | |
| | $LSD_2$‡ | 900 | |
| | | - - - - - - - - - - - - kg ha$^{-1}$ - - - - - - - - - - - - | |
| Plant N | V7 | 25.3 | 67.3 |
| | R4 | 3.3 | 13.5 |
| | $LSD_1$† | 28.9 | |
| | $LSD_2$‡ | 24.0 | |

† $LSD_1$ compares interseeded and corn removed treatments within planting date at $p \leq 0.05$.
‡ $LSD_2$ compares interseeded and corn removed treatments within cover crop species at $p \leq 0.05$.

Planting method and planting date significantly impacted fall cover crop biomass at $p \leq 0.05$. When the cover crops were planted early, mechanically planted cover crops produced the greatest amount of fall biomass (Table 8) and plant N uptake (data not shown). Within the planting methods, the cover crops planted at the V7 corn growth stage produced greater biomass for both planting methods (Table 8). Noland et al., (2018) reported similar results where mechanically placed seed produced greater biomass than broadcast and broadcast with incorporation. Although cover crop planting depth was not measured in this study, Noland et al., (2018) found that mechanically planting cover crops achieved the better adequate planting depth and seed-to-soil contact than other mthods, resulting in greater fall biomass. The findings of others also support the idea that increased seed-to-soil contact improves cover crop establishment (Boyd and Van Acker, 2003; Wilson et al., 2013).

Table 8. Planting date and planting method effect on fall cover crop biomass combined across Casselton and Hickson in 2018 and Hickson and Prosper in 2019.

| | Fall biomass | |
|---|---|---|
| Planting date | Broadcast | Mechanical |
| | kg $ha^{-1}$ | |
| V7 | 1349 | 1732 |
| R4 | 322 | 366 |
| | | |
| $LSD_1$† | 224 | |
| $LSD_2$‡ | 582 | |

† $LSD_1$ value compares planting methods within planting date at $p \leq 0.05$.
‡ $LSD_2$ value compares planting date within planting method at $p \leq 0.05$.

## Light Interception and Cover Crop Green Cover

Light is essential for cover crop growth and development. To better understand how much light a corn canopy absorbs, photosynthetic active radiation (PAR) was measured at the top of the cover crop canopy. Of the variables measured in this study, light intensity was found to be the main limiting factor for interseeded cover crop growth; although moisture was essential for germination and rejuvenating cover crop growth once the corn canopy starts to open again after physiological maturity.

There was a drastic decline of percent green cover with complete canopy closure (Figure 3). Gallo et al., (1985) suggests that less than 20% of PAR reaches below the corn canopy to the cover crops from V12 to the R4 corn growth stage. Complete canopy cover occurred roughly 5 weeks after the cover crops were planted at the V7 corn growth stage.

