COVER CROPS BENEFITS, NITROGEN CREDITS, AND YIELD EFFECTS IN MAIZE AND SUGARBEET IN THE NORTHERN GREAT PLAINS

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

DOCTOR OF PHILOSOPHY

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ABSTRACT

Fall-seeded cover crops (CC) provide soil coverage that prevents soil erosion and reduces NO_3-N leaching. It is believed N accumulated in CC biomass is available to the next crop. The main objective of this research is to determine if N in the CC biomass provides N to the next crop of maize (*Zea mays* L.) and sugarbeet (*Beta vulgaris* L.). Two experiments were conducted in Hickson and Prosper, ND from 2017-2019. Maize grain yield and quality and sugarbeet root yield and chemical composition of the root were evaluated after fall-seeded cover crops. Fall biomass was greater in radish (*Raphanus sativu*s L.) and oat (*Avena sativa* L.) than the other cover crops evaluated. Likewise, in the sugarbeet experiment, the check treatment (no CC) contained greater soil NO_3-N concentrations compared with all CC. Winter-hardy CC survived the winter and reduced gravimetric water content in the soil profile in comparison with winter-killed CC and the check. Winter camelina [*Camelina sativa* (L.) Crantz] and winter rye (*Secale cereale* L.) reduced maize grain yield compared with the check and other cover crop treatments. Winter camelina and winter wheat (*Triticum aestivum* L.) decreased sugarbeet stand establishment and root yield in Prosper and Hickson in 2018. The yield of both crops increased with increased N rate, but the N accumulated in the cover crops biomass did not make a difference in grain or root yield of either maize or sugarbeet, indicating there was no N cycling to the following crop in these experiments.

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CHAPTER 1. INTRODUCTION AND LITERATURE REVIEW

1.1. Introduction

The Midwest and northern Great Plains regions of the USA are the major crop production areas in North America. Maize (*Zea mays* L.) (30.5 million ha), soybean [*Glycine max* (L.) Merr] (30.2 million ha), wheat (*Triticum aestivum* L.) (9.7 million ha), and sugarbeet (*Beta vulgaris* var. *sachariffera* L.) (0.45 million ha) are the main crops in these regions. These crops together generate more than $85 billion dollars in revenue for the area (USDA-NRCS, 2019). A large part of this farmland is managed with conventional tillage, which leaves the soil uncovered a significant portion of the year, resulting in water and wind erosion. In the USA, soil erosion causes more than 1.7 billion tons of soil losses per year, with an average of 4.8 tons per hectare (USDA-NRCS, 2010). Soil loss negatively impacts soil fertility, organic matter, soil biodiversity, and physical soil properties, resulting in long-term economic losses and negative environmental impact (Mazzoncini et al., 2011).

Cover crops, defined as a temporary vegetative cover, provide soil protection when a cash crop is not growing. In the northern Great Plains, the adoption of no-till and the introduction of cover crops into the cropping system has improved long-term productivity (Mckay et al., 2002; Liebig et al., 2004). Cover crop growth forms a physical barrier at the soil surface and their roots help stabilize soil particles at and under the surface, greatly reducing wind and water erosion (Colazo and Buschiazzo, 2010; Blanco-Canqui et al., 2015; Marinari et al., 2015). It is estimated that losses to soil erosion may be decreased from 70 to 90 percent using cover crops mixtures (Kaspar et al., 2001a; Hartwig and Ammon, 2002). Soil compaction is reduced by deep-rooted cover crops, such as radish (*Raphanus sativus* L.). Taproots produce openings in the soil profile resulting in larger pore spaces, which promote water and oxygen movement (Oorts et al., 2006; Chen and Weil, 2010; Colazo and Buschiazzo, 2010; Lawley et al., 2011). Cover crop cereal mixtures may increase soil organic carbon ranging from 0.32 to 0.61 Mg ha^{-1} $year^{-1}$, improving physical, chemical, and biological soil properties (Mazzoncini et al., 2011; Poeplau and Don, 2015).

Cover crops have the ability to scavenge NO_3-N from the soil, thereby reducing leaching by 25 to 56%, depending on the cropping system, cover crop species, and environmental conditions (Dinnes et al., 2002; Salmerón et al., 2010; Teixeira et al., 2016; Alonso-Ayuso et al., 2018). Radish has the ability to produce more than 3.3 Mg ha^{-1} of dry matter per season, scavenging 50 to 170 kg N ha^{-1} (Dean and Weil, 2009; White and Weil, 2011; Couëdel et al., 2018b). Legumes also scavenge NO_3-N from the soil, and serve as a nitrate catch crop, servicing to reduce nitrate loss from leaching and/or denitrification (Tribouillois et al., 2016).

Cover crop benefits are multiple. In maize production, N credits from legumes increase grain yield adding N to the cropping system through biological N_2 fixation. Faba bean (*Vicia faba* Roth.), chickling vetch (*Lathyrus sativus* L.), forage pea (*Pisum sativum* L.), and hairy vetch *(Vicia villosa* Roth) provide soil N inputs ranging from 40 to 100 kg N ha^{-1} (Blanco-Canqui et al., 2015); however, the release of N to the subsequent crop is highly dependent on soil type and weather conditions (Frye et al., 1988; Büchi et al., 2015). Also, in maize, cover crops have been found to significantly decrease weed population, resulting in a decreased need for herbicide application and mechanical weed control intensity(Hartwig and Ammon, 2002).

In sugarbeet, cover crops have been found to increase soil organic matter and soil biological activity (Marinari et al., 2015), provide soil physical cover that results in decreased soil erosion (Etemadi et al., 2018; Keshavarz et al., 2018), and minimize surface water runoff (Laloy and Bielders, 2010). A significant benefit of cover crop growth in sugarbeet production is the protection they provide to sugarbeet seedlings from wind damage. Wind damage and subsequent reduction in stand is due to the orientation of young sugarbeet leaves those results in a 'helicopter' effect that twists the seedling stem and breaks it off below the growing point. In addition, blowing soil that skitters across the soil surface can 'sand-blast' young seedlings, also tearing the growing point away from the stem and causing death (Yonts et al., 2002). Cover crops have also been found to reduce sugarbeet impurities significantly, such as sodium, amino-N concentration, and potassium (Keshavarz Afshar et al., 2018)

Despite the many positive effects of cover crops, some problems with their introduction into cropping systems have been reported. Maize grain yield reduction of 10% was reported when cover crops were planted at the V3 stage because of early seedling competition (Reese et al., 2014). Late termination of winter rye before maize silage planting, can reduce maize biomass yield more than 4.5 Mg ha^{-1} due to reduced soil water content, early competition, and allelopathic effect (Krueger et al., 2011). Also, winter rye can be a green bridge for armyworm (*Mythimna unipuncta* Haworth), black cutworm (*Agrotis ipsilon* Hufnagel), and common stalk borer (*Papaipema nebris* affecting maize yield and grain quality (Dunbar et al., 2016). Optimum timing of cover crop termination is essential in sugarbeet because of the risk of yield and quality penalties. A yield reduction of 14 to 17 Mg ha^{-1} in maize has been reported if cover crop termination occurs later than the V2 stage (Keshavarz Afshar et al., 2018).

In North Dakota, wheat, maize, and sugarbeet face several challenges because tillage following these crops leaves the soil with a lack of coverage under conventional tillage management, increasing soil erosion rate and lowering subsequent crop yields. Cover crops and no-till increase sustainability in the cropping system, providing soil coverage, decreasing soil erosion, reducing NO_3-N leaching, and adding N credits into the systems. Moreover, it is crucial to evaluate and quantify these benefits in local conditions.

1.2. Objectives

Determine the N credits from fall-planted cover crops provided to maize and sugarbeet the following season and determine effect of these N credits on yield and quality parameters.

1.2.1. Specific objectives

a. Measured fall soil residue/cover crop coverage, biomass yield, quality, and N accumulation on aboveground biomass of cover crops established into spring wheat stubble previous to maize and sugarbeet crops
b. Determine soil NO_3-N in the fall after cover crops, in the spring before maize and sugarbeet planting, and after the cash crop harvest.
c. Determine the effect of faba bean, forage pea, and winter camelina on grain yield, seed quality, and total biomass in maize.
d. Determine the effect of winter camelina, radish, winter rye, winter wheat, and oat in root yield and quality parameters in sugarbeet.

1.3. Literature review

Conventional tillage and a crop rotation of sugarbeet, soybean, and sunflower (*Helianthus annuus* L.) leaves the soil uncovered, increasing the risk of soil losses through water and wind erosion. This cropping/tillage system in the Upper Midwest of the USA has resulted in an unsustainable farming model (Syswerda and Robertson, 2014). Conventional tillage has a negative long-term impact on physical, chemical, and biological soil properties, including increased soil bulk density and soil erosion rates, reduced soil organic matter, reduced soil biological activity, and generally reduced crop productivity (Mazzoncini et al., 2011). To achieve greater crop yields, many farmers in the USA have increased tillage, fertilizer rates, and crop protection chemical rates in a system known as conventional intensification of crop production.

The introduction of cover crops into the cropping system may maintain and rebuild soil quality in the Upper Midwest (Berti et al., 2019). The National Resources Conservation Service (NRCS) defines cover crops as grasses, legumes, and seasonal vegetative cover that reduce wind and water erosion, maintain or increase soil organic matter, reduce water degradation as a consequence of the excess of soil nutrients, suppress weed pressure, help to break pest cycles, improve soil water use efficiency, and minimize soil compaction (NRCS, 2014).

1.3.1. Cover crop benefits

Cover crop benefits are widely recognized, including their ability to reduce soil erosion, soil compaction, NO_3-N leaching, and increase soil organic matter, and soil carbon. If legumes are used as a cover crop, the system may introduce new N into the system through biological N_2 fixation. Also, cover crops may serve to suppress weeds and some diseases (Kaspar et al., 2001a; Snapp et al., 2005; Salmerón et al., 2010; Lawley et al., 2011; NRCS, 2011; Blanco-Canqui et al., 2015).

The USA agricultural census in 2017 showed that land in cover crops reached 6.28 million ha representing an increase of 49% in cover crop area compared with the 2012 USA census. In North Dakota, a similar positive trend was observed. Cover crop area in North Dakota was 163,605 ha in 2017, an increase of 89% over 2012. The best time to establish cover crops is after harvest of an early harvested crop such as wheat harvest. There are 3.13 million ha of wheat in North Dakota and additional acres of other early-harvested crops such as canola (*Brassica napus* L.), flax (*Linum usitatisimum* L.), or barley (*Hordeum vulgare* L.) that could support fall cover crop growth (SARE/CTIC, 2016; NASS, 2017).

1.3.2. Soil erosion

Soil erosion is one of the leading agricultural problems around the world. Soil losses impact chemical, biological, and physical soil properties, generally resulting in reduced crop productivity (Kagabo et al., 2013). Soil erosion is a natural process facilitated by water, wind, gravitation, and human activities (Patel, 2012). The efficacy of soil erosion prevention with cover crops is related to reducing soil detachment forces and transport through a physical soil biomass cover, and living roots (Kaspar and Singer, 2011).

The National Resources Conservation Service (NRCS) defines water erosion as the detachment and removal of soil material by water. There are different types of water erosion. Sheet erosion is defined as the process where the soil is removed uniformly from the soil surface. Inter-rill erosion is when soil is moved within the field boundary by raindrops when they strike uncovered soil. Rill erosion is where runoff cuts conspicuous channels into the soil surface (NRCS, 2001). Cover crop biomass intercepts raindrops, dissipating water impact force, and reducing inter-rill soil erosion (Kaspar and Singer, 2011). Consequently, cover crop biomass increases hydraulic resistance, decreasing water flow velocity (Brown, 1994). The use of cover crops such as winter rye and oat (*Avena sativa* L.) can also reduce rill erosion. Rye and oat reduced inter-rill erosion in 62 and 51% and rill erosion in 93 and 64% respectively, compared with no cover crop in a fine-loamy soil with slopes between 2.8 and 6.0% (Kaspar et al., 2001a)

Wind erosion is a natural process in which the wind moves soil particles from one place to another. Wind can move soil particles from the soil in three ways: surface creep, where large soil particles (0.5- to 2-mm) roll along the soil surface; saltation, when soil particles (0.05- to 0.5-mm) bounce along the surface, often hitting other soil particles which dislodges them and causes them to also move; and suspension, when soil particles (smaller than 0.1 mm) are suspended far above the soil surface and are carried away long distances (DERM, 2011). Conventional tillage in agriculture disturbs the soil, covers residues, and leaves the soil bare, increasing the risk of wind erosion. Suspended soil particles also contribute to atmospheric dust with negative environmental consequences on human health (Zhibao et al., 2000; Zhuang et al., 2015).

In the USA, about 90% of the wind soil erosion is concentrated west of the Mississippi River, and more than 60% is within the Great Plains (Ervin and Lee, 1994). Because of the topography in the relatively flat cropland, wind erosion is the most severe cause of soil losses in the northern Great Plains; these soil losses could reach values from 6 to 18 Mg ha^{-1} yr^{-1} in the most vulnerable areas (Hansen et al., 2012).

Cover crops provide a vegetative physical barrier on the soil surface, and help to hold soil particles through root growth, decreasing soil erosion by wind and water. The degree of soil erosion reduction depends on cover crop species and species mixtures, plant and root morphology, soil coverage, and biomass production (Blanco-Canqui et al., 2015). Soil cover and improved soil physical properties, such as increased aggregate stability, are important factors that reduce soil erosion (Colazo and Buschiazzo, 2010).

1.3.3. Nitrogen credits and scavenging

Adopting cover crops in a cropping system may enhance soil fertility through the scavenging of leachable N and/or adding N to the soil if legumes are included by their N_2 fixation (Dabney et al., 2007; Blanco-Canqui et al., 2015). The use of legume cover crops is a widely used practice that adds several benefits to farming systems (Fageria et al., 2005). The N contribution from legume cover crops to the cropping system is highly variable, and it has been reported to contribute with 50 to 200 kg N $ha^{-1}year^{-1}$ of which 5 to 95% of N was fixed from the atmosphere (Unkovich and Pate, 2000; Fageria et al., 2005; Blesh and Drinkwater, 2013). However, not all fixed N will be released to the subsequent cash crop. The mineralized N will be 50% or less, depending on weather and soil conditions (Dabney et al., 2007).

Austrian winter pea is an annual legume widely used as a cover crop on the USA East Coast and Europe (Chen et al., 2006; Holman et al., 2018). However, Austrian winter pea is gaining more attention in the Upper Midwest because of its potential to release N to the subsequent crop. In North Dakota, forage pea accumulated between 71.5 and 85 kg N ha^{-1} when planted by mid-August and harvested by mid-October (Samarappuli et al., 2014; Peterson et al., 2019; Andersen et al., 2020). Samarappuli et al. (2014) reported that the N fixed from the atmosphere was 14 kg N ha^{-1} out of the total 85 kg N ha^{-1} in the biomass, indicating pea took up the available soil N before it started fixing N_2 from the atmosphere.

Legume cover crops therefore also scavenge N and are highly dependent on environmental and soil conditions and rhizobium populations (Unkovich and Pate, 2000). Soil with high soil NO_3-N will decrease legume nodulation, resulting in soil N dependence (Waterer and Vessey, 1993).

Faba bean is another important annual cool-season legume, and it is considered the one with the highest biomass production potential among cool-season legumes. Some European cultivars can survive temperature as low as -15°C (Jensen et al., 2010), which is an important advantage for the Upper Midwest environments. In South Deerfield, MA, faba bean had an N accumulation between 67 and 193 kg N ha^{-1}. In Cass County, ND, several faba bean cultivars had a N accumulation ranging from 43.5 and 58.5 kg N ha^{-1} in the fall (August-October) (Andersen, 2019; Andersen et al., 2020). In Alaska, Sparrow et al. (1995) reported that forage pea and faba bean soil N uptake was 57 kg N ha^{-1} and 49 kg N ha^{-1}, respectively.

Nitrate (NO_3^-N) leaching is the primary source of N losses in agriculture (Robertson and Vitousek, 2009; Zhou et al., 2012), representing more than 19% of the total N applied to crops on a global scale (Lin et al., 2001). Total N losses from fertilization in wheat and maize range between 29 and 57.4 kg N ha^{-1} (Zhou and Butterbach-Bahl, 2014). Soil NO_3-N leached into water causes eutrophication and groundwater degradation. There is also some evidence that high concentrations of NO_3^-N in drinkable water also increase cancer risk in humans at (Rivett et al., 2008; Sutton et al., 2011).

Cover crops are a catch crop for soil residual NO_3^-N in fallow periods, where all the available NO_3^-N is exposed to leaching because there is not a cash crop actively growing. Cover crops from the *Brassicaceae* family are known for their ability to scavenge nutrients leached from the cash crop root zone because of their taproot and deep rooting architecture (Dean and Weil, 2009). Radish (*Raphanus sativus* L.) has been reported to take up 38 to 100 kg N ha^{-1} (Couëdel et al., 2018a). In Wisconsin, radish N uptake ranged from 19.7 to 202 kg N ha^{-1} (Ruark et al., 2018). In North Dakota, radish interseeded into soybean had 73.2 kg N ha^{-1} in the above-ground biomass (Peterson et al., 2019a).

Winter camelina is a plant in the *Brassicaceae* family and originated in the regions of southeast Europe and southeast Asia (Berti et al., 2016a). It is a very winter-hardy cover crop that can survive the cold Upper Midwestern winter, providing green soil cover in late fall and early spring (Gesch et al., 2014; Berti et al., 2017; Wittenberg et al., 2020). In North Dakota, winter camelina N content in above-ground biomass ranged between 24 to 59 kg N ha^{-1} (Berti et al., 2017). Wittenberg et al. (2020) reported a range between 7 to 59 kg N ha^{-1} in camelina biomass, which was positively related to planting date in the short fall in Cass County, ND.

Cereal cover crops are also good scavengers. Winter rye is the most widely grown cover crop in cold climates, as it is a winter-hardy cover crop that provides green cover in late fall and early spring (Krueger et al., 2011). In Michigan, winter rye has been reported to scavenge excess soil NO_3-N (Jewett and Thelen, 2007). In Boone County, IA, winter rye had an average N uptake of 47.5 kg N ha^{-1} and 59% less of soil NO_3-N leached compared with the control without cover crop (Kaspar et al., 2007). In Fargo and Prosper, ND, N uptake of winter rye averaged 47.2 kg N ha^{-1} (Peterson et al., 2019a).

Oat is a cereal cool-season cover crop that is well-adapted to fall conditions in the Upper Midwest (Franzen et al., 2019c). However, it is winter-killed by low temperatures (Kaspar et al., 2012a). In Wageningen, The Netherlands, N uptake in oat ranged between 22 and 61 kg N ha^{-1} when planted in August and harvested in November (Elhakeem et al., 2019), similar to what has been observed in the upper Midwest (Franzen et al., 2019).

Winter wheat is a winter-hardy cereal that survives the winter in the upper Midwest, but has less cold tolerance than winter rye (Peltonen-Sainio et al., 2011). Winter wheat N uptake ranged between 25.5 and 27.1 kg N ha^{-1} in Boone County, IA (Kaspar and Bakker, 2015).

1.3.4. Soil organic carbon (SOC)

Soil organic carbon (SOC) can improve soil physical properties such as water retention, bulk density, soil aggregation and porosity, and enhance soil flora and fauna, and decrease water runoff (Blanco-Canqui et al., 2015). Increased SOC is possible to achieve through no-till or conservation tillage systems, but it is a gradual and slow process in soils (Benjamin et al., 2010; Wang et al., 2015). Cover crops can significantly increase SOC with different tillage systems, where no-till presented the highest SOC compared with a chisel plow and moldboard plow (Olson et al., 2019).

Cover crops can increase SOC through the biomass produced above and below ground (Blanco-Canqui et al., 2013). Data collected from 37 studies worldwide indicated that cover crops sequestered on average 0.32 ± 0.08 Mg C ha^{-1} $year^{-1}$ (Poeplau and Don, 2015). Winter rye has a carbon content in the biomass between 1.7 to 2.7 Mg C ha $^{-1}$ (Sainju et al., 2005). In Garden City, KS, winter wheat increased soil C pool by 4.7 Mg C ha $^{-1,}$ and winter pea by 1.6 Mg C ha^{-1} averaged over four years compared with fallow treatment (Blanco-Canqui et al., 2013).