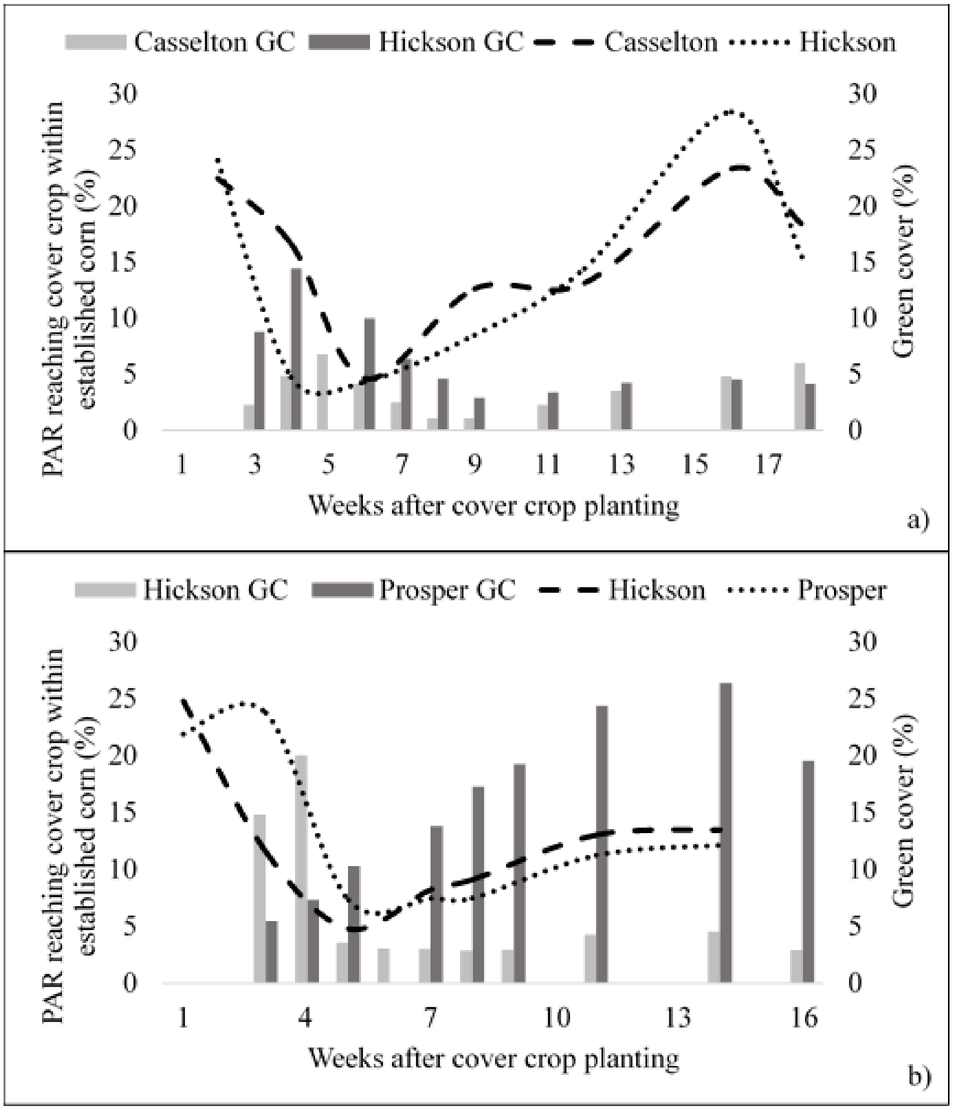


Figure 3. Cover crop percent green cover (GC) for cover crops planted at the V7 corn growth stage in relation to photosynthetically active radiation (PAR) reaching the cover crop canopy within the established corn at a) Casselton and Hickson, ND in 2018 and b) Hickson and Prosper, ND in 2019. The corn reached the R4 growth stage around week 8.

Cover crops planted at the V7 corn growth stage spent most of the growing season under a corn canopy that was intercepting greater than 80% of the available light. The later planted cover crops were planted when the corn canopy started to open and intercept less light, but less than 15% of light was reaching the soil surface at this time (Figure 3). Except for Prosper 2019, green cover had similar trends even though there were large differences in moisture between the two years (Figure 3). Since the leaf area index of corn at Prosper was reduced by hail/wind damage it allowed the cover crops to develop more biomass, prior to complete canopy closure. Roughly 8 weeks after cover crop planting and 3 weeks after complete corn canopy closure, percent green cover was lowest in all environments (Figure 3). Gradual increases in green cover occurred as the canopy opened, but only reached roughly 5% ground cover, except for Prosper that reached roughly 25% (Figure 3) with most of that cover being from radish (data not shown).

## Corn Yield

When combined across all environments there was no significant difference in corn yield between the three cover crop treatments. Berti et al. (2017) and Noland et al. (2018) suggests the V1-V6 corn growth stages of corn should be weed free, since the V7 cover crops were planted outside the weed free zone, there was no negatively affect corn yield. Also, cover crops planted at the V7 growth stage had no impact on corn yield as they had minimal biomass to be competitive. Geiszler and Ransom (2018) found similar lack of effect of cover crop on corn yield, for similar cover crop planting dates.

This study found a significant interaction between cover crop species and environments on corn yield. The differences in corn yield were not significantly different within environments, but exerted differences between environments. The lack of effect of cover crops on corn yield is probably due to the limited competitive effect of the intercropped cover crop.

Corn yield was lower in Hickson 2018 and Prosper 2019, compared with the other environments (Table 9). Both Hickson, 2018 and Prosper, 2019 locations began the corn growing season with environmental stress. In 2018, the Hickson location began the season dry and the corn did not receive rain in a timely manner after planting. Hickson only received a total of 29 mm within a month’s span after corn planting. Alternatively, in 2019 Prosper received hail and wind damage at the V7 corn growth stage, around 8 July (Figure 1). The hail damage reduced the amount of photosynthetic radiation uptake and canopy closure (Figure 3) due to damaged corn leaves, compared with other environments. Although Hickson 2018 and Prosper 2019 had different environmental stresses, both environments had similar yields (Table 9). Consistently, corn yield was not different between cover crop treatments within the environments (Table 9). Overall, differences in corn yield across environments can be attributed to various environmental weather conditions.

Table 9. Environment and interseeded cover crop species effect on corn yield combined across Casselton and Hickson 2018 and Hickson and Prosper 2019.

| | Corn Yield | | | |
|---|---|---|---|---|
| | 2018 | | 2019 | |
| Cover crop | Casselton | Hickson | Hickson | Prosper |
| | - - - - - - - - - - - - - - - Mg ha$^{-1}$ - - - - - - - - - - - - - - - | | | |
| Rye | 14.5 | 12.9 | 14.3 | 12.0 |
| Camelina | 14.6 | 12.0 | 13.3 | 12.9 |
| Radish | 14.2 | 12.2 | 14.3 | 12.8 |
| LSD† | 2.1 | | | |

† LSD value compares corn yield between environments and cover crop species at $p \leq 0.05$.

## Predicted Water Availability for Interseeded Cover Crops

Interseeding cover crops into corn is not a common practice due to the possibility of limited available soil water for the primary crop, especially in low rainfall areas (Unger and Vigil, 1998, Blanco-Canqui et al., 2015). Another concern with interseeding cover crops into corn is having enough soil water for cover crop emergence and growth. The APSIM model was used to estimate the amount of soil water available after corn water uptake and movement to lower soil profiles. Data were analyzed using weather from a 30-yr time span focusing on the period from 1 June to 15 September, when typically cover crops are interseeded during the growing season.