While cover crops increase SOC, the effects are usually not detectable in the first 3-5 years. Carbon sequestration takes time depending on the weather, crop rotation, and soil properties (Blanco-Canqui et al., 2013; Acuña and Villamil, 2014).

1.3.5. Reducing soil compaction

The use of farm equipment (combines, tractors, planters, grain carts, etc.) increases soil compaction year after year. This creates several problems such as slower infiltration, reduced root growth, reduced water and nutrient uptake, decreased gas flow in the soil, and diminished crop yields (Schäfer-Landefeld et al., 2004).

Cover crops with deep taproots can penetrate soil compacted layers, working as tillage tools or biological tillage, improving soil aggregation, water infiltration, and root growth (Chen and Weil, 2010). Radish, as a tap-rooted crop, creates root channels. These channels can be used by the following crop root system and alleviate soil compaction (Williams and Weil, 2004). In western Illinois, radish root was reported to have a root grow 1-m deep in 60 days, with root thickness of more than 2.5 cm, alleviating soil compaction and increasing water movement in the soil (Gruver et al., 2016).

1.3.6. Water use

In seasons with less than average rainfall, cover crops can compete for soil water with the following cash crop (Daigh et al., 2014). Soil water use in cover crops in different environments is essential, as some researchers have reported maize yield reduction following winter rye (Kaspar and Bakker, 2015). Conventional seeding of cover crops is not always possible in the northern Great Plains. The fall season is too short to plant cover crops after maize or soybean harvest with conventional methods, so more research is necessary to establish a cover crop.

Winter rye left a thick mulch after termination, resulting in greater surface soil moisture than with radish or without cover crop (Williams and Weil, 2004). In Boone County, IA, winter rye had a significantly higher water content in a rotation of four years, considering dry periods. Field capacity increased by 10 to 11% and plant-available water by 21 to 22% (Basche et al., 2016b). However, winter rye in a dry season presented significantly lower soil water content than the control without cover crop (Daigh et al., 2014).

1.3.7. Weed suppression

Cover crops suppress weeds through two mechanisms. One is through direct competition with growing weeds for light, nutrients, and water (Teasdale et al., 2007; Blanco-Canqui et al., 2015). The second is physical suppression (Teasdale and Mohler, 2000; Smith et al., 2011), or chemical suppression by plant secondary metabolites released to the soil rhizosphere, affecting weed germination and growth; this process is known as allelopathy (Weston and Duke, 2003).

Winter rye allelopathic compounds inhibit weed seed germination in plants from the *Amaranthaceae* family (Barnes and Putnam, 1987; Tabaglio et al., 2013a). The primary allelopathic secondary metabolites produced by winter rye are phytotoxic benzoxazinones. The allelopathic compounds are stored in the vacuole and then released when the plant tissue is damaged, inhibiting weed germination and growth (Barnes and Putnam, 1987).

Radish also has a significant weed suppression effect. One of the most important mechanisms is competitive fall growth and soil surface covering (Lawley et al., 2011, 2012). Cover crops in the *Brassicaceae* family suppress weeds through allelopathic glucosinolate breakdown products which inhibit weed seed germination and suppress some weed seed enzymes (Weil and Kremen, 2007).

1.3.8. Maize and cover crops

In maize production, N credits from legumes increase grain yield, adding nitrogen into the cropping system through biological N_2 fixation. Faba bean (*Vicia faba* Roth.), chickling vetch (*Lathyrus sativu*s L.), forage pea (*Pisum sativum* L.), and hairy vetch *(Vicia villosa* Roth) can add N into the soil at amounts from 40 to 100 kg N ha^{-1} (Blanco-Canqui et al., 2015) if the legumes are terminated enough in advance so that they sufficiently decompose. In addition, N contribution is maximized if the legume is incorporated by tillage. Maize grain yield was significantly increased by 1.7 Mg ha^{-1} after sunnhemp (*Crotalaria juncea* L.) (Balkcom and Reeves, 2005), 2.1 Mg ha^{-1} after winter pea (Decker et al., 1994), 0.7 Mg ha^{-1} after oat and winter rye (Maughan et al., 2009) compared with no cover crop. However, N release from legume and other cover crop biomass is highly dependent on soil and weather conditions (Frye et al., 1988; Büchi et al., 2015). In Cass County, faba bean and winter pea did not increase maize grain yield compared with no cover crop (Andersen et al., 2020).

Cover crops can have negative effect on crop yield. A grain yield reduction of 10% was reported when cover crops were planted at the V3 stage of maize because of early seedling competition (Reese et al., 2014). Late termination of winter rye before silage maize planting can reduce biomass yield as much as 4.5 Mg ha^{-1} due to reduced soil water content, early competition, and allelopathic effect (Krueger et al., 2011). Meta-analysis has been demonstrated that late-terminated winter cover crops can reduce maize yields in more than 30% respect to the control maize plots (Marcillo and Miguez, 2017). Cover crops actively growing into maize stages V1 to V12 are considered the most critical stages for biomass and yield reduction on maize (Keller et al., 2014; Tursun et al., 2016). Also, winter rye could be a green bridge for armyworm (*Mythimna unipuncta* Haworth), black cutworm (*Agrotis ipsilon* Hufnagel), and common stalk borer (*Papaipema nebris* Guenee), reducing maize yield and grain quality (Dunbar et al., 2016).

1.3.9. Sugarbeet and cover crops

In sugarbeet, cover crops increase soil organic matter and soil biological activity (Marinari et al., 2015) and provide soil physical cover reducing soil erosion (Etemadi et al., 2018; Keshavarz et al., 2018) and minimize runoff (Laloy and Bielders, 2010). A significant benefit is the protection of sugarbeet seedlings from wind damage in early spring because of wind-blown soil, mainly before the four-leaf stage (Yonts et al., 2002). Cover crops also can reduce sugarbeet impurities significantly, such as sodium, amino-N concentration, and potassium (Keshavarz Afshar et al., 2018). Optimum cover crop termination is essential in sugarbeet because late termination could result in yield and quality reduction. A yield reduction of 14 to 17 Mg ha^{-1} was reported when the cover crop termination was later than the V2 stage (Keshavarz et al., 2018).

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CHAPTER 2. FALL-PLANTED LEGUME COVER CROPS SLIGHTLY INCREASED MAIZE GRAIN YIELD IN NORTH DAKOTA

2.1. Abstract

Conventional tillage after wheat (*Triticum aestivum* L.) results in poor winter soil coverage, negatively affecting long-term soil health. The use of cover crops and no-tillage provides soil coverage, which reduces soil erosion, and NO_3-N leaching potential. The objective of this study was to evaluate maize grain yield response and grain quality due to cover crop. The experiment was organized as a randomized complete block design (RCBD) with a split-plot arrangement. The experiments were conducted at two locations, Prosper and Hickson, ND from 2017-2019. Forage pea (*Pisum sativum* L.), faba bean (*Vicia faba* Roth), and winter camelina [*Camelina sativa* (L.) Crantz] were established into spring wheat stubble in August 2017 and 2018. A check treatment with no cover crop was included. Cover crop fall biomass production and N accumulation in plant tissue averaged across locations were 1.59 Mg ha^{-1} and 67.7 kg ha^{-1}, respectively. Winter camelina survived the winters and accumulated biomass in the spring, resulting in significantly higher biomass (3.3 Mg ha^{-1}) compared with the previous fall biomass. Winter camelina decreased spring water content in Prosper and Hickson 2018, affecting maize (*Zea mays* L.) seedling growth because of early competition. Soil NO_3-N was not different among treatments. Maize was planted into the residue of fall-planted cover crops. Nitrogen rates of 0, 40, 80, and 160 kg N ha^{-1} were applied immediately after planting as urea. Maize grain yield was significantly higher when grown in plots that had faba bean (9.71 Mg ha^{-1}), forage pea (10.12 Mg ha^{-1}), and the no-cover crop check (9.85 Mg ha^{-1}), than those that had winter camelina (8.62 Mg ha^{-1}). Normalized difference vegetative index (NDVI) was used as a predictor of maize biomass and grain yield across all environments, with a Greenseeker device at V7 and V10

maize stages. Leguminous cover crops slightly increased maize grain yield compared with no-cover crop plots; however more research over more seasonal weather conditions is needed to understand this response and benefit.

2.2. Materials and methods

2.2.1. Field establishment

This research was conducted from 2017 to 2019 at Prosper (-97°01'W, 46°57'N, 240 m elevation) and Hickson (-96°49'W, 46°387'N, 281 m elevation), ND. The soil series at Prosper is a Fargo-Hegne silty clay, (Fargo: fine, montmorillonitic, frigid, Vertic Haplaquol, Hegne: fine, smectitic, frigid Typic Calciaquerts), and the soil series at Hickson is a Kindred-Bearden silty clay loam (Perella: fine-silty, mixed, superactive Typic Endoaquoll; Bearden: fine-silty, mixed, superactive, frigid Aeric Calciaquoll) (Web Soil Survey, 2017). Rainfall and daily temperature were recorded by the North Dakota Agricultural Weather Network (NDAWN) in both locations. The weather stations used were nearest to the research site (Figure 1).

2.2.2. Wheat and cover crops field design

The wheat cultivar used in the research was 'Glenn', it was seeding using a Great Plains™ 15-cm row space planter (Great Plains Manufacturing Co., Salinas, KS) at 4,450,000 pure live seed (PLS) ha^{-1} on 20 April 2017 and 15 May 2018 at Prosper and 25 April 2017 and 2 May 2018 at Hickson. The Prosper experiment was fertilized both years with 90 kg N ha^{-1} and 17 kg P_2O_5 ha^{-1} (urea 188 kg ha^{-1} and mono ammonium phosphate (MAP) 33 kg ha^{-1}). The Hickson experiment was fertilized both years with 88 kg N ha^{-1} and 24 kg P_2O_5 ha^{-1} (urea 180 kg ha^{-1} and MAP 46 kg ha^{-1}). Wheat harvest at Prosper was conducted on 5 August 2017 and 8 August 2018, and at Hickson wheat was harvested on 8 August 2017 and 9 August 2018.

The experimental design was constructed using a randomized complete block design (RCBD) with four replicates at both locations in both years. Treatments were faba bean (*Vicia faba* Roth, cv. Tabasco), forage pea (*Pisum sativum* cv. Arvika), winter camelina (*Camelina sativa* cv. Joelle), and a check plot (without cover crop).

The excess of wheat stubble was removed with a leaf blower (BR 299, Stihl, Waiblingen, Germany) to ensure correct seed drilling. Legume seed cover crops were treated with 6.1 kg ha^{-1} of inoculant (*Rhizobium legumisosarum*), (TagTeam™, Monsanto Company, St. Louis, MO). Cover crops were sown into wheat stubble without tillage with an XL Plot Seeder (Wintersteiger, Austria). Sowing dates were 14 August 2017 and 16 August 2018 in Prosper and 22 August 2017 and 13 August 2018 in Hickson.

The experimental units were treated with glyphosate 1.4 kg a.i. ha^{-1} (*N*-(phosphonomethyl)-glycine) after wheat harvest to kill volunteer wheat. Each experimental unit had eight cover crop rows, separated 15-cm from each with a surface of 10.5 m^2 (7.6 m x 1.4 m). Cover crop sowing rates were: faba bean, 245,000 pure live seed (PLS) ha^{-1} equivalent to115 kg ha^{-1}; forage pea, 1,317,000 PLS ha^{-1} equivalent to 140 kg ha^{-1}; and winter camelina, 10,190,000 PLS ha^{-1} equivalent to 10 kg ha^{-1} (Table 2.1). There were no fertilizer applications during the fall in any of the experiments.

Table 2.1. Cultivars, seed weight, and sowing rates of cover crop experiments at Prosper and Hickson, ND, 2017-2018.

Cover crop	Cultivar	100-seed weight	Sowing rate
		g	PLS ha^{-1}
Faba bean	Tabasco	46.83	245,000
Forage pea	Arvika	10.89	1,317,000
Winter camelina	Joelle	0.09	10,190,000

PLS: Pure live seed

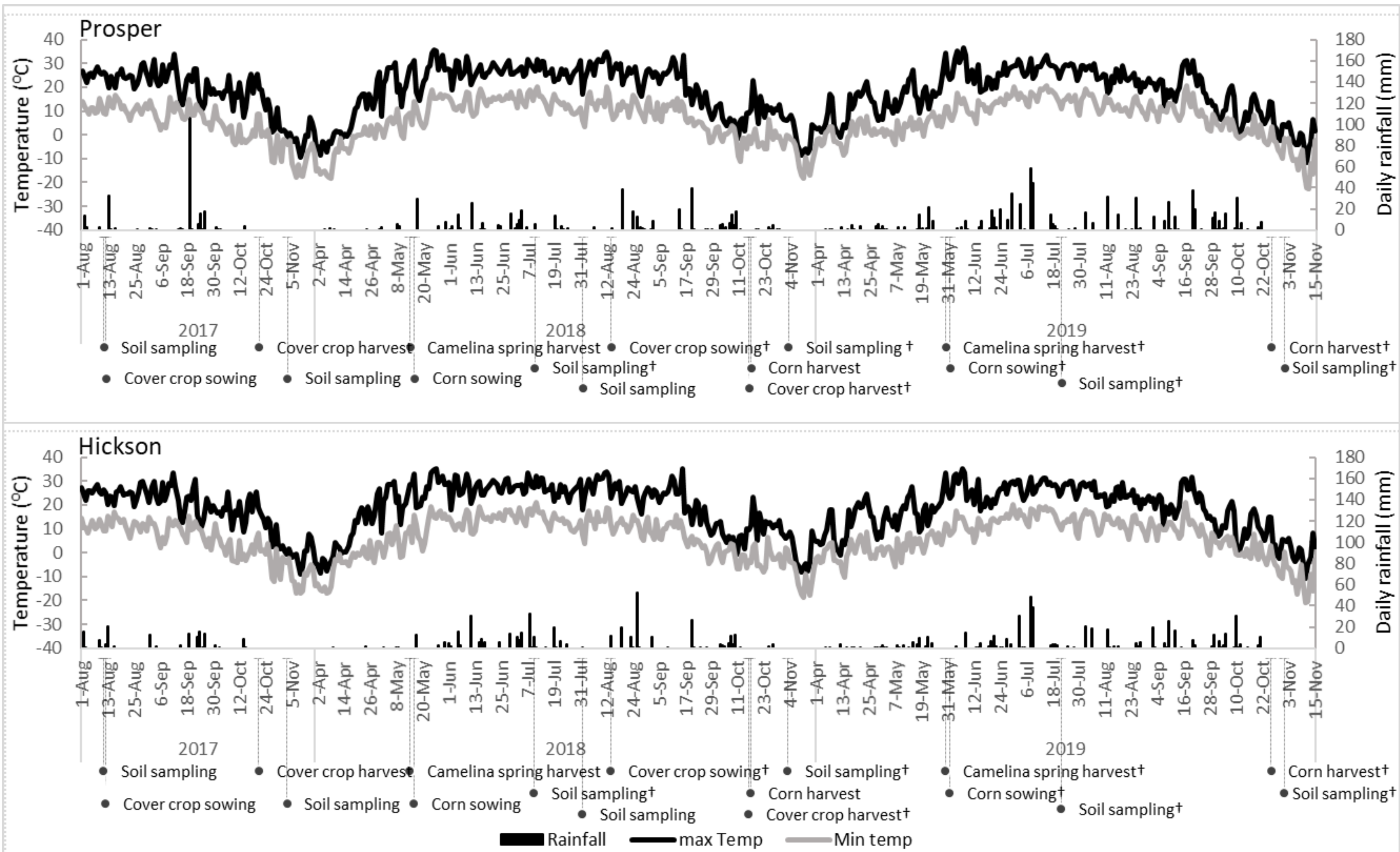

Figure 2.1. Daily rainfall, maximum, and minimum temperature, and main field activities at Prosper and Hickson, from August 2017 to November 2019.

† Field activities of the second environment from the same location

2.2.3. Maize experimental design

Maize was established into the cover crops treatments in the spring in both locations. The experimental design used was an RCBD with a split-plot arrangement with four replicates. The main plots were the previous season cover crop treatments. Sub-plots included four nitrogen rates: 0 (check), 40, 80, and 160 kg N ha^{-1}. Before maize sowing, all experimental units were sprayed with glyphosate 1.4 kg a.i. ha^{-1} to control weeds and winter camelina that was actively growing. Maize hybrid Peterson Farm Seed 75K85 VT2PRO (85-day maturity), was sown into residue without tillage in 56-cm rows with using a MaxEmerge XP™ planter (John Deer, Moline, IL) in Prosper on 15 May 2018 and 31 May 2019; and in Hickson on 10 May 2018. On 5 June 2019, Hickson was re-sown with the Pioneer Hybrid P7227R because the previous seeding suffered from poor emergence due to excess rainfall and cold soil temperatures. Each experimental unit consisted of three maize rows, 7.6-m in length. Urea, as the N source used, was broadcast at the date of initial planting. To reduce N losses, a urease inhibitor, Limus (urease inhibitor (N-(n-butyl) thiophosphoric triamide, and N-(n-propyl) thiophosphoric triamide), BASF), was impregnated onto the urea at a labeled rate of 0.59 kg a.i. per ton of urea prior to application. For weed control, glyphosate at 1.4 kg a.i. ha^{-1} was applied at the V6 growth stage.

2.2.4. Plant sampling and analysis

Cover crop green coverage and stand count were determined during fall before the first frost; variables were measured on 30 October 2017 and 2 October 2018, at both Prosper and Hickson. Cover crop green coverage was determined using Canopeo © application through a cell phone (Canopeo™, Oklahoma State University, Stillwater, OK). Camera images were taken 1-m nadir above the soil surface and then processed in Canopeo toolbox by Matlab R2020a, obtaining green ground coverage as a percentage of the total surface. Cover crops stand count was measured in 1 m^2 in each experimental unit; emergence was then calculated by calculating the ratio between pure live seed sown and emerged plants.

Cover crop aboveground biomass samples were collected before the first frost; at Prosper on 26 October 2017 and 15 October 2018, and at Hickson on 27 October 2017, and 16 October 2018. Biomass samples were taken by cutting off the plants directly above the soil surface from a 0.2-m^2 area in each experimental unit, placed in paper bags, and then dried at 70°C until they reached a constant weight. Biomass samples were ground to pass through 1-mm sieve using an electric mill (E3703.00, Eberbach Corporation, Bellville, MI). The same procedure was used for winter camelina samples taken in spring at both locations.

All cover crop biomass samples were analyzed using near-infrared spectroscopy (NIRS) with an XDS analyzer device (Foss, Denmark) to obtain crude protein, N, P, and ash content. Nitrogen content was calculated, dividing crude protein by 6.25. Biomass N and P accumulation were calculated by multiplying total biomass with N and P.

Normalized difference vegetation index (NDVI) was measured at the V5 and V7 maize growth stages using handheld GreenSeeker™ active-optical sensor (Trimble Inc., Sunnyvale, CA). The device was oriented 60-cm above the canopy, and measurements were taken over the two-center rows (7.6-m length) of each experimental unit. All measurements started in the front line to be consistent.

Maize stand count and aboveground biomass were obtained the same day as NDVI measurements; at Prosper on 17 October 2018 and 27 October 2019, and at Hickson on 23 October 2018 and 28 October 2019. Stand counts were taken in 3-linear-m in the center row of each plot to calculate plants ha^{-1}. Maize aboveground biomass from 1-m of a center-row was collected 10-cm above the soil surface. The samples were then dried at 70°C to reach constant weight to obtain dry biomass weight. When maize samples were dried, cobs were separated and shelled (SCS-2, Agriculex, Ontario, Canada). The remaining maize stover was weighed, separated, and harvest index was determined with the following equation:

$$Harvest\ index = \frac{dry\ grain\ weight}{total\ biomass\ weight}\ x\ 100$$

Maize was harvested on 18 October 2018 and 10 October 2019 in Prosper and on 24 October 2018 and 1 November 2019 in Hickson. The center-row was hand harvested (6.6-m length) and shelled using an HP 5 combine (Almaco, Nevada, IA). This harvester is a single row 76-cm wide head. For this reason, it was unable to harvest the experimental units directly. The grain obtained from the combine machine was immediately weighed and then analyzed for grain moisture using a Mini GAC 2500™ (Dickey-John, Inc., Auburn, IL). After field grain weight and moisture content were determined, maize grain yield was calculated for 15% standard moisture.