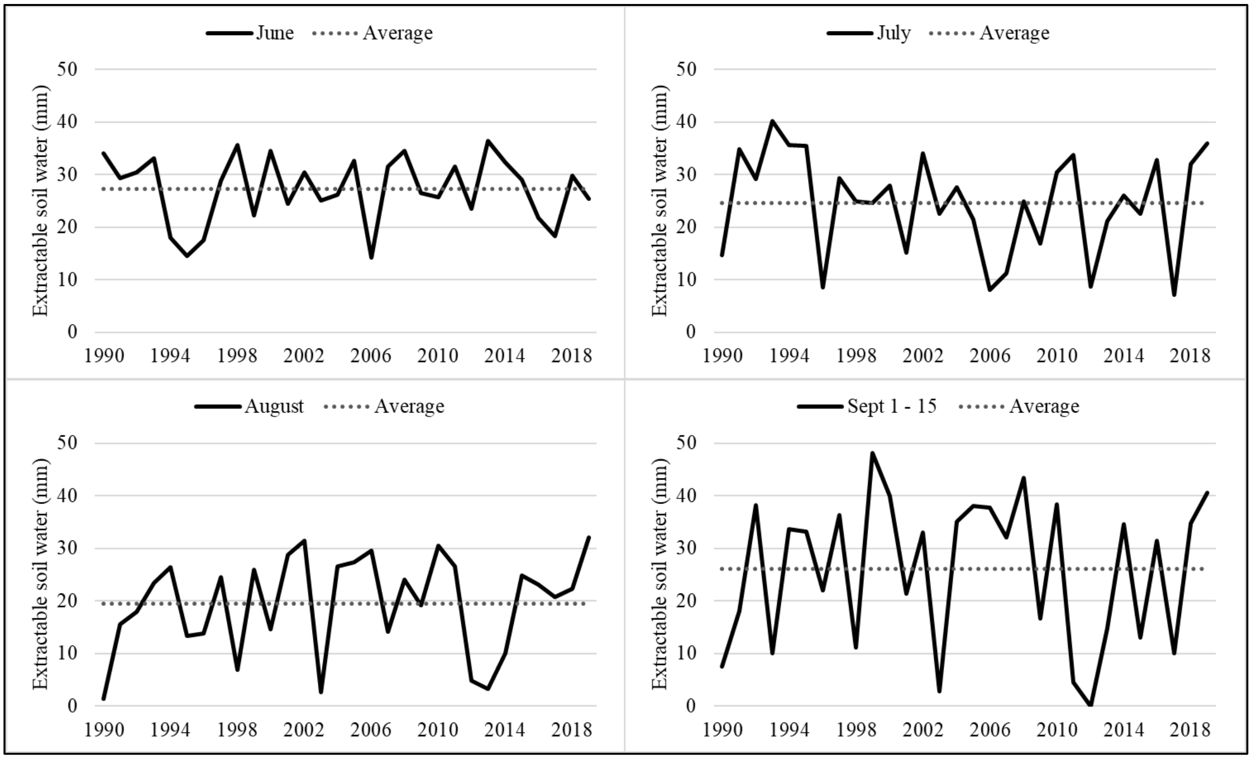


Figure 4. Extractable soil water trends and average extractable soil water (mm) for June, July, August, and 1 to 15 September, the typical interseeded cover crop growing season for North Dakota, over 30 years of weather data.

Based on APSIM output, interseeding cover crops into corn in June can give the cover crops the best opportunity to emerge, develop, and extract the largest amount of soil water. On average, there is 27 mm of extractable soil water when cover crops are interseeded at the V7 corn growth stage (Figure 4). Over the 30-years of weather data, there were only 9 days on average in the month of June where soil water is < 20 mm.

The month of August tends to have reduced precipitation in North Dakota and according to the model, there is an average of 9 days with less than 10 mm of extractable soil water (Table 10). Comparing all months, August has the lowest average of extractable soil water with only 19.5 mm. Within the first 15 days of September, extractable water increases to 26 mm. This suggests that if the cover crops planted at the R4 growth stage, typically around 15 August, receives a timely rain event for establishment, extractable soil water will typically increase beginning in September.

Table 10. Summary statistics for number of days with less than 40- 20- and 10 mm of extractable soil water averaged across 30 years of weather data for interseeded cover crops in corn within June, July, August, and 1 to 15 September using the Agricultural Production Systems Simulator.

| | Extractable soil water averaged across 30 years | | | | | |
|---|---|---|---|---|---|---|
| Month | Average | St. Dev. | Median | Min | Max | Range |
| | | | Days with <40 mm | | | |
| June | 27 | 3 | 27 | 21 | 30 | 9 |
| July | 28 | 3 | 29 | 22 | 31 | 9 |
| August | 29 | 2 | 30 | 23 | 31 | 8 |
| 1-15 September | 13 | 3 | 13 | 6 | 15 | 9 |
| | | | Days with <20 mm | | | |
| June | 9 | 8 | 8 | 0 | 28 | 28 |
| July | 11 | 10 | 8 | 0 | 31 | 31 |
| August | 16 | 10 | 16 | 0 | 31 | 31 |
| 1-15 September | 5 | 6 | 3 | 0 | 15 | 15 |
| | | | Days with <10 mm | | | |
| June | 1 | 2 | 0 | 0 | 6 | 6 |
| July | 5 | 7 | 0 | 0 | 24 | 24 |
| August | 9 | 10 | 6 | 0 | 31 | 31 |
| 1-15 September | 3 | 5 | 0 | 0 | 15 | 15 |

Overall, interseeding cover crops into corn in the month of June has the best chance of having sufficient soil water to germinate and establish. Extractable soil water in July is 25 mm, so cover crops planted in June typically will have enough soil water to carry them through corn canopy closure, but the month of August creates challenges. Since August typically has 16 days below 20 mm and 9 days below 10 mm of extractable water, it makes it very difficult to stablished interseeded cover crops at the R4 corn growth stage or carry the early planted cover crops through the rest of the season. These data suggest that there is a relatively high frequency of seasons when soil moisture could constrain cover crop establishment in August.

## Spring Cover Crop Production

Cover Crop Plant Density

Spring rye and camelina plant density was reduced compared with their plant density at fall harvest. Radish is a cover crop that does not overwinter, so all radish plants were winter killed. However, rye and camelina spring plant density was not different compared across all treatments. Although not significant, camelina planted at the V7 corn growth stage had the lowest plant density, 3 plants $m^{-2}$, compared with both early and late planting dates for rye, 25 and 54 plants $m^{-2}$, respectively, and the later planted camelina, 61 plants $m^{-2}$. Berti et al. (2017) found similar results where the earlier planted camelina loses its winterhardiness if it is exposed to summer heat. Again, focusing on the interseeded treatments, there was no difference between rye and camelina plant density, 33 and 35 plants $m^{-2}$.

Cover Crop Biomass

Cover crops that were grown in 2018 were carried through the winter and terminated in May 2019. Cover crops were terminated in the spring in hopes for more cover crop growth and biomass to be able to improve soil properties and increase water uptake, which might enable entrance into the fields earlier in the spring. Spring cover crop biomass was less, compared with fall biomass for interseeded and corn removed treatments. Interseeded treatments were 5 kg $ha^{-1}$ less and biomass where the corn was removed was 1335 kg $ha^{-1}$ less (Data not shown).

Spring cover crop biomass was impacted by planting date and whether the cover crops were interseeded or grown without corn. There was an interaction between species when compared within planting time and interseeded or corn removed treatments (Table 11). Spring biomass was different between rye and camelina when planted at the V7 corn growth stage without corn (Table 11). The early planted camelina without corn had lower spring biomass than the rye treatment because camelina struggled with the summer heat, which reduced its winter hardiness. Comparing planting date and whether the cover crops were interseeded or grown without corn within cover crop species there was no differences (Table 11).

Table 11. Planting date and the effect of removal of corn at planting on cover crop spring biomass combined across all locations.

| | Spring cover crop biomass | | | |
|---|---|---|---|---|
| | Interseeded | | Corn removed | |
| | V7 | R4 | V7 | R4 |
| | kg ha$^{-1}$ | | | |
| Rye | 53 | 110 | 815 | 743 |
| Camelina | 36 | 117 | 11 | 313 |
| | | | | |
| $LSD_1$ | 421 | | | |
| $LSD_2$ | 1326 | | | |

† $LSD_1$ compares cover crop species within planting date and interseeded or corn removed columns at $p \leq 0.05$.
‡ $LSD_2$ compares planting date within cover crop species and interseeded or corn removed columns at $p \leq 0.05$.

Cover crop spring biomass was impacted by planting method. There was no difference between planting methods for each cover crop species. However, when comparing cover crop species within a planting method, there was a difference in spring cover crop biomass (Table 12). Rye produced higher biomass compared to camelina for both broadcast and mechanical treatments (Table 12). Overall, broadcast and mechanical planting methods did not affect the production of spring cover crop biomass.

In the spring we had reduced cover crop plant density and biomass, so it was difficult to attain all N uptake measurements. Specifically, due to reduced camelina plant density for the early planted treatments, N uptake could not be measured due to inadequate sample size for the NIR machine. However, from the treatments where there was enough biomass to measure N uptake, there were no differences across all cover crop treatments (Data not shown). Due to minimal biomass, the amount of N uptake was minimal for all cover crop treatments. Specifically, rye grown without corn had the greatest N uptake (13 kg N $ha^{-1}$) compared with interseeded rye and camelina treatments (2.7 kg $ha^{-1}$). It should be noted that N uptake was measured from the above ground biomass so it is possible more of the N would be stored in the cover crop roots.

Table 12. Planting date and the effect of removal of corn at planting on cover crop spring biomass combined across all locations.

| | Spring cover crop biomass | |
|---|---|---|
| Cover crop | Broadcast | Mechanical |
| | kg $ha^{-1}$ | |
| Rye | 328 | 532 |
| Camelina | 106 | 133 |
| $LSD_1$ | 445 | |
| $LSD_2$ | 10 | |

† $LSD_1$ compares planting method within cover crop species at $p \leq 0.05$.
‡ $LSD_2$ compares cover crop species within planting method at $p \leq 0.05$.

Spring Soil Data

***Soil Nitrate***

There were no differences between treatments in N in the top 15-cm of soil when combined across environments. Although not significantly different, cover crop N residual for radish was 10.2 kg $ha^{-1}$, and camelina and rye were 4.8 and 6.7 kg $ha^{-1}$, respectively. Cover crops planted early with corn removed had soil N levels of 22.3 kg $ha^{-1}$, and the other treatments ranged from 4.6 to 9 kg $ha^{-1}$ of soil N. The early planted cover crops when corn was removed had the highest spring soil N levels. This can be attributed to no corn growth and the early planted cover crops not over wintering. Overall, soil N levels were minimal for all treatments.

***Soil Water Content***

There were no significant differences across all treatments for spring soil water content. Studies have shown rye can deplete soil water, especially when there is measurable accumulation of biomass (Hartzler, 2014; Martinez-Feria et al., 2016). Our results did correspond with Hartzler (2014) and Martinez-Feria et al. (2016), who found rye planted without corn produced the greatest amount of spring biomass (Table 13) but there was no difference in the amount of spring soil water content compared across all treatments. In this study, it was beneficial that rye had good water uptake, since it was a wet spring and the following soybean crop ended up having the greatest yield following rye.

Table 13. Cover crop planting date relative to corn growth stage and cover crop species effect on spring gravimetric water content for Casselton and Hickson, ND, 2019.

| | Spring gravimetric water content | | | |
|---|---|---|---|---|
| | Casselton | | Hickson | |
| Cover Crop | V7 | R4 | V7 | R4 |
| | - - - - - - - - - - g kg$^{-1}$ - - - - - - - - - - | | | |
| Rye | 233 | 218 | 231 | 232 |
| Camelina | 241 | 223 | 249 | 244 |
| Radish | 242 | 225 | 248 | 252 |

† No significant differences between means

## Soybean Yield Following Cover Crops

Soybean planting was delayed due to wet soil conditions in 2019. Soybeans were planted on 17 May in Casselton and on 3 June in Hickson. Not only was Hickson planted late, soil conditions were wet at the time of planting so the closing wheels on the planter were unable to close the furrow, resulting in poor soybean stands. At Casselton, soybean plant density was low due to high levels of residue and poor planting conditions. Soybean plant density at Casselton and Hickson were 110 000 and 190 000 plants $ha^{-1}$, respectively, although the target plant population was 432 000 plants $ha^{-1}$.