Maize grain samples were analyzed with an XDS analyzer device (Foss, Denmark) to obtain ash, fat, fiber, crude protein, and N content. Grain N accumulation was calculated by multiplying the total grain yield by N grain concentration.

2.2.5. Soil sampling and analysis

After wheat harvest, composite soil samples were taken at Prosper on 8 August 2018 and 9 July 2018, and at Hickson on 12 July 2017 and 17 August 2018. Three core samples (2.5-cm diameter) were collected 0-15 cm and 15-60 cm depth in each replicate (Table 2.2). Samples taken at 0-15 cm depth were tested for NO_3-N using the determination of soil nitrate by transnitration of salicylic acid method (Vendrell and Zupancic, 1990), soil pH was measured potentiometrically in a slurry using an electronic pH meter (Watson and Brown, 1998), organic matter was determined with the Loss in ignition (LOI) method (Hoogsteen et al., 2015), P content was determined with the Olsen method (Olsen, 1954), and K determined with the ammonium acetate method (Warncke and Brown, 1998); using an Atomic Absorption Spectrophotometer (Buck Scientific 210 VGP, East Norwalk, CT). Soil samples at 15-60 cm depth were analyzed for NO_3-N.

Table 2.2. Soil chemical properties for cover crop experiments after wheat in Prosper and Hickson, ND, in 2017 and 2018.

Environment	pH†	OM	P	K	NO_3-N	
					0-15 cm	15-60 cm
		g kg^{-1}	———mg kg^{-1}———		——kg ha^{-1}——	
Prosper 2017	6.63	33.5	26.0	201.5	23.8	40.9
Prosper 2018	8.05	40.7	20.8	240.5	2.2	4.2
Hickson 2017	7.43	59.5	20.8	374.5	32.3	37.3
Hickson 2018	7.75	49.3	10.3	345.0	12.6	5.9

†pH, organic matter (OM), P, and K values were taken at 0-15 cm soil depth

After cover crops died with the killing frost in late fall, soil samples were collected in each experimental unit, with three cores per experimental unit composite sample. These samples were tested for NO_3-N, using the method mentioned previously at 0-15 cm and 15-60 cm depth. Samples were taken on 2 November 2017 and 14 November 2018 in Prosper and on 2 November 2017 and 15 November 2018 in Hickson.

Spring soil sampling was performed on 9 July 2018 and 15 July 2919, in Prosper and on 23 July 2018 and 23 July 2019 in Hickson. These soil samples were obtained from each maize experimental unit. Soil NO_3-N was analyzed at 0-15 cm and 15-60 cm depths separately.

During late fall following maize harvest, soil samples were collected on 2 November 2018 and 30 October 2019, in Prosper and on 2 November 2018 and 1 November 2019 in Hickson. Only NO_3-N was tested at 0-15 cm and 15-60 cm depth. In 2019, samples from 15-60 cm depth were not taken because of excessive soil water at both locations.

2.2.6. Statistical analysis

Statistical analysis was conducted using standard procedures for a randomized complete block design (RCBD). Cover crop stand count, biomass yield, and biomass quality parameters were analyzed using analysis of variance with the MIXED procedure of SAS 9.4 (SAS Institute, Inc. 2013) and the mean separation test was performed using least significant difference (LSD) ($P \leq 0.05$). Environment was defined as a location-year combination. Homogeneity of variance for each trait was tested for four environments, and if homogenous, a combined analyzed procedure was conducted. Environments were considered a random effect, while the remaining experimental variables were considered fixed effects. All interactions of fixed effects with the environments were considered a random effect in the analysis.

Statistical analysis for maize experiments was based on an RCBD design with a split-plot arrangement. Maize stand count, aboveground biomass, grain yield, and grain quality parameters were analyzed using analysis of variance using the MIXED procedure of SAS 9.4 and the means separation test was performed using LSD ($P \leq 0.05$). Environments and their interactions were considered random effects and the other variables were considered fixed effects. Before the combined analysis, all the environments were tested for homogeneity of variance. Linear regression analysis of N rates and maize grain yield was conducted for each cover crop treatment. The regression coefficient for a polynomial model was tested with a *t*-test at 5% significance.

2.3. Results and discussion

2.3.1. Weather

Cover crops were grown from August to October each year. In Prosper, fall 2017, the average rainfall was 17.4 mm greater than the 30-year average for these months. On 19

September, a 106 mm rainfall event left the cover crops under flooding conditions for several days. The average daily temperature was 0.5º C less than the average (Table 2.3), and the first frost was recorded 9 September (-2.9º C). At Prosper in 2018, rainfall was 22-mm greater than the 30-year average, and the temperature 1.7ºC less than average. At Hickson in fall 2017, rain and temperature were 48.7 mm and 0.7º C less than the 30-year average. The first frost was recorded on 28 September (-3.3º C) (Table 2.3). Rainfall was 192 mm greater than the 30-year average, while the temperature was 1º C less than the 30-year average (Table 2.3). These lower-than-average temperatures may have reduced biomass accumulation of all cover crops during the fall.

Maize growing season was from May to November at Prosper and Hickson in 2018 and 2019. In Prosper in 2018, the season was dry with 78-mm less than the 30-year average with the period from May through June even dryer than normal with 56.6-mm less than average rainfall, which affected early maize growth. In addition, the temperature was 7.3º C greater than the 30-year average during May and June. In Prosper in 2019, the opposite situation was observed with rainfall 192-mm greater than the 30-year average. The temperature was 1º C less than the 30-year average (Table 2.3). In Hickson in 2018, rainfall was 62.8 mm less than the 30-year average, with May recording 54.6-mm less rainfall than the 30-year norm.

Table 2.3. The total monthly temperature, rainfall, and deviation from the 30-year average for Prosper and Hickson, ND, in 2017, 2018 and 2019.

		Temperature				Rainfall	
Year	Month	Max	Min	Avg	± Δ †	Total	± Δ ‡
		---------------------------ºC--------------------				------------mm---------	
				Prosper			
2017	Aug	24.8	11.3	18.1	-2.3	52.6	-13.9
	Sept	22.1	8.5	15.3	0.5	151.7	86.2
	Oct	15.1	0.0	7.5	0.3	6.9	-54.9
2018	Apr	5.5	-5.6	0.0	-6.4	3.8	-33.0
	May	25.0	8.7	16.9	3.4	53.9	-23.6
	June	26.8	14.2	20.5	1.8	79.3	-21.1
	July	26.9	13.6	20.3	-1.0	65.3	-22.6
	Aug	26.7	12.0	19.4	-1.0	78.5	12.0
	Sept	20.9	7.4	14.1	-0.7	70.9	5.4
	Oct	9.0	-1.4	3.8	-3.5	66.6	4.9
2019	Apr	9.8	0.3	5.0	-1.3	23.2	-13.6
	May	17.3	4.0	10.7	-2.8	60.0	-17.5
	June	26.0	12.3	19.2	0.5	122.0	21.7
	July	28.1	15.6	21.9	0.6	156.1	68.2
	Aug	24.3	12.5	18.4	-2.0	102.4	35.9
	Sept	20.7	10.3	15.5	0.7	147.7	82.1
	Oct	8.6	0.7	4.6	-2.7	77.0	15.3
				Hickson			
2017	Aug	25.0	11.6	18.3	-2.2	49.8	-12.9
	Sept	22.2	8.8	15.5	0.3	69.1	5.6
	Oct	15.1	0.2	7.6	-0.1	11.9	-41.4
2018	Apr	6.4	-5.0	0.7	-6.4	1.8	-36.6
	May	25.5	8.7	17.1	3.1	22.1	-54.6
	June	27.3	14.1	20.7	1.7	95.0	2.3
	July	27.2	14.2	20.7	-0.9	107.3	24.7
	Aug	26.4	12.2	19.3	-1.3	96.0	33.3
	Sept	21.1	6.8	13.9	-1.3	38.6	-24.9
	Oct	9.7	-1.7	4.0	-3.7	46.2	-7.1
2019	Apr	11.0	0.0	5.5	-1.6	9.4	-28.9
	May	17.6	3.9	10.8	-3.2	44.2	-32.5
	June	25.8	12.4	19.1	0.0	56.1	-36.6
	July	27.7	14.8	21.3	-0.4	132.9	50.4
	Aug	24.4	12.3	18.3	-2.2	71.9	9.2
	Sept	21.1	9.9	15.5	0.3	92.0	28.5
	Oct	9.3	0.1	4.7	-3.0	71.7	18.3

† Difference between observed temperature and the average temperature based on 1981-2010 (NDAWN, 2020)
‡ Difference between observed rainfall and the average rainfall based on 1981-2010 (NDAWN, 2020)

The dry conditions negatively affected maize germination and growth. In Hickson in 2019, the total rainfall was 8.4 mm greater than the 30-year average, and the temperature was 1.4ºC less than the 30-year average (Table 2.3).

2.3.2. Cover crop stand count, biomass, N and P accumulation, and soil cover

Cover crop stand count, emergence, cover crop biomass, and N and P accumulation in biomass were not significantly different ($P > 0.05$) among faba bean, forage pea, and winter camelina across four environments (Table 2.4 and 2.5).

Table 2.4. Combined analysis of variance and mean square values of three cover crops (CC) for fall stand count, CC emergence, aboveground fall biomass yield, N and P biomass accumulation, and fall green soil cover in four environments (Env), Prosper and Hickson, in 2017 and 2018.

SOV	df	Stand count ($x10^6$)	CC emergence	Biomass yield	N accumulation	P accumulation	df	Ground cover†
Env	3	21141993*	2967.2*	5421064*	15040.2*	199.3*	3	5284.9*
Rep(env)	12	508785	75.5	228724	884.2	13.2	12	71.2
CC	2	79135821	5337.4	37229	1203.1	8.5	3	7648.3*
Env x CC	6	18046225*	1195.1*	578706*	1493.5*	18.9	9	720.1*
Error	24	494081	73.2	200615	553.3	8.3	36	53.0
CV%		38	18.2	28	34.6	35.1		21.0

* Denotes significantly differences at $P \leq 0.05$.

† CC green soil cover includes check plot (without CC) in the analysis.

Table 2.5. Mean for fall CC stand count, CC emergence, aboveground CC fall biomass yield, N and P biomass accumulation, and fall green soil cover across four environments (Env), Prosper, and Hickson, in 2017 and 2018.

Cover crop	Stand count	CC emergence	Biomass yield	N accumulation	P accumulation	Ground cover
	plants ha^{-1}	%	Mg ha^{-1}	------------kg ha^{-1}	----------	%
Faba bean	165625	68	1.48	67	7	34
Forage pea	999026	76	1.57	72	8	62
Winter camelina	4366113	43	1.72	64	10	34
No cover crop	---	---	---	---	---	8
LSD (P = 0.05)	NS	NS	NS	NS	NS	21

The environment by cover crop interaction was significantly different among cover crop treatments (Table 2.4). In all the environments, the winter camelina plant density was significantly greater than faba bean and forage pea. Plant density differences were predictable between species, considering that the seeding rates were different (Table 2.1).

In Prosper in 2017, cover crop fall biomass yield was significantly greater in faba bean (3.02 Mg ha^{-1}) than forage pea (2.28 Mg ha^{-1}) and winter camelina (2.21 Mg ha^{-1}). These results agree with an experiment in a mild-winter environment, where faba bean reported had biomass compared with forage pea (Iglesias and Lloveras, 1998). In this study, the average temperature of September and October was greater than the 30-year average, and September had more than 80 mm of rainfall above average (Table 2.6). Similarly, Andersen et al. (2020) and Peterson et al. (2019), reported similar fall biomass yield of faba bean and forage pea in the USA upper Midwest.

Nitrogen accumulation was significant for the interaction of environment by cover crops. In Prosper in 2017, faba bean N accumulation (144.8 kg ha^{-1}) was significantly greater than that of winter camelina (40.7 kg ha^{-1}). Other authors have reported that faba bean has higher N_2 fixation rates than other annual legumes (Hardarson et al., 1991; Hauggard-Nielsen et al., 2009; Peoples et al., 2009). In Hickson in 2018, N accumulation in forage pea (70.4 kg ha^{-1}) was greater than faba bean (35.6 kg ha^{-1}) and winter camelina (26.8 kg ha^{-1}). In these environments, the higher N accumulation of faba bean and forage pea compared with camelina could be explained because legumes fix atmospheric N_2 while camelina does not. In addition, winter camelina requires vernalization to bolt, so it stays in rosette stage in the fall accumulating minimal biomass (Wittenberg et al., 2019). In the other three environments, N accumulation for all cover crops was similar. This could be a result of the short time all cover crops had to grow and accumulate biomass. In addition, environmental differences, soil fertility, soil temperature, residual nitrogen, soil tillage, soil moisture and organic matter etc. could influence N accumulation in cover crops (Carranca et al., 1999; van Kessel and Hartley, 2000). Unkovish and Pate (2000) determined that the contribution of N from N_2 fixation as the total N accumulated could vary between 5 to 97% in forage pea, and 19 to 97% in faba bean.

Ground cover in the fall varied among cover crops ($P \leq 0.05$) (Table 2.4). Forage pea green soil cover was 61.8% in late fall, which was greater than faba bean (34.2%) and winter camelina (34.3%) (Table 2.5). The greater forage pea coverage was due to its prostrate growth architecture, which resulted in a green carpet over the soil surface, while faba bean has an erect growth architecture. In addition, faba-bean plant density was less in comparison with the other cover crops species (Table 2.5). Winter camelina showed a less dense fall soil cover, possibly because it is a biannual plant in the vegetative rosette stage during fall, providing only partial cover (Berti et al., 2016; Gesch and Cermak, 2011; Wittenberg et al., 2019). Fryrear (1985) reported that 20% of soil cover reduced 57% soil by 57%, which faba bean and winter camelina exceeded in this study, and 50% cover reduced soil losses by 95%, which forage pea with prostrate growth exceeded (Fryrear, 1985). All cover crops treatments provided ground cover, but it is essential to consider that all these environments had wheat residue over the surface also, which protects against wind erosion (Kaspar et al., 2001), but in this study, wind erosion was not measured.

Table 2.6. Environment by cover crop interaction of stand count (SC), biomass (Bio), and N accumulation (N) in Prosper and Hickson, ND, in 2018 and 2019.

	Prosper						Hickson					
	2017			2018			2017			2018		
Cover crop	SC	Bio	N	SC	Bio†	N†	SC	Bio	N	SC	Bio	N
	plants ha^{-1}	Mg ha^{-1}	kg ha^{-1}	plants ha^{-1}	Mg ha^{-1}	kg ha^{-1}	plants ha^{-1}	Mg ha^{-1}	kg ha^{-1}	plants ha^{-1}	Mg ha^{-1}	kg ha^{-1}
Faba bean	131250	3.02	144.8	175000	0.58	26.9	176250	1.39	60.1	180000	0.93	35.6
Forage pea	1062937	2.28	114.4	1237850	1.00	43.5	592015	1.42	60.0	1103301	1.56	70.4
Winter camelina	2717889	2.21	91.5	9916257	.	.	1533858	1.70	68.0	3296449	1.25	33.6
LSD (*P* = 0.05)	1025874	0.65	34.6	1025874	0.65	34.6	1025874	0.65	34.6	1025874	0.65	34.6

† Prosper 2019 Biomass and N accumulation was not possible to determine because winter camelina plants were too small for sampling

2.3.3. Cover crop nutrient content

Cover crop crude protein, ash, and P averaged across four environments concentration in the biomass were similar ($P \geq 0.05$) between cover crops (Table 2.7). However, there was significant interaction of environment by cover crop these variables (Table 2.7).

Table 2.7. Combined analysis of variance and mean square values of three cover crops (CC) for cover crop biomass nutrient concentration in four environments (Env), Prosper and Hickson, in 2017 and 2018.

SOV	df	Crude protein	Ash	P	N
Env	3	9462.6*	5192.7	5.67*	204.2*
Rep(env)	12	1418.0	1543.7	0.83	45.0
CC	2	22260.7	64745.8	0.68	339.6*
Env x CC	5	5136.2*	13599.9*	4.67*	52.7
Error	21	1107.0	2779.4	0.99	28.0
CV%		13.9	44.5	19.80	12.8

Forage parameters are important to consider in cover crops because cover crops are a possible grazing resource for animals in late fall. Crude protein (CP) was significantly greater in winter camelina (328 g kg^{-1}) than in legume cover crops at Prosper in 2017. Forage pea CP (276 g kg^{-1}) was greater than faba bean (183 g kg^{-1}) in the same environment. At Hickson in 2018, forage pea CP (286 g kg^{-1}) was greater than faba bean (229 g kg^{-1}) (Table 2.8). Previous studies reported that CP of faba bean was greater than forage pea (Wichmann et al., 2005) which was contrary to the results at Hickson and Prosper. This contradiction might be explained because faba bean suffered from frost damage and a portion of the leaves was lost, decreasing leaf-to-stem ratio. The greatest concentration of CP in faba bean is in the leaves (Andersen et al., 2020), so if these are lost CP would be expected to decrease (Alkhtib et al., 2016). Overall, legume cover crops CP levels were high and values were comparable with average crude protein reported for alfalfa (*Medicago sativa* L.) (Aponte et al., 2019).

Table 2.8. Environment by cover crop interaction of crude protein (CP), ash and phosphorus (P) concentration at Prosper and Hickson, ND, in 2017 and 2018.

	Prosper						Hickson					
	2017			2018			2017			2018		
Cover crop	CP	Ash	P	CP	Ash	P	CP	Ash	P	CP	Ash	P
	---g kg^{-1}---											
Faba bean*	183	81	4.7	269	100	4.6	232	147	5.5	229	100	4.4
Forage pea	276	43	4.8	274	56	4.8	184	152	6.1	286	56	4.8
Winter camelina	328	187	7.3	.	.	.	169	162	5.3	203	280	3.3
LSD (*P* = 0.05)	49	78	1.5	49	78	1.5	49	78	1.5	49	78	1.5

*Faba bean lost leaves due to an early frost, which did not affect forage pea and winter camelina.

† In Prosper 2019, CP, ash and P concentration was not possible to measure because winter camelina plants were too small for sampling.

Ash concentration was greater in winter camelina than in the legumes at Prosper in 2017. This was most likely due to soil contamination since the rosette of winter camelina is situated close to the soil surface and is susceptible to rainfall splash of soil particles onto leaves. The plants were not washed before drying in these experiments. In addition, in the same environment, the P content was greater in winter camelina (7.3 g kg^{-1}) than in the legume cover crops. In Hickson 2018, the ash content was greater in winter camelina (280 g kg^{-1}) than in the legumes; however, the P content (3.3 g kg^{-1}) was than in forage pea (4.8 g kg^{-1}). All cover crop P concentrations were greater than the 1.4 g kg^{-1} considered sufficient for beef cattle grazing nutrition.

Table 2.9. Mean cover crop biomass nutrient concentration averaged across four environments (Env), in Prosper and Hickson, in 2017 and 2018.

Cover crop	Crude protein	Ash	P	N
	----------------------------------g kg^{-1}	--------------------------------		
Faba bean	251.6	98.6	4.8	43.4
Forage pea	268.0	69.6	5.1	44.4
Winter camelina	183.1	210.1	5.3	34.7
LSD (*P* = 0.05)	NS	NS	NS	4.1

The N concentration of the biomass was different among cover crops ($P < 0.05$) and across four environments (Table 2.9). The N concentration in faba bean (43.4 g kg^{-1}) and forage pea (44.4 g kg^{-1}) were significantly greater than that of winter camelina (34.7 g kg^{-1}). Legumes acquire part of the N in the biomass by N_2 fixation, which could explain the higher N concentrations in both legumes compared with camelina (Peoples et al., 1995; Brewin and Legocki, 1996). Legumes can also scavenge NO_3-N from the soil if it is available, providing a catch crop service and reducing the risk of nitrate leaching (Tribouillois et al., 2016).