Environmental factors negatively affected soybean yield. Since the soybean populations were roughly one quarter of our planting rate, yield was dramatically reduced. This could be due to the amount of corn stalk and cover crop residue covering the ground, which kept the soils cool and moist in a wet spring, negatively effecting soybean planting. Yields were roughly 6.6 and 3.7 Mg $ha^{-1}$ for Casselton and Hickson, respectively (Data not shown).

Soybean yields at Hickson were favored when the cover crop did not overwinter, there was no corn grown prior, and residue was minimal. For example, radish has a low C:N ratio, the large amounts of fall biomass decomposed quickly, which left a more ideal seed bed for soybean planting the following spring (Lawley et al., 2011). Although Hartzler (2014) suggests rye could reduce the following crop's yield due to depleting the soil water, we did not see those results in this study. Davis (2010) found that, although soybeans were planted late, yields were greatest following rye treatments; however, for this study the cover crops did not produce enough spring biomass to significantly impact soil water content. Overall, the poor field conditions at soybean planting hindered soybean yield. Due to poor planting and growing season conditions, we are not confident with the soybean production results for this study.

## CONCLUSION

Based on literature review, cover crops can benefit a corn-soybean crop rotation by reducing soil erosion, increasing soil organic matter, and retaining soil water. However, challenging planting conditions and short growing seasons may impact the adoption of cover crops in a corn-soybean crop rotation. Interseeding cover crops into corn can give cover crops a chance to establish and have a longer growing season, when compared with planting them following corn harvest.

Cover crop seed size varied between the three species, so camelina had roughly 1.2 million seeds planted at the 7.8 kg $ha^{-1}$ seeding rate, whereas rye and radish had 450 000 and 250 000 seeds planted at the 44.8 and 7.8 kg $ha^{-1}$ seeding rate, respectively. Initial cover crop plant densities were impacted by the amount of seeds planted. Since camelina had a higher amount of seeds planted, it had significantly higher initial plant densities compared with rye and radish. However, at the time of harvest, camelina that was planted at the V7 corn growth stage had a similar plant density compared with rye and radish. Camelina struggled to survive through the summer heat, compared with the other cover crops. Also, the later planted cover crops had a higher plant density compared with the early planted cover crops at the time of fall harvest.

Light and soil moisture competition did impact cover crop growth when interseeded into corn. The interseeded cover crop fall biomass was drastically less compared with the corn removed treatments. It was determined that although planting cover crops early in the season gave the cover crops a longer growing season, fall biomass was not different between the two planting dates. Mechanical planting did have higher fall biomass for the early planted cover crops but planting method had no effect on fall biomass for the later planted cover crops.

Photosynthetically active radiation absorption rapidly increased from roughly 50 to 90% between the V7 and V12 corn growth stages and remained higher than 80% until the dough stage of grain fill. The amount of photosynthetically active radiation reaching below the corn canopy to the cover crops was the limiting factor for interseeded cover crop growth, even when there was adequate soil water moisture. Corn yield was different between environments but cover crop species did not impact corn yield within the environments. Since there was minimal cover crop biomass produced, corn yield was not affected by interseeding cover crops regardless of the planting date, planting method, or cover crop species.

According to the APSIM, moisture should be adequate if cover crops are planted in June. However, cover crop establishment can be hindered by dry conditions and large amounts of corn water uptake in August. According to the model, half the days in August will have less than 20 mm of extractable moisture. Also, 11 out of the 30-years were below the average extractable moisture.

Spring cover crop production was reduced compared with fall production. Camelina that was planted at the V7 corn growth stage had the lowest plant density and spring biomass, due to lack of winter survival. Rye plant density and biomass did decrease, but rye seemed to be a hardier plant compared with camelina. Interseeded spring biomass was reduced by 5 kg $ha^{-1}$, whereas cover crop biomass where the corn was removed decreased by 1335 kg $ha^{-1}$ compared with fall biomass. There was no difference in spring biomass for all interseeded treatments and rye grown without corn produced the highest amount of spring biomass.

Soybean production following the cover crops was impacted by environmental conditions. Although not confident on the results, poor soybean production can possibly be attributed to the amount of corn residue, wet spring conditions, poor plant and growing season conditions.

Overall, planting method did not impact the success of cover crop growth. Although interseeding cover crops early in the growing season gives them a longer growing season, there was no benefit in cover crop production compared with planting later in the growing season. Since interseeding cover crops into corn reduces the amount of biomass cover crops can produce and the minimal amounts of cover crop biomass produced does not improve soil conditions, interseeding cover crops in corn is not recommended in a corn-soybean rotation in the northcentral plains of North America.

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## APPENDIX

Table A1. Sources of variation, degrees of freedom, and levels of significance for the ANOVA of cover crop production for 4 environments in 2018 and 2019.

| Source of variation | df | ID | Pr>F | HD (X10e4) | Pr>F | df | FB (X10e6) | Pr>F | df | Plant N | Pr>F |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Planting date (PD) | 1 | 195318 | 0.05 | 52.24 | 0.01 | 1 | 101.47 | 0.01 | 1 | 31777.00 | 0.02 |
| Corn Removal (R) | 1 | 29034 | 0.02 | 0.11 | 0.39 | 1 | 212.43 | 0.02 | 1 | 37215.00 | 0.03 |
| PD x R | 1 | 377 | 0.68 | 0.01 | 0.93 | 1 | 103.11 | 0.01 | 1 | 14490.00 | 0.01 |
| Cover Crop (C) | 2 | 854564 | 0.01 | 21.89 | 0.02 | 2 | 3.45 | 0.18 | 2 | 3067.54 | 0.13 |
| PD x C | 2 | 18444 | 0.42 | 12.56 | 0.00 | 2 | 2.64 | 0.20 | 2 | 1403.25 | 0.28 |
| R x C | 2 | 7871 | 0.03 | 0.03 | 0.89 | 2 | 3.55 | 0.19 | 2 | 129.27 | 0.61 |
| PD x R x C | 2 | 653 | 0.46 | 0.23 | 0.44 | 2 | 2.27 | 0.29 | 2 | 36.50 | 0.93 |
| Planting Method (M) | 1 | 56465 | 0.04 | 0.76 | 0.15 | 1 | 3.15 | 0.02 | 1 | 696.88 | 0.01 |
| PD x M | 1 | 4993 | 0.03 | 0.00 | 0.99 | 1 | 2.09 | 0.04 | 1 | 164.59 | 0.34 |
| R x M | 1 | 393 | 0.72 | 0.07 | 0.30 | 1 | 2.24 | 0.07 | 1 | 425.04 | 0.27 |
| PD x R x M | 1 | 1 | 0.99 | 0.01 | 0.79 | 1 | 1.56 | 0.11 | 1 | 37.64 | 0.63 |
| C x M | 2 | 4946 | 0.40 | 0.01 | 0.64 | 2 | 0.32 | 0.38 | 2 | 109.28 | 0.52 |
| PD x C x M | 2 | 11342 | 0.01 | 0.50 | 0.05 | 2 | 0.42 | 0.45 | 2 | 88.87 | 0.80 |
| R x C x M | 2 | 1887 | 0.49 | 0.01 | 0.76 | 2 | 0.28 | 0.43 | 2 | 13.21 | 0.87 |
| PD x R x C x M | 2 | 511 | 0.56 | 0.01 | 0.91 | 2 | 0.61 | 0.32 | 2 | 26.49 | 0.85 |
| Env | 3 | 62730 | 0.49 | 3.67 | 0.44 | 3 | 7.90 | 0.53 | 3 | 6751.46 | 0.33 |
| rep(Env) | 8 | 757 | 0.96 | 0.10 | 0.53 | 8 | 0.77 | 0.09 | 8 | 727.93 | 0.06 |
| Env x PD | 3 | 19428 | 0.42 | 1.98 | 0.32 | 3 | 2.20 | 0.63 | 3 | 1330.00 | 0.57 |
| Env x R | 3 | 1584 | 0.97 | 0.11 | 0.93 | 3 | 8.43 | 0.27 | 3 | 2449.26 | 0.72 |
| Env x C | 6 | 65704 | 0.08 | 2.50 | 0.12 | 6 | 1.48 | 0.57 | 6 | 1176.44 | 0.73 |
| Env x M | 3 | 4750 | 0.62 | 0.20 | 0.76 | 3 | 0.17 | 0.83 | 3 | 32.45 | 1.00 |
| Env x PD x R | 3 | 1785 | 0.64 | 0.79 | 0.12 | 3 | 3.50 | 0.18 | 3 | 438.42 | 0.59 |
| Env x PD x C | 6 | 18497 | 0.02 | 0.77 | 0.12 | 6 | 1.24 | 0.58 | 6 | 966.65 | 0.49 |
| Env x PD x M | 3 | 332 | 0.95 | 0.11 | 0.49 | 3 | 0.18 | 0.72 | 3 | 118.88 | 0.83 |
| Env x R x C | 6 | 1107 | 0.80 | 0.23 | 0.52 | 6 | 1.60 | 0.43 | 6 | 246.62 | 0.81 |
| Env x R x M | 3 | 2464 | 0.66 | 0.04 | 0.63 | 3 | 0.29 | 0.69 | 3 | 229.61 | 0.83 |
| Env x C x M | 6 | 4603 | 0.27 | 0.03 | 0.88 | 6 | 0.28 | 0.64 | 6 | 136.09 | 0.87 |
| Env x PD x R x C | 6 | 742 | 0.53 | 0.25 | 0.05 | 6 | 1.46 | 0.09 | 3 | 462.84 | 0.39 |
| Env x PD x R x M | 3 | 2774 | 0.09 | 0.07 | 0.39 | 3 | 0.31 | 0.59 | 3 | 100.26 | 0.71 |
| Env x PD x C x M | 6 | 1119 | 0.35 | 0.10 | 0.24 | 6 | 0.45 | 0.49 | 5 | 355.87 | 0.76 |
| Env x R x C x M | 6 | 2373 | 0.10 | 0.04 | 0.66 | 6 | 0.28 | 0.70 | 6 | 89.48 | 0.74 |
| Env x PD x R x C x M | 6 | 796 | 0.92 | 0.06 | 0.82 | 6 | 0.44 | 0.42 | 1 | 139.27 | 0.54 |
| Residual | 183 | 2452 | | 0.11 | | 182 | 0.44 | | 123 | 369.69 | |

†ID = Initial cover crop plant density. HD = Cover crop plant density at harvest. FB = Fall cover crop biomass. Plant N = Cover crop N uptake in fall.