2.3.4. Cover crop total biomass yield, and nitrogen, and phosphorus accumulation

Total biomass yield, which is the sum of fall and spring biomass, was greater in winter camelina since it was the only cover crop in this study that survived the winter (Gesch and Cermak, 2011; Berti et al., 2016; Wittenberg et al., 2019). Total biomass yield of winter camelina was 3.3 Mg ha^{-1}. A similar result was reported by Berti et al. (2017) for winter camelina that followed a maize crop, and was sampled the subsequent spring. Faba bean (1.48 Mg ha^{-1}) and forage pea (1.56 Mg ha^{-1}) biomass accumulation was significantly less than winter camelina. Legume biomass accumulation consisted of fall growth only, because they did not survive the winter (Table 2.9).

Table 2.10. Mean for aboveground total CC biomass yield (fall and spring), and P and N total accumulation in four environments (Env), Prosper and Hickson, in 2017 and 2018.

SOV	df	Total biomass yield†	P accumulation	N accumulation
Env	3	9040481.5*	365.9*	26314.9*
Rep(env)	12	398123.4	17.3	1057.8
CC	2	16875447.7*	451.9*	10114.8
Env x CC	6	615859.4	48.3*	1986.2*
Error	24	447506.7	9.9	730.8
CV%		31.6	29.7	32.2

* Significantly different ($P \leq 0.05$).
† CC total biomass includes winter camelina because it is the only cover crop that survives winter across the four environments.

Phosphorus accumulation in winter camelina was 16.7 kg P ha^{-1}, which was greater than that of faba bean and forage pea, with an average of 7.5 kg P ha^{-1}. This difference is related to spring biomass production in camelina. Winter camelina root system scavenges nutrients in the soil profile. It has been reported that 6% of the total root system could reach depths between 0.6 to 1 m during early spring (Gesch and Johnson, 2015).

Total N accumulation in the aboveground biomass was similar among cover crops ($P \geq 0.05$) (Table 2.10). Faba bean and forage pea averaged 69.5 N kg ha^{-1} and winter camelina 112.8 N kg ha^{-1} (Table 2.11).

Table 2.11. Combined analysis of variance and mean values of three cover crops (CC) for aboveground total biomass yield (fall and spring), and P and N total accumulation averaged across four environments (Env), Prosper and Hickson, in 2017 and 2018.

Cover crop	Total biomass yield †	P accumulation	N accumulation
	----------------------------------	kg ha^{-1}	--------------------------------
Faba bean	1481	7.0	66.8
Forage pea	1565	8.0	72.1
Winter camelina	3300	16.7	112.8
LSD (*P* = 0.05)	679	6.0	NS

† CC total biomass includes winter camelina because it is the only cover crop that survives winter across the four environments.

2.3.5. Soil residual NO_3-N and gravimetric water content

Soil residual NO_3-N was similar among cover crops treatments including the check in the fall and early spring at both soil depths (0-15 and 15-60 cm) (Table 2.12). Gravimetric water content (0-15 cm) was also similar in fall and spring among cover crops treatments. There were significant differences in the environment by cover crop interaction for soil NO_3-N content (0-15 cm) during late fall sampling (Table 2.12). In Prosper 2017, soil under winter camelina plots had less NO3-N values than soil under faba bean.

In Hickson 2017, the soil NO_3-N in winter camelina, faba bean, and forage pea were less than the check plots (Table 2.13). These results are in agreement with several studies that report a decrease of nitrate leaching and fall soil nitrate content ranging between 25 to 56%, depending on the cropping system, cover crop species, and environmental conditions (Dinnes et al., 2002; Salmerón et al., 2010; Teixeira et al., 2016; Alonso-Ayuso et al., 2018).

Table 2.12. Combined analysis of variance and mean square values of three cover crops (CC) for fall and spring soil gravimetric water and soil NO3-N in four environments (Env), in Prosper and Hickson, in 2017 and 2018.

		Fall			Spring		
SOV	df	Soil gravimetric water	Soil NO_3-N (0-15 cm)	Soil NO_3-N (15-60 cm)	Soil gravimetric water	Soil NO_3-N (0-15 cm)	Soil NO_3-N (15-60 cm)
Env	3	452.8*	1798.0*	3615.5*	504.1*	189.8*	987.2*
Rep(env)	12	18.9	11.5	106.6	2.9*	29.7*	226.4*
CC	3	15.0	9.5	88.3	34.4	4.1	3.0
Env x CC	9	15.1	21.6*	77.0	10.5*	6.4	44.6
Error	36	12.9	6.1	101.5	1.1	14.0	83.5
CV%		14.8	23.7	61.3	4.2	44.7	72.8

* Significantly different ($P \leq 0.05$).

Table 2.13. Means for fall and spring soil gravimetric water and soil NO_3-N for cover crop treatments averaged across four environments (Env), Prosper and Hickson, in 2017 and 2018.

	Fall			Spring		
Cover crop	Soil gravimetric water	Soil NO_3-N (0-15 cm)	Soil NO_3-N (15-60 cm)	Soil gravimetric water	Soil NO_3-N (0-15 cm)	Soil NO_3-N (15-60 cm)
	%	----------kg ha^{-1}---------		%	----------kg ha^{-1}---------	
Faba bean	23.0	10.7	19.1	25.8	7.7	12.6
Forage pea	25.4	10.0	16.2	26.7	8.8	13.0
Winter camelina	24.2	9.7	13.5	23.2	8.3	12.6
No cover crop	24.3	11.4	17.0	25.5	8.7	12.0
LSD (P = 0.05)	NS	NS	NS	NS	NS	NS

Differences in soil NO_3-N between treatments were not observed in Prosper and Hickson, 2018. This could be explained because in 2018 rainfall was less than the 30-year average, and the temperature was also less than average. Consequently, biomass production was low in all cover crops with a less developed root system unable to effectively scavenge soil NO_3-N.

Table 2.14. Environment by cover crop interaction for soil NO_3-N, in the first sampling depth (0-15 cm), during fall in Prosper and Hickson, 2017 and 2018

	Prosper		Hickson	
Cover crop	2017	2018	2017	2018
	------------------------------NO_3-N, kg ha^{-1}----------------------------			
Faba bean	10.1	3.1	26.1	3.4
Forage pea	8.7	4.8	22.4	4.2
Winter camelina	5.0	3.6	24.9	5.0
No cover crop	8.1	2.2	30.8	4.5
LSD (*P* = 0.05)	------------------------------------3.5--------------------------------			

Gravimetric water content (0-15 cm) was significantly less at maize planting date under winter camelina treatments (16.6 and 19.2%) at Prosper and Hickson in 2017, compared with the other treatments (Table 2.15). Winter camelina was actively growing in early spring (Gesch and Cermak, 2011; Berti et al., 2016). The greater spring water use by camelina was expected because more than 82% of the winter camelina root system is present in the upper 30-cm of soil in the spring (Gesch and Johnson, 2015). When it is actively growing, winter camelina uses significantly more water than where there is no cover crop (Gesch and Johnson, 2015). The early spring in 2017 was dryer and had 15 days without rain (Figure 1) before planting maize, explaining the water use for winter camelina plants. This is similar to camelina-soybean relay cropping, where winter camelina uses more than 26 to 50 mm of water than where winter camelina is not present, with the water uptake variable depending on the season (Gesch and Johnson, 2015).

Table 2.15. Environment by cover crop interaction for gravimetric water content (0-15 cm), during spring in Prosper and Hickson, in 2018 and 2019

	Prosper		Hickson	
Cover crop	2018	2019	2018	2019
	----------	----------	%----------	----------
Faba bean	21.2	23.9	24.6	33.4
Forage pea	22.4	24.2	26.6	33.5
Winter camelina	16.6	24.0	19.2	33.1
No cover crop	21.3	23.9	23.3	33.5
LSD (*P* = 0.05)	----------	----------	1.5----------	----------

Gravimetric water content was not different during early spring at Prosper and Hickson in 2019 (Table 2.15). Winter camelina was actively growing, but rainfall events were frequent (Figure 1). Due to this, the gravimetric water content was similar among treatments (Table 2.13).

2.3.6. Cover crop biomass relationship with ground cover and biomass N accumulation

The interaction of cover crops biomass with ground cover and N accumulation across four environments is a relevant comparison for understanding the effect of cover crops in the cropping system**.** Soil cover is one a major benefit of cover crops, with the ability of the coverage to reduce wind erosion (Kaspar et al., 2001). The faba bean treatment showed a high coefficient of determination between soil cover and biomass production (r^2 = 0.93) (Figure 2). Forage pea soil cover and biomass production show a low association (r^2 = 0.28). This could be explained because of its prostrate growth. Forage pea can cover the soil surface successfully, even with low biomass production.

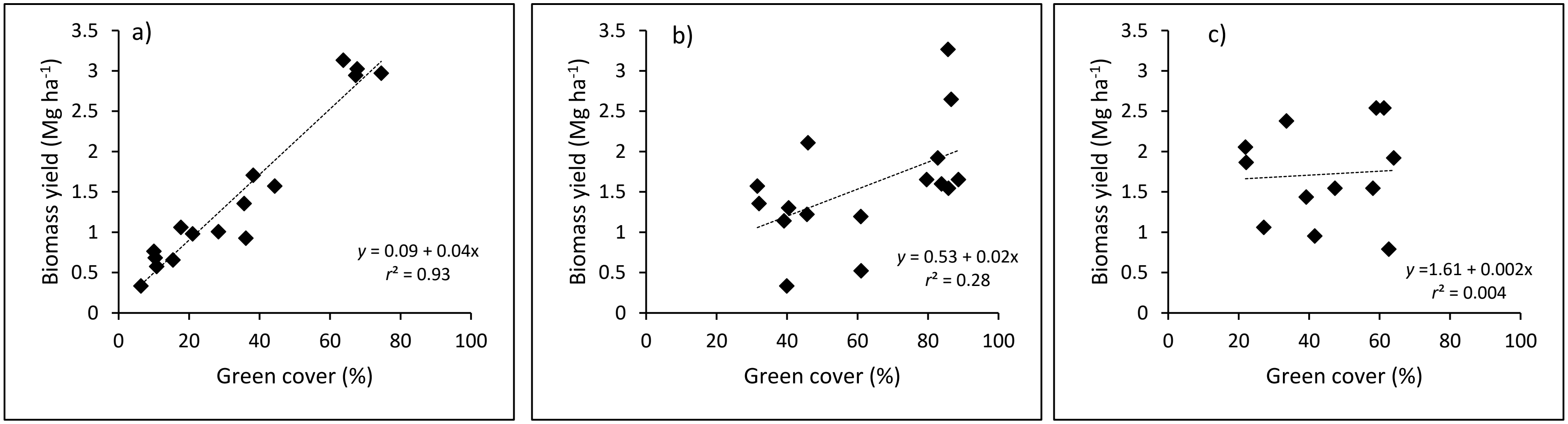

Figure 2.2. Cover crops fall biomass and soil green cover interaction by cover crop treatment averaged across four environments, Prosper and Hickson, ND, in 2017 and 2018: a) faba bean, b) forage pea, and c) winter camelina.

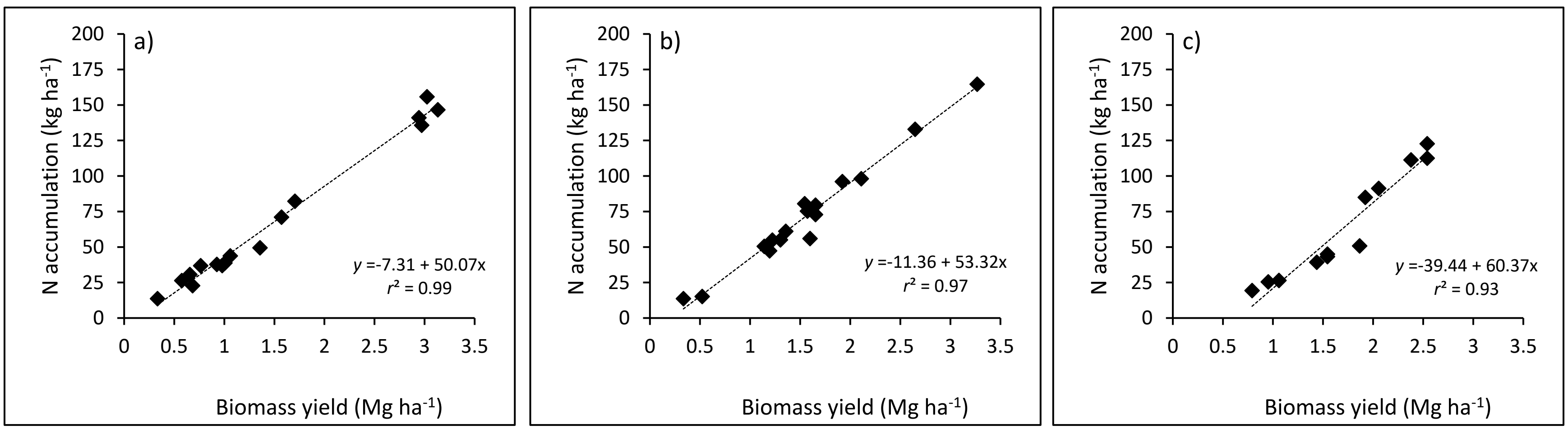

Figure 2.3. Cover crops fall biomass and nitrogen accumulation interaction by cover crop treatment and averaged across four environments, Prosper and Hickson, ND, 2017 and 2019: a) faba bean, b) forage pea, and c) winter camelina.

Winter camelina soil cover and biomass production (r^2 = 0.004) were not related likely due to the vegetative rosette stage during fall, which covers only the surrounding area to the main plant but is not associated with higher biomass productivity (Gesch and Cermak, 2011; Berti et al., 2016). Soil cover is not always a good indicator of biomass in all cover crops species, but it is a good predictor in faba bean.

Total biomass yield and N accumulation were positively associated in all cover crops (Figure 3). Faba bean, forage pea, and winter camelina coefficients of determination for the relationship of total biomass yield and N accumulation were 0.99, 0.97, and 0.93, respectively. This was expected because with more biomass, more N accumulation is possible (Kaspar et al., 2001; Blanco-Canqui et al., 2015; Kaspar and Bakker, 2015; Rutan and Steinke, 2019). With a high determination coefficient, it is possible to predict how much N was scavenged by the cover crop during the fall in non-leguminous crops; however, N accumulated in legumes may also include N from biological fixation.

2.3.7. Maize yield response after cover crops

There were no significant differences in the interaction between cover crop and nitrogen rate across all environments ($P \geq 0.05$) for all variables evaluated (Table 2.16). Cover crops and the check were different in NDVI readings at the V8-leaf stage, total aboveground biomass, grain yield, and harvest index for different N rates averaged across four environments.

Significant differences were reported in NDVI measurements between cover crops. Values for NDVI in faba bean and forage pea were 0.7031 and 0.7089, respectively and significantly higher than winter camelina NDVI (0.6886) (Table 2.17). The early-reduced vigor in maize seedlings was observed in plots that had winter camelina, likely due to soil water depletion under this cover crop, which may have limited maize seedling growth. Winter camelina was terminated at maize planting date (glyphosate spraying).

Table 2.16. Combined analysis of variance and mean square values of variables measured in three cover crops (CC) and four N rates (N rate) in four environments (Env), Prosper and Hickson, in 2018 and 2019.

SOV	df	NDVI V5††	NDVI V8††	Stand count	Total biomass†	Grain yield	Harvest Index
Env	3	1.0804*	0.4906*	164711175	1639880535*	719344652*	0.0161*
Rep(env)	12	0.0200*	0.0199*	233097586	29978487*	10386944*	0.0044*
CC	3	0.0130	0.0048*	198070400	124070004*	27776390*	0.0103*
Env x CC	9	0.0066*	0.0003	93544828	26642555	3442894	0.0013
Env x rep x CC	36	0.0025	0.0017*	176386903	13657860	2198186	0.0028
Nrate	3	0.0488*	0.0490	138023794	618814779*	343932830*	0.0325*
Env x Nrate	9	0.0034	0.0143*	55737706	14349794	4551984*	0.0037
CC x Nrate	9	0.0007	0.0007	84649034	9050947	1498429	0.0019
ENV x CC x Nrate	27	0.0031	0.0007	116525627	8316700	2758000	0.0026
Error	144	0.0020	0.0005	134965865	12149378	2196948	0.0020
CV%		7.1338	3.0633	13	20	15	8.4565

* Significantly different ($P \leq 0.05$).
† Maize total biomass aboveground
††Normalized difference vegetation index (NDVI) at V5 and V8 leaf stage

Maize biomass and grain yield were significantly greater after faba bean, followed by maize following forage pea, and the check. Maize following winter camelina plots had less maize biomass (15.5 Mg ha^{-1}) and grain yield (8.6 Mg ha^{-1}) (Table 2.17) in comparison with other treatments. The decrease in biomass and grain values after winter camelina might be due to multiple factors. Early in the season, soil in winter camelina treatments had less soil water content at Prosper and Hickson 2017 (Table 2.15), which reduced maize seedling growth. Less growth was also observed *in situ* by field observation (no measurements recorded); however, the V8 NDVI was less in maize following winter camelina, indicating less growth than other treatments. It has been reported that maize seedlings can be affected by weed presence within 24 h after germination, affecting seedling biomass and development (Page et al., 2009), so perhaps winter camelina terminated the day of planting might serve to provide the same negative interaction as weeds.

Winter camelina was terminated using glyphosate, as detailed in the methods, but the plants were still standing more than eight days after planting. The presence of terminated, but still standing plants and their root aura biochemistry may have affected maize early seedling growth negatively, because germination and early season maize seedling vigor was reduced compared with all the other treatments (field observation). Early weed competition for soil resources with maize in the seedlings stage has been widely documented in research, with critical growth stages ranging from V1 to V12 as critical stages for biomass and yield reduction (Keller et al., 2014; Tursun et al., 2016). Meta-analysis indicates that late-terminated winter rye can reduce maize yield more than 30% (Marcillo and Miguez, 2017).

The dry spring of 2017 (Figure 1) increased the apparent effect of winter camelina interference on maize seedlings, resulting in less biomass and grain yield. Harvest index in maize was less following winter camelina (0.503) compared with other treatments. This could be explained by early competition factors from winter camelina and less available water, based on the environmental data from 2017 (Table 2.3). Harvest index in maize decreases with less available soil water or from seasonal dry periods (Ran et al., 2016).

Organic matter mineralization is controlled by residue composition, soil moisture, and temperature, with an ideal range of microbes associated with N mineralization between 20 and 30° C (Davidson and Janssens, 2006; Lawson et al., 2012). However, average temperatures in April (2017 and 2018) and May (2018) were less than the 30-year average in Prosper and Hickson. In addition, winter camelina significantly decreased soil moisture in early spring 2017.

These factors may have negatively affected early organic matter mineralization from winter camelina biomass.

Soil microbes play an important role in all cropping systems and are highly dependent on crop rotations. When maize follows non-mycorrhizal plants, such as winter camelina, the decreased arbuscular mycorrhizal fungi association may result in less P uptake in early spring, affecting grain yield negatively. Although mycorrhizal number was not measured in this research, it is certainly something to consider in the future (Karasawa et al., 2001; Turrini et al., 2016; Chatterjee and Franzen, 2020).

Another important characteristic of winter camelina is that it contains glucosinolates, which are allelopathic compounds known to suppress weeds. When the tissue of camelina breaks down, glucosinolates are released to the soil and converted to isothiocyanates, which are strong inhibitors of seed germination of weeds and some crop including tobacco (*Nicotiana tabacum* L.) and dry bean (*Phaseolus vulgaris* L.) (Al-Khatib et al., 1997). There are no reports of inhibition of maize germination by glucosinolates. However, it may be an important topic to investigate in future research.

Maize grain yield did not increase after a legume cover crop compared with the check (Table 2.17). The lack of release of N following a cover crop has been observed before by others, and although the reason for this are not entirely clear why the N in the cover crops biomass is not being released to the next maize crop, several reasons might explain it. Winter cover crop meta-analysis indicates that legume cover crops residues can provide additional N to maize. Thus, maize following a legume cover crop can have a 21% yield increase when compared with the control with no added N (Miguez and Bollero, 2005; Marcillo and Miguez, 2017;), but these yield increments were not observed in our research. One of the reasons could be the variable N accumulation of faba bean and forage pea across the environments (Table 2.6), affecting N mineralization from the cover crop biomass.

Table 2.17. Mean for maize parameters of three cover crop treatments averaged across four nitrogen rates and four environments (Env), Prosper and Hickson, in 2018 and 2019.