Table A2. Sources of variation, degrees of freedom, and levels of significance for the ANOVA of spring cover crop production for 2 environments in 2019.

| Source of variation | df | TopN | Pr>F | BotN | Pr>F | TotalN | Pr>F | df | SD | Pr>F | SB (x10e2) | Pr>F |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Planting date (PD) | 1 | 333.1 | 0.28 | 2809 | 0.25 | 5077 | 0.26 | 1 | 44505.0 | 0.11 | 2024.01 | 0.51 |
| Corn Removal (R) | 1 | 817.0 | 0.29 | 3721 | 0.46 | 8025 | 0.41 | 1 | 311.8 | 0.31 | 36824.50 | 0.09 |
| PD x R | 1 | 430.6 | 0.11 | 9506 | 0.44 | 13983 | 0.40 | 1 | 1283.3 | 0.15 | 126.04 | 0.65 |
| Cover Crop (C) | 2 | 361.6 | 0.15 | 952 | 0.61 | 550 | 0.70 | 1 | 1239.8 | 0.34 | 23206.82 | 0.00 |
| PD x C | 2 | 138.4 | 0.24 | 3862 | 0.57 | 2608 | 0.62 | 1 | 5236.3 | 0.21 | 2364.13 | 0.16 |
| R x C | 2 | 355.3 | 0.18 | 409 | 0.63 | 3 | 0.99 | 1 | 625.3 | 0.14 | 22466.52 | 0.04 |
| PD x R x C | 2 | 83.4 | 0.45 | 500 | 0.50 | 719 | 0.43 | 1 | 110.5 | 0.73 | 1848.01 | 0.00 |
| Planting Method (M) | 1 | 0.1 | 0.98 | 8556 | 0.49 | 8510 | 0.51 | 1 | 1283.3 | 0.57 | 3222.48 | 0.19 |
| PD x M | 1 | 3.7 | 0.72 | 64 | 0.41 | 98 | 0.51 | 1 | 0.1 | 0.99 | 193.80 | 0.19 |
| R x M | 1 | 12.8 | 0.61 | 576 | 0.53 | 417 | 0.51 | 1 | 1197.1 | 0.33 | 4205.55 | 0.29 |
| PD x R x M | 1 | 11.7 | 0.74 | 6 | 0.73 | 35 | 0.74 | 1 | 1480.5 | 0.19 | 17.68 | 0.48 |
| C x M | 2 | 95.8 | 0.35 | 1259 | 0.46 | 2040 | 0.42 | 1 | 263.3 | 0.64 | 1877.97 | 0.01 |
| PD x C x M | 2 | 96.5 | 0.40 | 5007 | 0.44 | 6136 | 0.44 | 1 | 742.6 | 0.69 | 706.33 | 0.48 |
| R x C x M | 2 | 74.7 | 0.37 | 5021 | 0.47 | 6136 | 0.46 | 1 | 1917.1 | 0.30 | 958.87 | 0.12 |
| PD x R x C x M | 2 | 93.2 | 0.52 | 1191 | 0.59 | 1877 | 0.58 | 1 | 1060.0 | 0.34 | 775.21 | 0.50 |
| Env | 1 | 35.0 | 0.78 | 200256 | 0.15 | 205587 | 0.15 | 1 | 1060.0 | 0.71 | 2007.51 | 0.56 |
| rep(Env) | 4 | 13.6 | 0.86 | 56225 | <0.0001 | 57727 | <.0001 | 4 | 1406.3 | 0.07 | 1431.44 | 0.00 |
| Env x PD | 1 | 76.6 | . | 484 | 0.85 | 946 | 0.80 | 1 | 1480.5 | . | 2105.63 | 0.52 |
| Env x R | 1 | 189.1 | 0.74 | 2916 | 0.69 | 4590 | 0.69 | 1 | 90.1 | . | 787.76 | 0.60 |
| Env x C | 2 | 65.6 | 0.70 | 1473 | . | 1295 | . | 1 | 420.8 | . | 0.01 | 1.00 |
| Env x M | 1 | 47.8 | 0.90 | 8010 | . | 9296 | . | 1 | 2007.5 | . | 294.70 | 0.73 |
| Env x PD x R | 1 | 12.8 | 0.89 | 6642 | . | 7239 | . | 1 | 75.3 | 0.83 | 340.51 | . |
| Env x PD x C | 2 | 44.4 | 0.84 | 5171 | 0.50 | 4320 | 0.61 | 1 | 635.5 | 0.71 | 164.33 | . |
| Env x PD x M | 1 | 16.7 | 0.89 | 36 | 0.93 | 102 | 0.90 | 1 | 918.8 | 0.67 | 19.08 | . |
| Env x R x C | 2 | 79.0 | 0.95 | 682 | 0.84 | 303 | 0.92 | 1 | 29.3 | 0.88 | 98.82 | . |
| Env x R x M | 1 | 25.8 | 0.99 | 676 | 0.74 | 438 | 0.81 | 1 | 396.1 | 0.72 | 1017.90 | . |
| Env x C x M | 2 | 51.1 | 0.97 | 1056 | 0.86 | 1499 | 0.83 | 1 | 645.8 | 0.71 | 0.15 | . |
| Env x PD x R x C | 2 | 67.3 | 0.60 | 510 | 0.77 | 552 | 0.83 | 1 | 546.3 | 0.44 | 0.08 | 0.99 |
| Env x PD x R x M | 1 | 62.7 | 0.51 | 30 | 0.91 | 180 | 0.82 | 1 | 142.6 | 0.64 | 16.01 | 0.91 |
| Env x PD x C x M | 2 | 64.5 | 0.61 | 3886 | 0.30 | 4843 | 0.35 | 1 | 2635.5 | 0.23 | 612.06 | 0.54 |
| Env x R x C x M | 2 | 44.1 | 0.70 | 4514 | 0.27 | 5315 | 0.33 | 1 | 508.8 | 0.45 | 34.32 | 0.87 |
| Env x PD x R x C x M | 2 | 101.0 | 0.10 | 1699 | 0.40 | 2611 | 0.29 | 1 | 364.3 | 0.44 | 779.76 | 0.11 |
| Residual | 92 | | | | | | | | | | 298.38 | . |

† TopN = Spring soil N levels in top 0-15 cm. BotN = Spring soil N levels in bottom 15-61 cm. TotalN = Spring soil N levels in 0-61cm soil profile. SD = Spring cover crop plant density. SB = Spring cover crop biomass.