Cover crop	NDVI V5††	NDVI V8††	Stand count	Biomass yield †	Grain yield	Harvest index
			plants ha^{-1}	Mg ha^{-1}	Mg ha^{-1}	
Faba bean	0.640	0.703	91714	18.27	9.72	0.531
Forage pea	0.642	0.709	91155	17.78	10.12	0.526
Winter camelina	0.613	0.689	87800	15.47	8.62	0.508
Check	0.622	0.697	90876	18.51	9.85	0.538
LSD (P = 0.05)	NS	0.006	NS	2.06	0.74	0.015

† Maize total biomass aboveground

††Normalized difference vegetation index at V5- and V8 leaf stage

The N accumulation of legume cover crops during fall averaged across environments (Table 2.5) was similar to that of winter camelina, which shows that the legumes cover crops did not accumulate as much N as was expected across locations. Significant differences were observed for the environment by cover crop interaction (Table 2.6), but the values were highly variable among both legumes and environments. Variability in N_2 fixation has been reported in previous work. In a meta-analysis, N_2 fixation ranged from 19 to 97% in faba bean and 5 to 95% in forage pea of the total N in plant tissue, depending on different environmental conditions (Unkovich and Pate, 2000). Other researchers show that one of the main reasons for low legume N_2 fixation is the lack of soil moisture (Carranca et al., 1999). However, this case was the opposite of what was observed because in late September (2017 and 2018) was wet and soil moisture was high in all plots across environments.

Another critical factor is the short cover crop growing period after wheat at Hickson and Prosper, ND, and considering that the first frost in both years was in early to mid- September (Figure 1), decreasing biomass accumulation in winter legumes. Several studies reported that N_2

fixation could be negatively affected by natural soil fertility, soil temperature, fertilization rate from previous crops, soil tillage and soil moisture (Carranca et al., 1999; Unkovich and Pate, 2000; van Kessel and Hartley, 2000).

Several studies indicate that legume cover crops improved crop yields by increasing N availability (Torbert et al., 1996; Gabriel and Quemada, 2011; Mazzoncini et al., 2011; Blanco-Canqui et al., 2015; Lundy et al., 2015). In this research, no additional soil NO_3-N was found for any of the cover crop treatments compared with the check (Table 2.16). Most N credit analyses do not consider transitional no-till, including soil in the first and second year of conversion into a no-till system. The soil microbes in this study were in a period of adaptation to the no-till condition (Franzen et al., 2019). Lower soil microbial populations could affect the mineralization of cover crop dead biomass and decrease the N credit availability to the maize crop. It is crucial to consider that wheat stubble was present on the ground, and it could have immobilized an important amount of N in the mineralization process, but that was not measured in this research.

The cover crop mineralization is positively related to the residue composition and C/N ratio. Cover crops with a C/N ratio less than 20 tend to have high mineralization during the cash crop growing period, providing in theory N credits (Jensen et al., 2005; Lawson et al., 2012). Cover crops and cover crop mixtures with a C/N ratio less than 20 did not significantly increase maize yield in recent experiments (Ruark and Franzen, 2020). Forage pea, faba bean, and winter camelina did not provide N credits to maize (Ruark and Franzen, 2020).

This study, under transitional no-till conditions, did not show a nitrogen release from faba bean and forage pea biomass, suggesting that the mineralization process did not occur or was not great enough to create a significant improvement in maize grain yield. This was also observed in mineralization studies under no-till conditions, where the N mineralization was also not consistent (Parr et al., 2011a). Organic matter mineralization and N transformation are a temperature-dependent processes, with an optimum temperature range of between 20 and 30°C (Davidson and Janssens, 2006; Lawson et al., 2012). However, average temperatures in April (2017 and 2018) and May (2018) were less than the historical average in Hickson and Prosper, which probably slowed early organic matter mineralization from the legume cover crops. This could be one of the main reasons why N credits were not observed in any of the experiments. Similar results were observed on maize following faba bean, field pea and forage pea, where non-N credits or yield improvements were reported (Andersen et al., 2020).

North Dakota soils in the Red River Valley, with a high smectite:illite ratio (higher than 3.5), the majority of 2:1 smectite clay minerals tie-up potassium (K^+) in considerable amounts, and also can tie-up ammonium (NH_4^+), because both cations have a similar ionic radius (Franzen and Bu, 2018; Breker et al., 2019). In preliminary studies, soil following winter rye and forage radish presented a significant increase in non-exchangeable NH_4^+ (Franzen et al., 2019). Smectite clay minerals (2:1) can easily tie-up NH_4^+ coming from cover crop biomass mineralization, especially during dry seasons, adding more complexity to the understanding of N credits in the transitional no-till system and the short growing season in North Dakota. However, this possible scenario needs more research to confirm its importance.

Maize harvest index was significantly higher on faba bean (0.531), forage pea (0.526), and the no cover crop control (0.538) than that of winter camelina (0.508) (Table 2.17). This means that legume cover crops and no-cover crop had greater grain yield in proportion with total biomass produced.

2.3.8. Maize grain chemical parameters

There were no significant differences in ash, fat, fiber, and protein content among cover crop treatments across the study environment (Table 2.18). Similarly, the wheat grain composition of ash, fat and fiber following forage pea, winter camelina, and winter radish was affected by cover crop species (Peterson et al., 2019b). In the Red River Valley, ND, maize grain following faba bean, forage, and field pea were similar in ash, fat, and protein concentration compared with the no-cover crop control (Andersen, 2019; Andersen et al., 2020).

Grain N accumulation was different among cover crop treatments averaged across environments (Table 2.18). In Table 2.19, the lowest grain N accumulation was after winter camelina. This is coincident with grain yield because grain N accumulation is a function of grain N content and maize grain yield.

Table 2.18. Combined analysis of variance and mean square values of maize grain quality components for three cover crops (CC) and four N rates (N rate) in four environments (Env), Prosper and Hickson, 2018 and 2019.

SOV	df	Ash	Fat	Fiber	Protein	Grain N accumulation
Env	3	46.407*	12.118*	31.695*	3334.2*	42569.9*
Rep(env)	12	0.642*	0.149*	0.488*	99.2*	1436.6*
CC	3	0.015	0.044	0.070	25.3	2662.6*
Env x CC	9	0.102	0.018	0.053	56.5*	650.1*
Env x rep x CC	36	0.098*	0.019*	0.087	25.9	248.5
Nrate	3	0.042	0.210	0.064	490.3*	39077.5*
Env x Nrate	9	0.122*	0.054*	0.072	126.2*	791.1*
CC x Nrate	9	0.051	0.014	0.060	17.6	119.9
ENV x CC x Nrate	27	0.075	0.008	0.085	18.0	226.6
Error	144	0.053	0.009	0.070	23.0	210.6
CV%		2.139	0.296	1.046	9.2	18.2

* Significantly different ($P \leq 0.05$)

Grain protein content was significant for the interaction between cover crop and environment (Table 2.18). In Prosper 2018, the grain protein content in the maize grown on the check plot was significantly lower than the grain coming from maize following cover crops (Table 2.20), but it is not clear why. In Hickson 2018, maize grain protein was less following winter camelina plots than the check and forage pea treatments (Table 2.20). These results might be explained by winter camelina interference early in the season.

Table 2.19. Mean for maize grain quality of three cover crops treatments averaged across four nitrogen rates and four environments (Env), Prosper and Hickson, in 2018 and 2019.

Cover crop	Ash	Fat	Fiber	Protein	Grain N accumulation
	--------------------------g kg^{-1}	---------------------------			kg ha^{-1}
Faba bean	10.73	31.77	8.38	52.4	80.9
Forage pea	10.73	31.79	8.45	52.8	85.9
Winter camelina	10.76	31.73	8.22	51.4	70.6
Check	10.73	31.75	8.40	52.5	81.5
LSD (P = 0.05)	NS	NS	NS	NS	10.2

2.3.9. Effect of four N rates on maize parameters

The nitrogen rate main effect was significant ($P < 0.05$) for NDVI measured at the V5 growth stage, and maize aboveground biomass yield, grain yield, harvest index (Table 2.18), grain protein, and N accumulation in the biomass (Table 2.21) for cover crop treatments averaged across four environments. Maize grain yield and aboveground biomass yield increased with increasing N rates. Grain yield and biomass yield responses to N have been reported in many previous studies using different N sources (Bundy et al., 2011; Halvorson and Bartolo, 2014; Safdarian et al., 2014; Amado et al., 2017; Rutan and Steinke, 2017a, 2019).

GreenSeeker NDVI measurements at V5 differed significantly among four increasing N rates across environments (Table 2.18). This positive relationship between NDVI measurement and N rates has been reported before (Amado et al., 2017).

Table 2.20. Environment by cover crop interaction for maize grain protein concentration in Prosper and Hickson, ND, in 2018 and 2019.

	Prosper		Hickson	
Cover crop	2018	2019	2018	2019
	---------------------------------g kg^{-1}	------------------------------------		
Faba bean	51.9	60.6	43.3	53.7
Forage pea	51.2	61.3	45.5	53.5
Winter camelina	49.1	61.4	42.1	53.0
Check	46.1	62.2	46.4	55.3
LSD (P = 0.05)	3.3	3.3	3.3	3.3

Grain protein content was different among N rates averaged across four environments (Table 2.18), as N rates increased, protein content increased, where the highest protein content was reported in 160 kg N ha^{-1} rates (Table 2.21). Similar values of protein concentration in maize grain were reported with increasing N rates (Jellum et al., 1973), sweet maize (Safdarian et al., 2014), and maize and sorghum [*Sorghum bicolor* (L.) Moench.] used as forage (Almodares et al., 2009).

2.3.10. Soil residual NO_3-N during maize growth

In early spring, soil residual NO_3-N did not differ between cover crops treatments, nitrogen rate, or their interactions across four environments. These results were observed in both sampling depths (0-15 and 15-60 cm depth) ($P \geq 0.05$). In the fall, after maize harvest, soil residual NO_3-N was similar among cover crop treatments, N rate, or their interactions in both sampling dates and across environments. Similarly, Andersen et al. (2020) did not report any differences in soil residual NO_3-N (0-60 cm) following maize harvest subsequent to faba bean and forage pea growth in the fall. Peterson et al. (2019) similarly did not find any differences in soil NO_3-N after wheat harvest (0-60 cm), subsequent to previous fall legumes and winter camelina growth.

Table 2.21. Mean for maize biomass, grain yield, and quality parameters for four nitrogen rates averaged across cover crop treatments and four environments, Prosper and Hickson, in 2018 and 2019.

Nitrogen rate	NDVI V5	Biomass yield	Grain yield	Harvest index	Protein	Grain N accumulation
kg ha^{-1}		-------Mg ha^{-1}----			g kg^{-1}	kg ha^{-1}
0	0.59	13.7	6.8	0.50	50.4	52.6
40	0.53	16.8	8.8	0.52	50.5	69.3
80	0.65	18.3	10.4	0.53	52.0	86.5
160	0.65	21.2	12.3	0.55	56.3	110.4
LSD (*P* = 0.05)	0.02	1.5	8.5	0.02	4.5	11.3

Environment by N rate interaction showed significant differences among two N rates (0 and 160 kg N ha^{-1}) in spring, where 160 kg N ha^{-1} rate presented significantly higher values of soil NO_3-N in 0-15 cm depth in Prosper and Hickson 2019, and in 15-60 cm depth in all the environments. Similar results were observed by Halvorson and Bartolo (2014), where the soil NO_3-N values increased significantly as the N rates increased in the first 60-cm depth of the soil profile.

Table 2.22. Combined analysis of variance and mean square values for spring and fall soil NO_3-N in three cover crops (CC) and four nitrogen rates (N rate) in maize at four environments (Env), in Prosper and Hickson, in 2018 and 2019.

	Spring			Fall			
SOV	df	Soil NO_3-N (0-15 cm)†	Soil NO_3-N (15-60 cm)†	df	Soil NO_3-N (0-15 cm)‡	df	Soil NO_3-N (15-60 cm)ǂ
Env	3	21706.1*	24427.9*	3	182.1*	1	186.9*
Rep(env)	12	1054.7*	1380.0*	12	13.5*	6	72.0*
CC	3	608.8	498.6	3	11.7	3	8.7
Env x CC	9	409.2	252.2	9	8.6	3	6.2
Env x rep x CC	36	382.3	540.2	36	5.1	18	8.9
Nrate	1	61785.5	48371.7	3	5.0	3	15.8
Env x Nrate	3	16350.0*	12667.1*	9	5.6	3	5.8
CC x Nrate	3	553.0	438.8	9	4.1	9	4.9
ENV x CC x Nrate	9	314.9	205.4	27	4.8	9	4.1
Error	48	489.8	522.9	144	6.3	72	10.1
CV%		72.9	71.5		44.0		61.6

* Significantly different ($P \leq 0.05$).
† Spring soil NO_3^--N only included two N rates treatments, 0 and 160 kg ha^{-1}.
‡ Fall soil NO_3^--N (0-15 cm) included all CC and N rates levels in four environments.
§ Fall soil NO_3^--N (15-60 cm) included 2018 Prosper and Hickson environments in the analysis. 2019 Prosper and Hickson environments were not included, due to the excess of soil moisture conditions.

Table 2.23. Environment by N rate interaction for spring soil nitrate (NO_3-N) content in Prosper and Hickson, ND, in 2018 and 2019.

	Prosper				Hickson			
	2018		2019		2018		2019	
Nitrogen rate	NO_3-N (0-15 cm)	NO_3-N (15-60 cm)	NO_3-N (0-15 cm)	NO_3-N (15-60 cm)	NO_3-N (0-15 cm)	NO_3-N (15-60 cm)	NO_3-N (0-15 cm)	NO_3-N (15-60 cm)
kg ha^{-1}	----------	----------	----------	----------kg ha^{-1}	----------	----------	----------	----------
0	5.9	8.2	13.1	23.1	5.7	5.3	8.8	13.7
160	18.8	18.1	118.1	118.5	12.4	17.4	59.9	51.7
LSD (P = 0.05)	14.2	11.5	14.2	11.5	14.2	11.5	14.2	11.5

Table 2.24. Mean of soil NO_3-N tested in maize for three cover crops and check treatments averaged across four N rates for spring and fall at four environments (Env), Prosper and Hickson, in 2018 and 2019.

	———Spring———		———Fall———	
Cover crop	Soil NO_3-N (0-15 cm)†	Soil NO_3-N (15-60 cm)†	Soil NO_3-N (0-15 cm)‡	Soil NO_3-N (15-60 cm)§
	------------------kg ha^{-1}------------------			
Faba bean	22.14	6.22	59.44	29.70
Forage pea	22.71	5.57	74.47	36.64
Winter camelina	18.95	5.20	56.22	26.80
Check	21.82	5.81	59.23	28.23
LSD (*P* = 0.05)	NS	NS	NS	NS

† Spring soil NO_3^--N only included two N rates treatments, 0 and 160 kg N ha^{-1}.
‡ Fall soil NO_3^--N (0-15 cm) included all CC and N rates levels in four environments.
§ Fall soil NO_3^--N (15-60 cm) included 2018 Prosper and Hickson environments in the analysis. 2019 Prosper and Hickson environments were not included due to the excess of soil moisture conditions.

2.3.11. Maize biomass and grain yield relationship with NDVI index

Normalized difference vegetation index (NDVI) measured with the Greenseeker™ active-optical sensor at the V8 stage has been used to predict grain yield and aboveground biomass. Grain yield prediction models presented a coefficient of determination (r^2) greater than 0.62 in all treatments averaged across environments (Figure 4). The positive relationship between NDVI values and yield at V8 has been documented in previous research with the Greenseeker™ (Amado et al., 2017). The use of grain yield prediction with Greenseeker has been previously investigated in several crops in the Red River Valley with positive results (Bu et al., 2017). Maize biomass yield versus NDVI models had r^2 values greater than 0.49 in all cover crops treatments (Figure 5), confirming the valuable model prediction using NDVI with an active-optical sensor as Greenseeker™ (Tucker 1978; Rutan and Steinke, 2017).

2.3.12. Cover crops, nitrogen rates, and maize grain yield interactions

The maize N response models (Figure 6) indicate that forage pea increased maize grain yield slightly among all N rates and across four environments, with respect to all the cover crops treatments and the check. When forage pea is compared with the check at 40 kg N ha^{-1} rate, an increment of 7.7% in grain yield is observed, and at 160 kg N ha^{-1} rate, forage pea increased maize grain yield by 3.5%. However, it is not clear why the yield increase was greater at 40 kg ha^{-1} rate than at 160 kg ha^{-1} rate. This could be result of the N credit from pea but additional NO_3-N was not observed in soil tests, but could have mineralized after soil samples were taken (which is why there is an N credit). In addition, this could be related to slow cover crop biomass mineralization because of low temperatures during April 2018 and 2019 or lack of soil moisture in July 2018, but it is unknown how much N might have mineralized during the season.

The winter camelina response equation indicates reduced grain yield compared with that in the check response equation. At 0 kg N ha^{-1}, maize yield reduction was 22.5% following winter camelina. As previously discussed, the yield reduction is probably related to several factors related to winter camelina water use and possible allelopathic effects on maize seedling vigor. A drought period in early spring in 2018 resulted in lower soil water content following winter camelina with respect to the other treatments, affecting maize seedling growth and early germination.

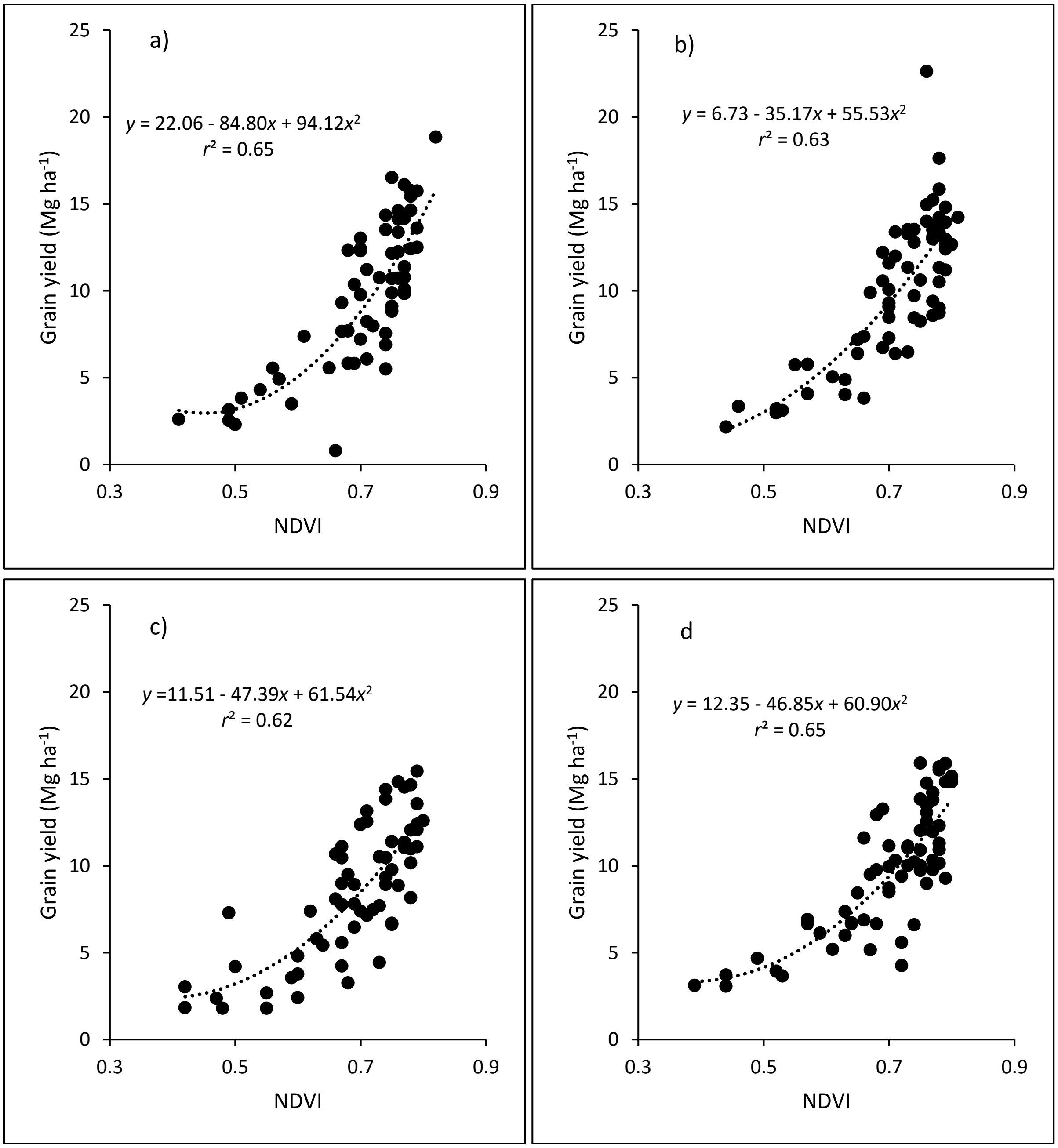

Figure 2.4. Prediction models for maize grain yield vs. NDVI measurements at the V8-stage: a) faba bean, b) forage pea, c) winter camelina, and d) check with no cover crop, averaged among four N rates and across four environments, Prosper and Hickson, in 2018 and 2019.

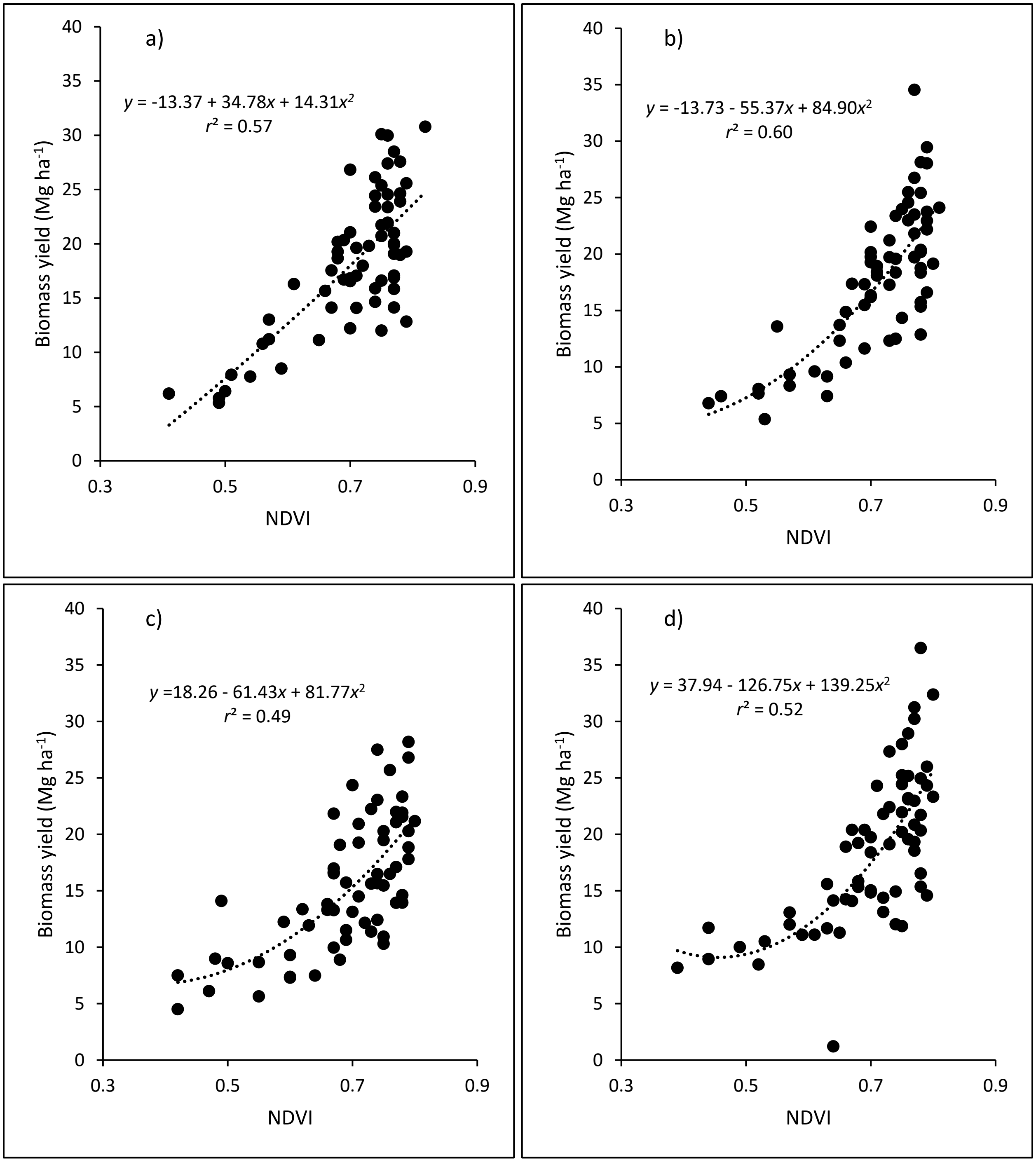

Figure 2.5. Prediction models for maize aboveground biomass vs. NDVI measured at the V8-stage: a) faba bean, b) forage pea, c) winter camelina, and d) check with no cover crop, averaged among four N rates and across four environments, Prosper and Hickson in 2018 and 2019.

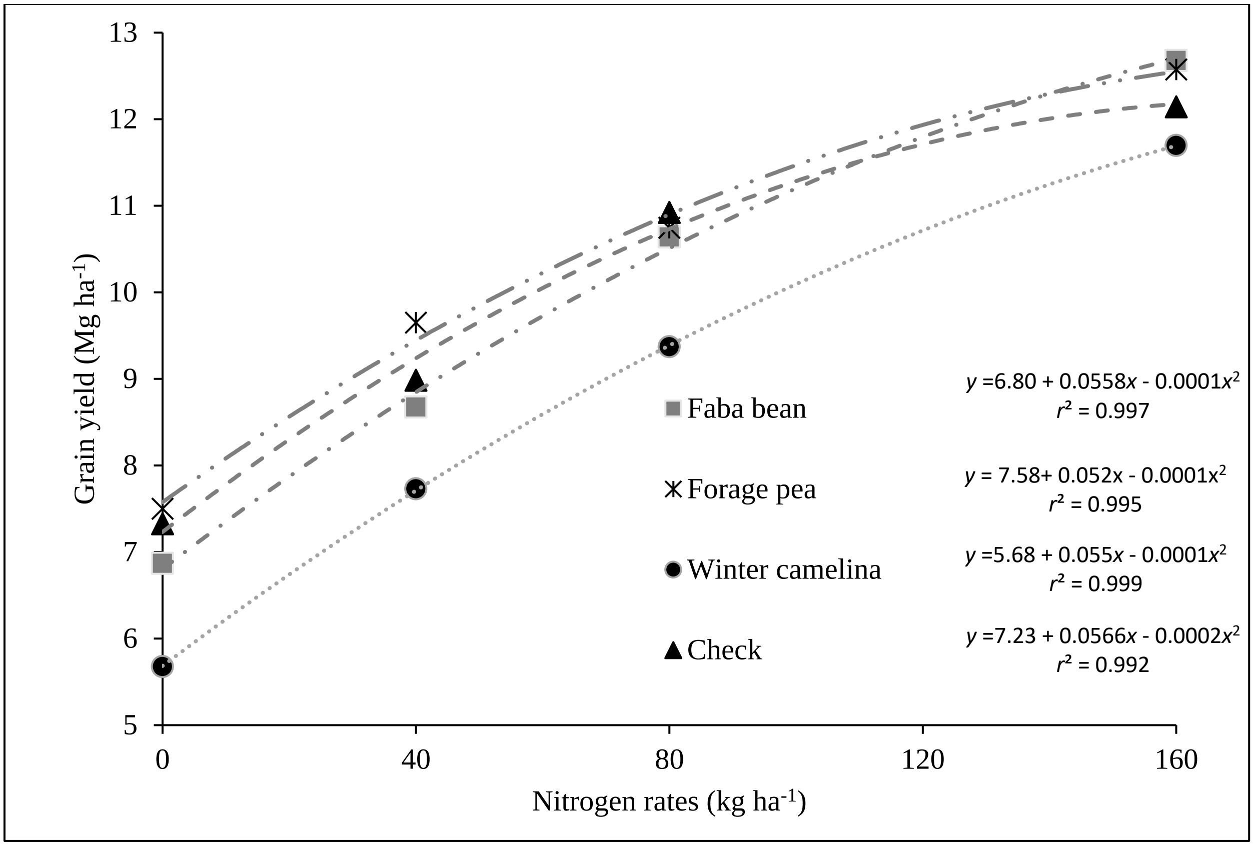

Figure 2.6. Interaction between maize grain yield and four N rates and cover crops treatments averaged across four environments, Prosper and Hickson, in 2018 and 2019.

2.4. Conclusions

Averaged fall biomass for all cover crops was 1.59 Mg ha^{-1} and soil coverage was greater in faba bean, forage pea, and winter camelina than in the check. Forage pea had the greatest ground cover because of its prostate growth. No differences in soil residual NO_3-N in late fall (0-60 cm) was observed after any of the cover crops. However, cover crops biomass N accumulation averaged 67 N kg ha^{-1}.

Winter camelina negatively affected maize grain yield in comparison with the other cover crop treatments averaged across environments. Grain yield reduction could be related to the late termination of the cover crop and a dry spring in 2018. Winter camelina reduced the soil water content significantly in Prosper and Hickson. Legumes cover crops slightly increase maize grain yield. However, this increment was not significant compared with the check plot.

Normalized difference vegetation index (NDVI), measured with an active-optical sensor, is a powerful tool to predict maize biomass and grain yield. This research demonstrated that NDVI predicts grain yield when measured at the V8 stage regardless of cover crop or N rate treatment. These results have considerable potential when cover crops are included in the cropping systems allowing farmers to take action to correct N rate early in the season to achieve target yields.

There are multiple advantages to using faba bean, forage pea, and winter camelina as a cover crop in the crop rotation. However, some disadvantages need to be considered: water use in drought conditions, cover crop late termination and early competition with cash crops, and slow cover crop biomass mineralization.

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CHAPTER 3. COVER CROPS DECREASE INITIAL WATER CONTENT, SUGARBEET ROOT YIELD, AND RESIDUAL NO_3-N

3.1. Abstract

Sugarbeet is a valuable crop in the Red River Valley of North Dakota and Minnesota, but it leaves the soil uncovered after harvest. Cover crops and no-tillage provide soil coverage, preventing soil erosion, and reducing NO_3-N leaching. The objective of this study was to evaluate sugarbeet yield response and sugarbeet chemical composition under different cover crop treatments. The experiment was constructed as a randomized complete block design (RCBD), with a split-plot arrangement, at two locations; Prosper and Hickson, ND, from 2017-2019. Forage radish (*Raphanus sativus* L.), winter camelina [*Camelina sativa* (L.) Crantz], winter wheat (*Triticum aestivum* L.), oat (*Avena sativa* L.), and winter rye (*Secale cereale* L.) were established into spring wheat stubble in August 2017 and 2018. A check treatment without cover crop was included. In late fall, soil NO_3-N (0-15 cm) was 46% greater in the check plots than with cover crops. Cover crop biomass yield was greater in forage radish and oat than the other cover crops. Winter-hardy cover crops were actively growing early in the spring, and the greatest biomass was with winter rye (1.93 Mg ha^{-1}). Prosper and Hickson in 2018 experienced a dry spring and gravimetric water content was less under winter rye and winter camelina compared with the check. Sugarbeet was planted into the residue of fall-planted cover crops. Two N treatments, 0 and 112 kg N ha^{-1}, applied. At Prosper and Hickson 2018, sugarbeet establishment and root yield was less following winter rye and winter camelina. Cover crops scavenged residual soil NO_3-N, reducing risk of loss through leaching or denitrification and surface run-off. Winter-hardy cover crops provided green soil cover in the spring and decreased gravimetric water content, stand count, and sugarbeet yield. Reducing soil water content can be advantageous

in some years, allowing earlier sugarbeet planting in high clay soils during wet springs but reduced soil water content is detrimental to sugarbeet establishment and yield in dry springs.

3.2. Materials and methods

3.2.1. Field establishment

This research was conducted from 2017 to 2019 in Prosper, ND (-97°01’ W, 46°57’ N, 240 m elevation) and Hickson, ND (-96°49’ W, 46°387’ N, 281 m elevation). The soil series at Prosper is a Fargo-Hegne silty clay, (Fargo: fine, montmorillonitic, frigid, Vertic Haplaquol with a leached and degraded nitric horizon, Hegne: fine, smectitic, frigid Typic Calciaquerts), and the soil type at Hickson is a Perella?-Bearden silty clay loam (Perella: fine-silty, mixed, superactive Typic Endoaquoll, Bearden: fine-silty, mixed, superactive, frigid Aeric Calciaquoll) (Web Soil Survey, 2017).

Rainfall and the daily temperature were recorded by the North Dakota Agricultural Weather Network (NDAWN) stations nearest both locations (Figure 1).

3.2.2. Experimental layout and design

The wheat cultivar used in the research was ‘Glenn.’ It was seeded using a Great Plains™ 15-cm row space grain drill (Great Plains Manufacturing Company, Salinas, KS) at 4,450,000 pure live seed (PLS) ha^{-1} on 20 April 2017 and 15 May 2018, at Prosper on 25 April 2017, and 2 May 2018, in Hickson. The experiment at Prosper was fertilized, both years, with 90 kg N ha^{-1} and 17 kg P_2O_5 ha^{-1} (urea 188 kg ha^{-1} and mono ammonium phosphate (MAP) 33 kg ha^{-1}) and at Hickson fertilization was 88 kg N ha^{-1} and 24 kg P_2O_5 ha^{-1} (urea 180 kg ha^{-1} and MAP 46 kg ha^{-1}). Wheat harvest at Prosper was on 5 August 2017 and 8 August 2018, and at Hickson wheat harvest was on 8 August 2017 and 9 August 2018.

The cover crop experiments were constructed using a randomized complete block design (RCBD) with four replicates at both locations in both years. Treatments included in the field experiments were winter rye, winter camelina, winter wheat, oat, radish, and a check without cover crop.

Cover crops were sown after excess wheat stubble was removed in each experimental unit with a leaf blower (BR 299, Stihl, Waiblingen, Germany), and cover crops were sown after. Cover crops were sown into the remaining standing wheat stubble with a XL Plot seeder (Wintersteiger, Austria). The sowing dates were 14 August 2017 and 16 August 2018 at Prosper, 22 August 2017 and 13 August 2018 at Hickson.

The experimental units were treated with glyphosate (N-(phosphonomethyl)-glycine, 1.4 kg a.i. ha^{-1},) after wheat harvest to kill volunteer wheat. Each experimental unit consisted of eight cover crop rows, with a 15-cm spacing over an experimental unit surface area of 10.45 m^2 (7.6 m length x 1.37 m width). Cover crop seeding rates were based on pure live seed (PLS) ha^{-1} (Table 3.1). Cover crops were not fertilized in the fall.

Table 3.1. Cultivar, 100-seed weight, and sowing rate (pure live seed, PLS) of cover crops at Prosper and Hickson, ND, 2017-2018.

Cover crop	Cultivar	100-seed weight	Sowing rate	Sowing density
		g	kg PLS ha^{-1}	PLS ha^{-1}
Winter rye	ND Dylan	2.509	86	3,432,000
Winter camelina	Joel	0.098	10	10,190,000
Winter wheat	Jerry	3.356	100	2,994,000
Oat	Souris	3.198	100	3,142,000
Radish-Daikon	SoilBuster	1.635	16	965,000

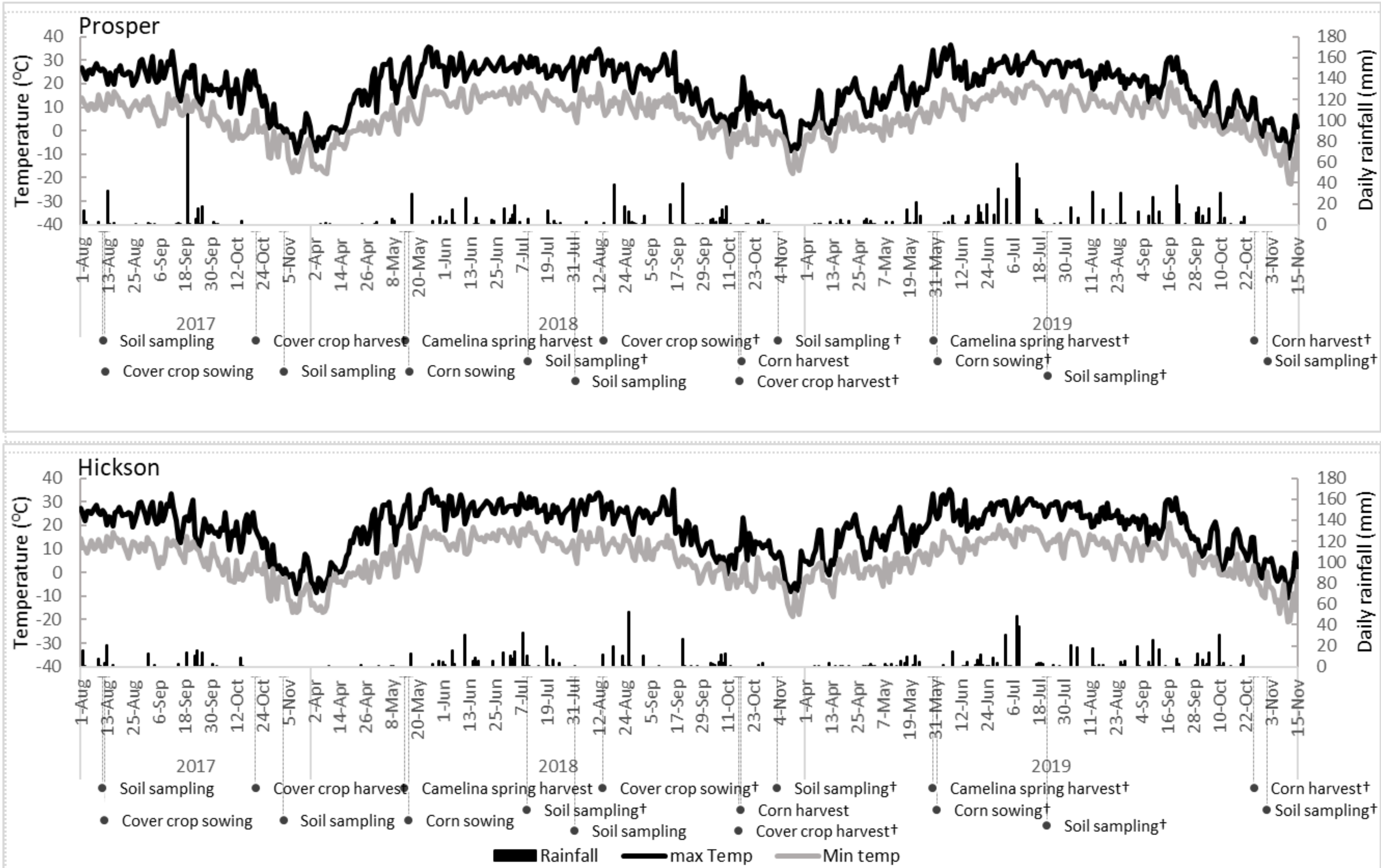

Figure 3.1. Daily rainfall, maximum, and minimum temperature, and main field activities in Prosper and Hickson, from August 2017 to November 2019.

† Field activities of the second environment from the same location

3.2.3. Sugarbeet experiment design

Sugarbeet was sown where cover crop treatments were present the previous fall. The experiment was a RCBD with a split-plot arrangement and four replicates. The main plots were the previous season cover crop treatments. Sub-plots were the two N rates, 0 (check) and 112 kg N ha^{-1}. Before sugarbeet sowing, all experimental units were sprayed with glyphosate at the rate (N-(phosphonomethyl)-glycine, 1.4 kg a.i. ha^{-1}) to control weeds and winter-hardy cover crops that were actively growing. Sugarbeet hybrid, SVRR747 from SES Vanderhoff, was sown into wheat stubble/cover crop residue in 56-cm spaced rows using a MaxEmerge XP™planter (John Derr, Moline, IL) at Prosper on 14 May 2018 and 30 May 2019; and at Hickson on 15 May 2018 and 3 June 2019. Each experimental unit consisted of three sugarbeet rows, each 7.6-m in length. Urea, as the N source used, was broadcast at sowing. To reduce N losses, a urease inhibitor, Limus™ (urease inhibitor (N-(n-butyl) thiophosphoric triamide and N-(n-propyl) thiophosphoric triamide, Nitrogen Management, BASF), was impregnated onto the urea pellets at a rate of 0.59 kg a.i. per metric ton of urea prior to application. For weed control, glyphosate was used at 1.4 kg a.i. ha^{-1}, at the V13 stage prior to canopy closure. Weed control was excellent in all locations and years.