Table A3. Sources of variation, degrees of freedom, and levels of significance for the ANOVA of soybean production for 2 environments in 2019.

| Source of variation | df | Soybean density (X10e8) | Pr>F | df | Soybean yield | Pr>F |
|---|---|---|---|---|---|---|
| Planting date (PD) | 1 | 10.81 | 0.01 | 1 | 0.9 | 0.75 |
| Corn Removal (R) | 1 | 4.89 | 0.58 | 1 | 35.0 | 0.18 |
| PD x R | 1 | 6.01 | 0.05 | 1 | 1.6 | 0.18 |
| Cover Crop (C) | 2 | 8.76 | 0.83 | 2 | 1.3 | 0.89 |
| PD x C | 2 | 10.72 | 0.46 | 2 | 1.1 | 0.35 |
| R x C | 2 | 11.86 | 0.73 | 2 | 1.4 | 0.76 |
| PD x R x C | 2 | 9.82 | 0.55 | 2 | 1.3 | 0.81 |
| Planting Method (M) | 1 | 4.38 | 0.52 | 1 | 1.4 | 0.11 |
| PD x M | 1 | 1.89 | 0.82 | 1 | 0.3 | 0.72 |
| R x M | 1 | 0.03 | 0.97 | 1 | 0.1 | 0.59 |
| PD x R x M | 1 | 4.38 | 0.13 | 1 | 0.6 | 0.38 |
| C x M | 2 | 8.43 | 0.21 | 2 | 3.0 | 0.05 |
| PD x C x M | 2 | 1.72 | 0.86 | 2 | 1.8 | 0.40 |
| R x C x M | 2 | 22.01 | 0.37 | 2 | 8.8 | 0.08 |
| PD x R x C x M | 2 | 0.43 | 0.95 | 2 | 1.9 | 0.10 |
| Env | 1 | 2102.39 | 1.00 | 1 | 302.5 | 0.02 |
| rep(Env) | 4 | 9.11 | 0.50 | 4 | 10.5 | <.0001 |
| Env x PD | 1 | 0.00 | 0.99 | 1 | 5.3 | . |
| Env x R | 1 | 7.89 | 0.70 | 1 | 3.1 | . |
| Env x C | 2 | 41.65 | 0.64 | 2 | 10.3 | . |
| Env x M | 1 | 4.89 | 0.76 | 1 | 0.1 | . |
| Env x PD x R | 1 | 0.03 | 0.97 | 1 | 0.1 | 0.88 |
| Env x PD x C | 2 | 9.25 | 0.64 | 2 | 0.6 | 0.91 |
| Env x PD x M | 1 | 22.30 | 0.80 | 1 | 1.3 | 0.42 |
| Env x R x C | 2 | 31.44 | 0.39 | 2 | 4.3 | 0.56 |
| Env x R x M | 1 | 15.10 | 0.65 | 1 | 0.2 | 0.69 |
| Env x C x M | 2 | 2.23 | 0.88 | 2 | 0.2 | 0.91 |
| Env x PD x R x C | 2 | 12.19 | 0.40 | 2 | 5.2 | 0.04 |
| Env x PD x R x M | 1 | 0.18 | 0.90 | 1 | 0.3 | 0.38 |
| Env x PD x C x M | 2 | 10.45 | 0.44 | 2 | 1.2 | 0.15 |
| Env x R x C x M | 2 | 13.08 | 0.38 | 2 | 0.8 | 0.22 |
| Env x PD x R x C x M | 2 | 8.09 | 0.48 | 2 | 0.2 | 0.81 |
| Residual | 92 | 10.87 | | | | |

† Soybean density = Soybean plant density.

Table A4. Sources of variation, degrees of freedom, and levels of significance for the reduced ANOVA for corn yield, total spring soil N, and spring soil water content in 2018 and 2019.

| Source of variation | df | CY | Pr>F | df | SPN | Pr>F | df | SGW | Pr>F |
|---|---|---|---|---|---|---|---|---|---|
| Planting date (PD) | 1 | 0.02 | 0.92 | 1 | 1.8 | 0.85 | 1 | 9.42 | 0.46 |
| Cover crop (C) | 2 | 0.51 | 0.85 | 1 | 353.4 | 0.31 | 2 | 15.39 | 0.08 |
| PD x C | 2 | 0.82 | 0.36 | 1 | 63.1 | 0.29 | 2 | 0.94 | 0.11 |
| Env | 3 | 36.77 | 0.13 | 1 | 98.1 | 0.53 | 1 | 20.85 | 0.32 |
| rep(Env) | 8 | 12.35 | <.0001 | 4 | 123.1 | 0.01 | 4 | 3.22 | 0.35 |
| Env x PD | 3 | 2.12 | 0.11 | 1 | 29.0 | 0.40 | 1 | 7.38 | 0.01 |
| Env x C | 6 | 3.13 | 0.04 | 1 | 101.4 | 0.22 | 2 | 1.29 | 0.08 |
| Env x PD x C | 6 | 0.68 | 0.78 | 1 | 15.0 | 0.51 | 2 | 0.12 | 0.96 |
| Residual | 110 | 1.25 | | 56 | 33.5 | | 53 | 2.83 | |

† Cy = Corn yield. SPN = Spring cover crop plant N uptake. SGW = Spring gravimetric water content