3.2.4. Plant sampling and analysis

Cover crop green foliage coverage and stand count were determined in the fall before the first frost on 30 October 2017 and 2 October 2018, in Prosper and Hickson, respectively. Green coverage was determined using Canopeo © application (Canopeo, Oklahoma State University, Stillwater, OK). Images were taken 1-m NADIR above the soil surface and then processed in Canopeo toolbox for Matlab R2020a, obtaining green ground coverage as a percentage of the total surface. Cover crops stand count was measured in a 1-m^2 area in each experimental unit. The percentage of emergence was calculated as the ratio between PLS sown and emerged plants

Cover crop aboveground biomass samples were collected before the first frost, at Prosper on 26 October 2017 and 15 October 2018, and in Hickson on 27 October 2017 and 16 October 2018. Biomass samples were taken immediately above the soil surface from a 0.2-m^2 area in each plot, placed in paper bags, and dried at 70°C until a constant weight. Biomass samples were ground to pass through a 1-mm sieve using an electric mill (E3703.00, Eberbach Corporation, Bellville, MI). The same procedure was used for winter camelina samples obtained in spring at both locations.

Cover crops biomass samples were analyzed using near-infrared reflectance spectroscopy (NIRS) with an XDS analyzer device (Foss, Denmark) to obtain N, P, and ash concentration. Crude protein (CP) was obtained by multiplying by 6.25 the N value. Biomass N and P accumulation were calculated by multiplying total biomass by N and P concentration.

Normalized difference vegetation index (NDVI) was measured at V7 and V10 sugarbeet stage using a handheld GreenSeeker™ active-optical sensor (Handheld crop sensor, Trimble Inc., Sunnyvale, CA). The device was positioned so that the light emitting/receiving instrument was directly 60-cm above the canopy, and measurements were taken over the center-row (7.6-m in length) within each experimental unit. All measurements began at the beginning of the experimental unit borders to avoid differences in plant angle.

Sugarbeet leaf biomass was collected at Prosper on 5 October 2018 and 15 September 2019 and in Hickson on 31 October 2018 and 15 September 2019. Leaf biomass was collected and weighed from 1-linear meter of each center-row. The leaf samples were dried at 70°C to reach constant weight, which was used to calculate dry weight biomass, and leaf biomass ha^{-1}.

Sugarbeet harvest stand count and root biomass yield were obtained on the same days, at Prosper on 19 October 2018 and 19 September 2019, and at Hickson on 15 October 2018 and 18 September 2019. Stand counts were taken from a 7.62-m length in the center-row of each plot to calculate plants ha^{-1}. On harvest day, sugarbeet plants were defoliated using a three-row sugarbeet defoliator and harvest was performed using a sugarbeet plot harvester. Then, the beets from the center-row (7.62-m) of each plot was collected and weighed and the root yield determined. Sugarbeet samples (500 g per plot approx.) were collected and dried at 70°C to reach constant weight to obtain root dry biomass. A sugarbeet sample of 10 kg (fresh weight) from each plot was taken and sent to Crystal Sugar Company, East Grand Forks, ND, to determine sucrose concentration (g kg^{-1} and %), α-amino nitrogen (AM-N), Na, and K concentration in sugarbeet roots. The ICUMAS Copper method, with a spectrophotometer at 610-nm wavelength range was used to determine amino-N (mg kg^{-1}) (International Commission for Uniform Methods for Sugar Analysis, 2007), and flame photometry was used to determine Na and K content (mg kg^{-1}). Sucrose loss to molasses (SLM) was determined with the following equation (Campbell and Fugate, 2013; Chatterjee et al., 2018; Olson et al., 2019):

$$SLM = 1.5x[(3.5xNa) + (2.5xK) + (9.5xAM - N)]/11000$$

Root yield (Mg ha^{-1}), sucrose purity (%), and recoverable sucrose (Mg ha^{-1}) were calculated with the following equations (Campbell, 2002; Chatterjee et al., 2018; Olson et al., 2019):

$$Root\ yield\ \left(\frac{Mg}{ha}\right) = \frac{\left[\frac{harvested\ plot\ weight\ (kg)}{\text{hectare of harvested plot}}\ x\ 100\right]}{1000}$$

$$Sucrose\ purity\ (\%) = \frac{\%\ sucrose\ content - \%\ sucrose\ losss\ to\ molasses\ (SLM)}{\%\ sucrose\ content} x\ 100$$

$$Recoverable\ sucrose\ \left(\frac{Mg}{ha}\right) = (\frac{Purity\ (\%)}{100})\ x\ Root\ yield$$

3.2.5. Soil sampling and analysis

After wheat harvest, composite soil samples were taken in Prosper on 8 August 2018 and 9 July 2018, and in Hickson on 12 July 2017 and 17 August 2018. Three core samples (2.5 cm diameter) were collected at 0-15 cm and 15-60 cm depth in each replicate (Table 2.2). Samples taken at 0-15 cm depth were tested for NO_3-N using the determination of soil nitrate by transnitration of salicylic acid method (Vendrell and Zupancic, 1990), soil pH was measured potentiometrically in a slurry using an electronic pH meter (Watson and Brown, 1998), organic matter was determined with the Loss in ignition (LOI) method (Hoogsteen et al., 2015), P content was determined with the Olsen method (Olsen, 1954), and K determined with the ammonium acetate method (Warncke and Brown, 1998); using an Atomic Absorption Spectrophotometer (Buck Scientific 210 VGP, East Norwalk, CT). Soil samples at 15-60 cm depth were analyzed for NO_3-N with the same Vendrell and Zupanic (1990) method.

In late fall, after cover crops were terminated with frost, three soil core samples were collected in each experimental unit. These samples were tested for NO_3-N, using the method mentioned previously at 0-15 cm and 15-60 cm depth. Samples were taken on 2 November 2017 and 14 November 2018 in Prosper and on 2 November 2017 and 15 November 2018 in Hickson.

Spring soil sampling was performed on 9 July 2018 and 15 July 2019 at Prosper and on 23 July 2018 and 23 July 2019 at Hickson on all experimental units. Soil NO_3-N was analyzed on the 0-15 cm and 15-60 cm depths separately.

After sugarbeet harvest, soil samples were collected on 19 October 2018 and 19 September 2019 at Prosper, and on 10 October 2018 and 18 September 2019 at Hickson, using the same procedure as in the spring sampling.

Table 3.2. Soil chemical properties for cover crops experiments after wheat in Prosper and Hickson, ND, in 2017 and 2018.

Environment	pH†	OM	P	K	NO_3^--N	
					0-15 cm	15-60 cm
		g kg^{-1}	———mg kg^{-1}———		————kg ha^{-1}————	
Prosper 2017	6.63	33.5	26.00	201.5	23.82	40.88
Prosper 2018	8.05	40.7	20.75	240.5	2.24	4.20
Hickson 2017	7.43	59.5	20.75	374.5	32.34	37.27
Hickson 2018	7.75	49.3	10.25	345	12.61	5.88

†pH, organic matter (OM), P, and K values were taken at 0-15 cm soil depth

Soil NO_3-N was analyzed for the 0-15 cm and 15-60 cm depths in 2018. In 2019, it was not possible to take samples at the 15-60 cm depth because of excessive of soil water at both experimental locations below 15 cm.

3.2.6. Statistical analysis

Statistical analysis for cover crop experiments was conducted using standard procedures for an RCBD. Cover crop stand count, biomass yield, and biomass quality parameter differences were analyzed using analysis of variance with the MIXED procedures of SAS 9.4 (SAS Institute, Inc. 2013). The means separation test was performed using the least significant difference (LSD) ($P \leq 0.05$). An environment was defined as a location-year combination. Homogeneity of variance for each trait was tested for four environments, and if homogenous, a combined analyzed procedure was conducted. Environments were considered a random effect, while the remaining variables were considered fixed effects. All interactions of fixed effects with environments were considered random effects in the analysis.

For sugarbeet experiments, statistical analysis was performed using the standard procedure for a RCBD with a split-plot arrangement. Sugarbeet stand count, total biomass, root yield, and sugarbeet quality parameter differences were determined using analysis of variance with the MIXED procedures of SAS 9.4, and the means separation test was performed using

LSD ($P \leq 0.05$). As in the previous experiment, environment was considered a location-year combination. Environments and their interactions were considered random effects, and the remaining variables were considered fixed effects. Before the combined analysis, all of the environments were tested with homogeneity of variance.

3.3. Results and discussion

3.3.1. Weather

Cover crops were growing from August to October. In Prosper, fall 2017, the average rainfall was 17.4-mm higher than an average year. On 19 September, a 106-mm rain event left the cover crops under flooded conditions for several days. Temperature was 0.5ºC lower than the 30-yr average (Table 3.3) and the first frost was 9 September (-2.9 ºC). At Prosper in 2018, rainfall was 22-mm greater than the 30-year average and the temperature was 1.7º C less than the average. At Hickson, fall 2017 rain and temperature were 48.7-mm and 0.7-ºC less than the 30-year average, respectively. The first frost was on 28 September (-3.3 ºC) (Table 3.3), and rainfall was 192-mm greater than average, while the temperature was 1º C less than average (Table 3.3). These lower-than-average temperatures probably negatively affected biomass accumulation of all cover crops during the fall.

Sugarbeet was grown from May to October at Prosper and Hickson in 2018 and from May to September in 2019. At Prosper 2018, the growing season was dry with 78-mm less than average and conditions were even dryer during May and June with 56.6-mm less than the 30-year rainfall average, which probably affected early sugarbeet growth. The temperature was 7.3ºC greater than average. The opposite situation occurred at Prosper in 2018, with rainfall 192-mm greater than an average year, and the temperature was 1ºC less than average (Table 3.3).

Table 3.3. Monthly temperature, rainfall and comparison with the 30-year average for Prosper and Hickson, ND, in 2017, 2018, and 2019.

			Temperature				Rainfall	
Location	Year	Month	Max	Min	Avg	±(x̅) †	Total	±(x̅) ‡
			-------------------------ºC--------------------				------------mm---------	
Prosper	2017	Aug	24.8	11.3	18.1	-2.3	52.6	-13.9
		Sept	22.1	8.5	15.3	0.5	151.7	86.2
		Oct	15.1	0.0	7.5	0.3	6.9	-54.9
	2018	Apr	5.5	-5.6	0.0	-6.4	3.8	-33.0
		May	25.0	8.7	16.9	3.4	53.9	-23.6
		June	26.8	14.2	20.5	1.8	79.3	-21.1
		July	26.9	13.6	20.3	-1.0	65.3	-22.6
		Aug	26.7	12.0	19.4	-1.0	78.5	12.0
		Sept	20.9	7.4	14.1	-0.7	70.9	5.4
		Oct	9.0	-1.4	3.8	-3.5	66.6	4.9
	2019	Apr	9.8	0.3	5.0	-1.3	23.2	-13.6
		May	17.3	4.0	10.7	-2.8	60.0	-17.5
		June	26.0	12.3	19.2	0.5	122.0	21.7
		July	28.1	15.6	21.9	0.6	156.1	68.2
		Aug	24.3	12.5	18.4	-2.0	102.4	35.9
		Sept	20.7	10.3	15.5	0.7	147.7	82.1
		Oct	8.6	0.7	4.6	-2.7	77.0	15.3
Hickson	2017	Aug	25.0	11.6	18.3	-2.2	49.8	-12.9
		Sept	22.2	8.8	15.5	0.3	69.1	5.6
		Oct	15.1	0.2	7.6	-0.1	11.9	-41.4
	2018	Apr	6.4	-5.0	0.7	-6.4	1.8	-36.6
		May	25.5	8.7	17.1	3.1	22.1	-54.6
		June	27.3	14.1	20.7	1.7	95.0	2.3
		July	27.2	14.2	20.7	-0.9	107.3	24.7
		Aug	26.4	12.2	19.3	-1.3	96.0	33.3
		Sept	21.1	6.8	13.9	-1.3	38.6	-24.9
		Oct	9.7	-1.7	4.0	-3.7	46.2	-7.1
	2019	Apr	11.0	0.0	5.5	-1.6	9.4	-28.9
		May	17.6	3.9	10.8	-3.2	44.2	-32.5
		June	25.8	12.4	19.1	0.0	56.1	-36.6
		July	27.7	14.8	21.3	-0.4	132.9	50.4
		Aug	24.4	12.3	18.3	-2.2	71.9	9.2
		Sept	21.1	9.9	15.5	0.3	92.0	28.5
		Oct	9.3	0.1	4.7	-3.0	71.7	18.3

† Difference between observed temperature and the average temperature based on 1981-2010 (NDAWN, 2020)
‡ Difference between observed rainfall and the average rainfall based on 1981-2010 (NDAWN, 2020)

At Hickson in 2018, rainfall was 62.8-mm less than the 30-year average. Rainfall during May was 54.6-mm less than average. The dry conditions negatively affected sugarbeet germination and growth. Over the growing season, temperature was 1.3ºC less than average, which also negatively impacted sugarbeet growth. Hickson conditions in 2019 were different from the previous year, with a total rainfall of 8.4-mm greater than average and temperature was 1.4ºC less than average (Table 3.3).

Table 3.4. Combined analysis of variance and mean square values of five cover crops (CC) for fall CC stand count, emergence (CC planted seed vs. CC stand count), and CC ground cover at four environments (Env), Prosper and Hickson, in 2017 and 2018.

SOV	df	Plant density ($x10^6$)	Emergence	df	Ground cover†
Env	3	2184811	68.4	3	5767.2*
Rep(env)	12	1530674	114.9	12	800.8*
CC	4	96354983*	9412.4*	5	3000.1*
Env x CC	12	3849420	131.6	15	834.1*
Error	48	4999590	148.3	60	149.3
CV%		31	18.6		30.8

* Significantly different ($P \leq 0.05$).

† CC green soil cover included also check plot (without CC) in the analysis.

3.3.2. Cover crops emergence and soil green cover

Cover crops plant density was significantly different ($P < 0.05$) among cover crop treatments across four environments (Table 3.4). This result was expected because the cover crops are from different botanical families and have different growth habits. Consequently, sowing rates were different (Table 3.1). Winter rye, winter wheat, and oat averaged 2,378,152 plants ha^{-1}, which was significantly higher than that of forage radish (1,057,891 plants ha^{-1}). Winter camelina had significantly higher plant density than all cover crops in the study (3,185,466 plants ha^{-1}). The fall plant stand observed was similar to that reported in another winter camelina study in the Red River Valley in which the optimum fall sowing date was evaluated (Wittenberg et al., 2020) (Table 3.5).

The percent emergence was also significantly different ($P < 0.05$) among cover crop treatments across four environments (Table 3.4). The greatest emergence was in forage radish with more than 100% (within the expected range of experimental error). Winter wheat and oat emergence was 75.1 and 82.3%, respectively, and winter rye was 67%. The lowest value was in winter camelina with 31.3% emergence (Table 3.5). Wittenberg et al. (2020) reported pure live seed emergence of winter camelina ranged from 3 to 45%, depending on the sowing date. The highest emergence observed of winter camelina (45%) was obtained at a similar sowing date as in this study.

Table 3.5. Mean for five cover crops (CC) and check for fall CC stand count, emergence (CC planted seed vs. CC stand count), and CC green soil cover averaged across four environments (Env), Prosper and Hickson in 2017 and 2018.

Cover crops	Plant density	Emergence	Ground cover
	plants ha^{-1}	--------------------------%-------------------------	
Winter rye	2300787	67.0	45.5
Winter camelina	3185446	31.3	32.7
Winter wheat	2246967	75.1	28.4
Oat	2586703	82.3	51.9
Forage radish	1057891	109.6†	55.7
Check	-	-	20.8
LSD (*P* = 0.05)	477939	9.8	21.8

†Radish emergence was 109.6 % because of sampling experimental error.

Ground cover was different among cover crops averaged across environments (Table 3.4). Cover crops provide soil ground cover that serves as a physical barrier, decreasing soil erosion (Kaspar et al., 2001b; Blanco-Canqui et al., 2015). Also, the absence of tillage gives extra protection to the soil structure and surface from previous residue (Kaspar et al., 2001b; Ward et al., 2012; Blanco-Canqui et al., 2015; Basche et al., 2016a). In this study, standing wheat stubble, combined with biomass from previous crops as well as the cover crops provided soil protection. The greatest ground cover was in oat and forage radish with 51.9 and 55.7% coverage (Table 3.5). Winter rye ground cover was 45.5%, with good tillering and plant growth at the end of the season. Winter camelina soil green cover was 32.7% (Table 3.5), which was significantly less than that of oat and radish. Winter camelina can survive the winter in North

Dakota and it has been useful as a green soil cover during early spring in the USA upper Midwest (Gesch and Cermak, 2011; Berti et al., 2016b), but during fall, it is in the rosette stage and provides only partial soil cover. Soil coverage reduces run-off and wind erosion significantly (Blanco-Canqui et al., 2015). One study recorded 57% soil loss reduction from 20% soil cover and 95% soil losses from 50% soil cover (Fryrear, 1985). In our study, winter rye and winter camelina exceeded 20% coverage with oat and forage radish exceeding 50% coverage.

3.3.3. Cover crop biomass yield

Fall biomass yield was significantly different among cover crops and across environments (Table 3.6). Oat produced the greatest biomass yield of all cover crops averaged across the four environments. This result indicates that an oat cover crop is well adapted to the North Dakota conditions when planted in August (Franzen et al., 2019d). Forage radish biomass yield was also high averaged across environments (1.77 Mg ha^{-1}), with similar biomass yield reported in some other studies, although biomass is considerably variable among environments (Samarappuli et al., 2014; Ruark et al., 2018; Peterson et al., 2019b). Winter-hardy cover crops (winter rye, winter wheat, and winter camelina) produced less biomass than radish (Table 3.6). Winter annual crops require vernalization to bolt, so they remain in the vegetative stage in the fall. Similarly, other studies in the upper Midwest (Gesch and Cermak, 2011; Kaspar and Bakker, 2015; Berti et al., 2016b) indicate these crops partially exhibit their full growth potential in the fall.

In the spring, winter rye produced significantly higher biomass than winter wheat (Table 3.7). These results are similar to other studies where winter rye had better winter survival and greater biomass than winter wheat (Peltonen-Sainio et al., 2011). Kaspar et al. (2015) reported that 12 winter rye cultivars had greater biomass and better winter survival than two winter wheat cultivars in the USA upper Midwest. In our study, winter rye and winter wheat were terminated two weeks before sugarbeet planting, which means that these cover crops had a 14-day shorter growth period than winter camelina.

Table 3.6. Combined analysis of variance and mean square values in five cover crops (CC) for aboveground biomass, P and N biomass accumulation in fall, spring, and total (fall and spring) at four environments (Env), Prosper and Hickson, in 2017, 2018, and 2019.

	CC Fall				CC Spring†				CC Total			
SOV	df	Biomass	P	N	df	Biomass	P	N	df	Biomass	P	N
Env	3	4656583*	232.3*	7195*	3	1492720*	19.9*	458*	3	2522926*	146.0*	5697*
Rep(env)	12	870022*	40.2*	1795*	12	86992	1.3	85	12	1103715*	45.7*	2385*
CC	4	1647594*	38.9	1102*	2	1405440*	34.6	643	4	6760554*	180.7*	10141*
Env x CC	12	276139	15.7	194	6	151916*	8.7*	400*	12	533289	30.3*	620
Error	48	205972	8.6	317	23	55143	1.5	105	48	343562	11.3	457
CV%		31	38.5	44		15	16.7	18		24	28.1	29

* Significantly different ($P \leq 0.05$).

† CC spring only includes cover crops that were actively growing on spring across four environments, Prosper and Hickson, 2018 and 2019.

Table 3.7. Aboveground biomass, P and N biomass accumulation in fall, spring, and total (fall and spring) for cover crops (CC) averaged across four environments (Env), Prosper and Hickson, in 2017, 2018, and 2019.

	CC Fall			CC Spring†			CC Total		
Cover crop	Biomass	P	N	Biomass	P	N	Biomass	P	N
	Mg ha^{-1}	------kg ha^{-1}----		Mg ha^{-1}	-----kg ha^{-1}----		Mg ha^{-1}	-----kg ha^{-1}----	
Winter rye	1.43	8.1	39.3	1.93	9.0	62.6	3.36	17.1	101.9
Winter camelina	1.19	6.3	36.5	1.41	7.0	58.0	2.52	12.9	83.1
Winter wheat	1.12	5.6	31.4	1.39	6.1	49.7	2.51	11.8	89.3
Oat	1.81	8.9	42.0	-	-	-	1.82	8.9	42.0
Radish	1.78	9.1	53.7	-	-	-	1.78	9.1	53.7
LSD (P = 0.05)	0.40	NS	10.7	0.17	NS	NS	0.56	4.2	19.2

† CC spring only includes cover crops that were actively growing on spring across four environments, Prosper and Hickson, 2018 and 2019

Winter camelina had excellent winter survival in the four environments, producing 1.42 Mg ha^{-1} (Table 3.7), similarly to results from several studies in the USA upper Midwest (Gesch and Cermak, 2011; Gesch et al., 2014; Berti et al., 2016b; Peterson et al., 2019b). Winter camelina was bolting when sugarbeet was planted but its presence did not result in any problem to the planter. Winter wheat had good winter survival in all the environments. However, the biomass yield was significantly less than that of winter rye, 1.39 Mg ha^{-1}; the lower biomass of winter wheat agreed with observations presented by Kaspar et al. (2015). All winter-hardy cover crops produced enough biomass in the early spring to cover the soil, which reduced the risk of wind erosion.

Winter-hardy cover crops had greater total biomass (fall + spring) than annual cover crops (Table 3.6). Winter rye had the greatest overall biomass yield, which is the sum of fall and spring biomass (Table 3.7). Kaspar et al. (2012) reported similar results, where winter rye biomass yield was greater than oat biomass due to the additional biomass produced by winter rye in early spring. These results follow the same trend as previous studies where winter rye biomass yield is compared with that of other cover crops (Kaspar et al., 2001b; Dinnes et al., 2002; Basche et al., 2016a; Peterson et al., 2019b). Forage radish had the least overall biomass yield, with 1.77 Mg ha^{-1}. Forage radish is a cool-season crop that had excellent growth in the fall and produced significantly greater biomass yield than winter-hardy cover crops in the fall. In addition, forage radish has considerable belowground biomass due to the taproot, but this was not evaluated in this research. Another study in the USA upper Midwest reported that radish had 68% more above ground biomass than oat during a similar growing period (Rutan and Steinke, 2019).

Fall N biomass accumulation was significantly different among cover crops averaged across the four environments. The highest N accumulation was in forage radish with 53.6 kg N ha^{-1}. The forage radish used in this study is a Daikon type which has with the potential to produce a prominent taproot and has the ability to scavenge N deep from the soil profile if the growing period is sufficiently long, which, moves nutrients to the surface soil (White and Weil, 2011). Forage radish biomass N accumulation was greater than that of oat (42 N kg ha^{-1}) and all winter-hardy cover crops. A previous study showed similar results, in which forage radish had the highest N accumulation compared with oat in the fall (Rutan and Steinke, 2019). The least N accumulation was from winter wheat(31.4 kg ha^{-1}). Winter camelina and winter rye N accumulation was similar. In spring, N content in the biomass did not differ significantly different between winter rye, winter camelina, and winter wheat which averaged 56.7 kg ha^{-1}. Winter rye accumulated 101.9 N kg ha^{-1}, in both fall and spring summed up, which was similar to winter camelina (83.1 N kg ha^{-1}) and winter wheat (83.3 N kg ha^{-1}) for total N accumulation.

Phosphorus accumulation in the biomass was similar among cover crops averaged across environments in the fall and spring. However, the sum of P accumulated in the fall and spring was different among cover crops. Winter rye took up 17.1 kg P ha^{-1}. Forage radish is a good scavenger and recovers significant amounts of P from the soil (Maltais-Landry et al., 2014). Winter camelina and winter wheat were actively growing in early spring and had the highest P accumulation. Similar values of P extraction by cover crops were reported by Peterson et al. (2019) and Berti et al. (2015).

The ash concentration was different among cover crops averaged across environments in the fall (Table 3.8). Winter camelina (203 g kg^{-1}) and radish (193 g kg^{-1}) had the greatest ash concentration among all cover crops (Table 3.9).

Table 3.8. Combined analysis of variance and mean square values in five cover crops (CC) for cover crop biomass crude protein (CP), ash, P and N concentration in four environments (Env), Prosper and Hickson, in 2017 and 2018.

	CC Fall					CC Spring†				
SOV	df	CP	Ash	P	N	df	CP	Ash	P	N
Env	3	15818*	10454*	7.66*	404*	3	17922*	15034*	1.18*	470*
Rep(env)	12	7957*	2592	0.60	123*	12	855*	677*	0.07	22
CC	4	15920	15528*	1.13	192	2	18826*	47382	1.08	376*
Env x CC	12	14852*	2629	3.24*	91*	6	1402*	26396*	1.22*	29*
Error	48	2232	1691	0.39	32	23	333	132	0.08	10
CV%		25	25	12.42	21		9	7	5.95	9

* Significantly different ($P \leq 0.05$).

† CC spring only includes cover crops that were actively growing on spring across four environments, Prosper and Hickson, in 2018 and 2019.

Table 3.9. Cover crop (CC) biomass, crude protein (CP) ash, P, and N concentration averaged across four environments, Prosper and Hickson, 2017 and 2018.

	CC Fall				CC Spring†			
Cover crop	CP	Ash	P	N	CP	Ash	P	N
	g kg^{-1}							
Winter rye	201	154	5.5	25.1	195	221	4.7	33.1
Winter camelina	219	204	5.0	30.3	184	115	5.1	36.7
Winter wheat	196	154	5.0	27.2	249	190	4.5	42.6
Oat	135	127	4.9	21.7	-	-	-	-
Radish	183	193	4.8	29.2	-	-	-	-
LSD (P = 0.05)	NS	39	NS	NS	13	NS	NS	2.4

† CC spring only includes cover crops that were actively growing on spring across four environments, Prosper and Hickson, in 2018 and 2019.

In early spring, CP and N concentration were significantly different among cover crops averaged across environments. Crude protein was greater in winter wheat than winter rye and winter camelina. This was expected because winter wheat forage yield was less in comparison with other cover crops and crops in the earlier vegetative stages usually have greater CP concentration. As cereals grow and develop, the N concentration in the biomass decreases, and the C:N ratio increases as tissues mature (Muldoon, 1986; Kaspar and Bakker, 2015).

Gravimetric water content was not significantly different among cover crops averaged across environments. Gravimetric water content average was 224 g kg^{-1} in the fall and 261 g kg^{-1} in the spring averaged across all treatments. However, in the spring, the interaction of environment by cover crop was significant (Table 3.8). In the early spring of 2018 at Prosper and Hickson, gravimetric water content was less in winter rye (190 and 208 g kg^{-1}, Prosper and Hickson, respectively) and winter camelina (190 and 201 g kg^{-1}, Prosper and Hickson, respectively) than the soil with winter-killed cover crops or no cover crop (Table 3.12). These results were similar to those reported in Iowa in 2012 during a drought, where soils with winter rye had significantly less available soil water than without cover crops (Daigh et al., 2014). A different situation happened in 2019, when the spring was wet (Figure 3.1). There were no significant differences in gravimetric water content among cover crops. This is similar to other studies where no differences in soil water availability among cover crops was recorded in a wet spring, because rainfall filled back the soil profile, regardless of the amount of water extracted previously for cover crops (Daigh et al., 2014; Hill et al., 2016).

Table 3.10. Combined analysis of variance and mean square values of five cover crops (CC) for fall and spring soil gravimetric water and soil NO_3-N in four environments (Env), Prosper and Hickson, in 2017 and 2018.

		Fall			Spring		
SOV	df	Gravimetric water	NO_3-N (0-15 cm)	Soil NO_3-N (15-60 cm)	Gravimetric water	NO_3-N (0-15 cm)	NO_3-N (15-60 cm)
Env	3	261.1*	93.5*	240.9*	597.8*	663.1*	2302.0*
Rep(env)	12	8.1*	7.2	34.5*	3.3	126.0*	184.8*
CC	5	8.1	11.2	53.6*	16.0	17.2	161.0*
Env x CC	15	3.1	6.5	13.0	9.3*	36.9	55.4
Error	60	3.8	4.8	16.3	2.2	22.4	80.9
CV%		8. 7	45.2	48.8	5.7	38.3	66.0

Table 3.11. Fall and spring soil gravimetric water and soil NO_3-N for cover crops and the check averaged across four environments, Prosper and Hickson, in 2017 and 2018.

	Fall			Spring		
Cover crop	Gravimetric water	NO_3-N (0-15 cm)	NO_3-N (15-60 cm)	Gravimetric water	NO_3-N (0-15 cm)	NO_3-N (15-60 cm)
	$g\ kg^{-1}$	-------kg ha^{-1}-------		$g\ kg^{-1}$	---------kg ha^{-1}-------	
Winter rye	227	4.3	7.1	254	12.1	13.0
Winter camelina	234	4.8	8.8	244	12.2	12.0
Winter wheat	216	4.3	8.2	268	10.7	9.9
Oat	216	4.2	6.3	271	12.3	12.4
Radish	223	5.3	7.6	265	13.2	15.6
Check	227	6.4	11.6	265	13.7	18.9
LSD (*P* = 0.05)	NS	NS	2.7	NS	NS	5.6

* Significantly different ($P \leq 0.05$).

Soil residual NO_3-N at a depth of 0-15 cm was not different among cover crops averaged across environments. (Table 3.10). Soil NO_3-N average at 0-15 cm depth in the fall and spring was 4.8 and 12.4 kg NO_3-N ha^{-1}, respectively. In late fall and spring, soil residual NO_3-N was significantly different among cover crops at the 15-60 cm soil depth. Soil residual NO_3-N was significantly less in all cover crop treatments than the check treatment (Table 3.11). Cover crop treatments had 34% less available NO_3-N than the check in the fall, mainly because cover crops were actively growing and were taking up soil NO_3-N, reducing the risk of N loss from leaching or denitrification (Kaspar et al., 2012b). Similar results were reported in different studies where fall cover crops can reduce soil NO_3-N from 20 to 68% in comparison with not having cover crops (O'Reilly et al., 2011a; Rutan and Steinke, 2019). Similar results were also reported in the USA northern Corn Belt in the spring, where winter rye decreased soil NO_3-N by 13% (Strock et al., 2004), and in southwestern Minnesota, the reduction was 45% (Feyereisen et al., 2006).

Table 3.12. Environment by cover crop interaction for gravimetric water content in Prosper and Hickson, ND, in 2018 and 2019.

	Prosper		Hickson	
Cover crop	2018	2019	2018	2019
	----------------------------g kg^{-1}------------------------			
Winter rye	199	267	208	344
Winter camelina	190	259	201	327
Winter wheat	233	271	243	325
Oat	223	269	268	324
Radish	220	259	254	328
Check	227	253	248	332
LSD (P = 0.05)	--------------------------------21---------------------------------			

3.3.4. Cover crop biomass related to ground cover and biomass N and accumulation

The interaction of cover crops biomass with ground cover and N accumulation across four environments is a relevant comparison for understanding the effect of cover crops in the cropping system. Canopy cover, before and after cash crops has the ability to reduce the risk of wind and soil erosion (Kaspar et al., 2001b). Soil erosion reduction is a function of cover crop biomass production (Blanco-Canqui et al., 2015). In this research, soil erosion was not measured directly, but a positive relationship between cover crop fall biomass yield and fall ground cover is indicative of reduction in soil erosion potential (Figure 2). The most robust relationship between soil cover and biomass was for radish (r^2 =0.74) and oat (r^2 =0.49).

Winter rye had the highest biomass yield and N accumulation, with a high determination coefficient (r^2 =0.84). Radish also had a very high determination coefficient (r^2 =0.86) (Figure 3). This was expected because increased biomass leads to higher N accumulation as reported in several other studies (Kaspar et al., 2001c; Blanco-Canqui et al., 2015; Kaspar and Bakker, 2015; Rutan and Steinke, 2019).

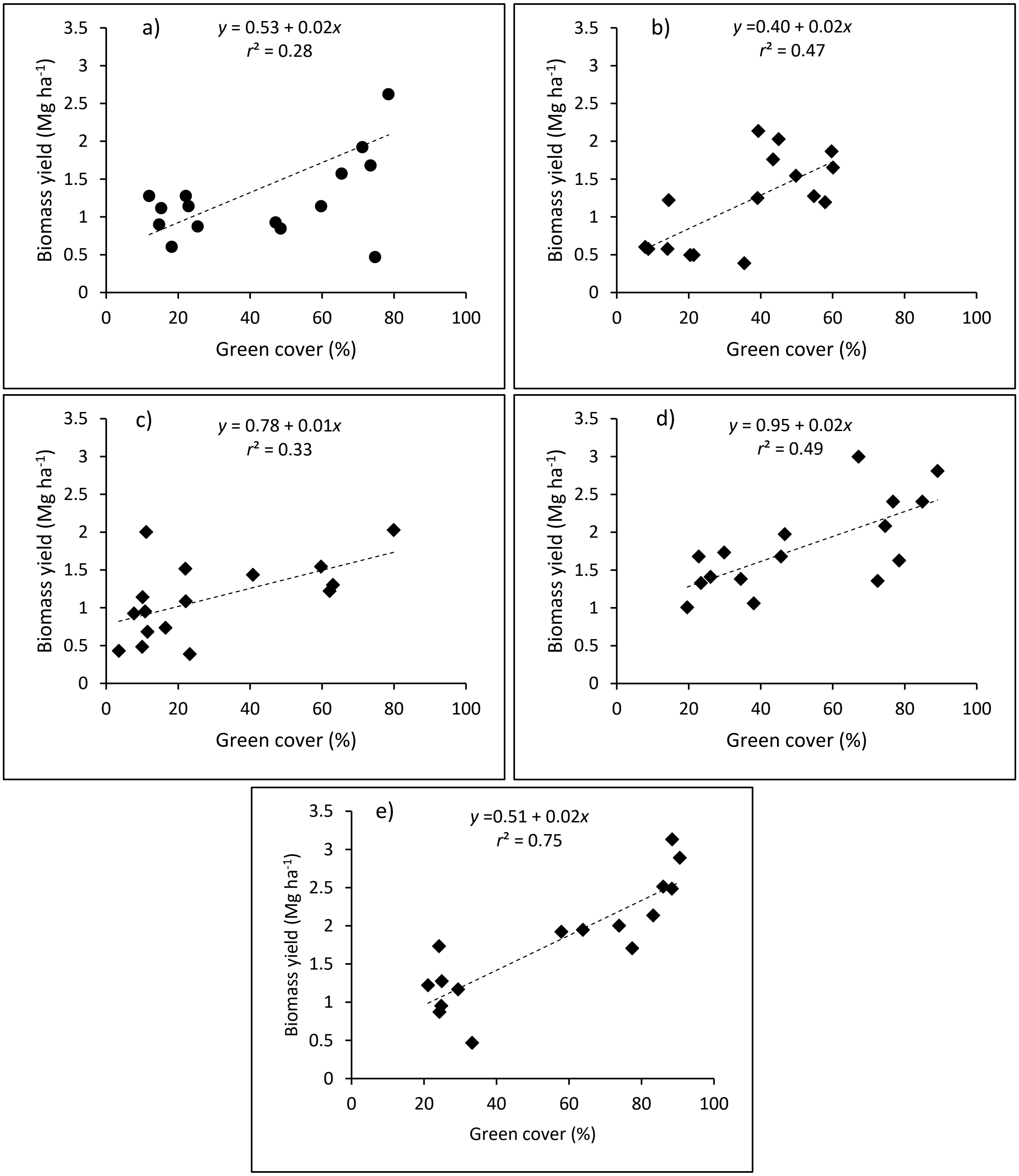

Figure 3.2. Cover crop fall biomass and soil green cover interactions by cover crop treatment: a) winter rye, b) winter camelina, c) winter wheat, d) oat, and e) radish.

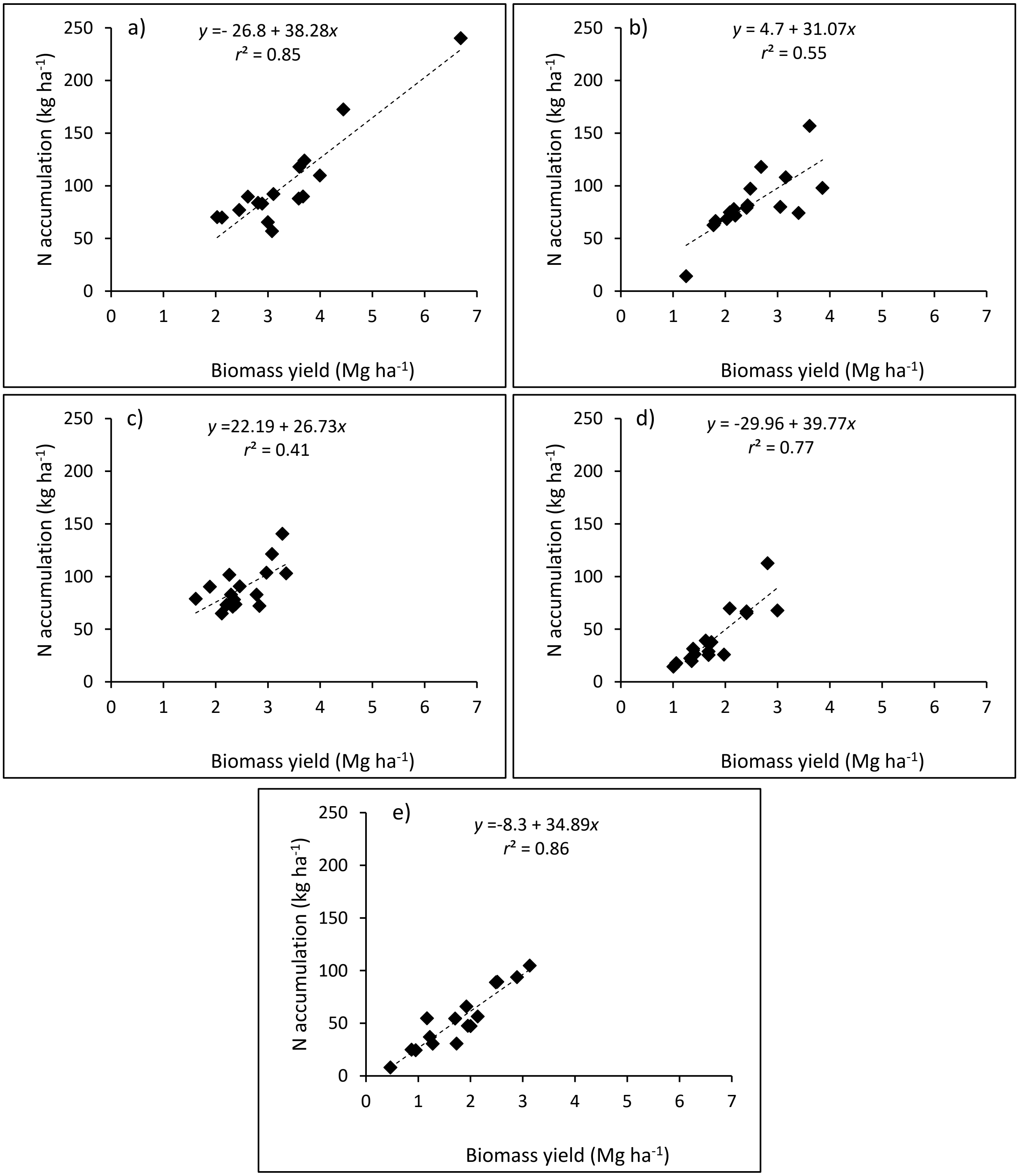

Figure 3.3. Cover crops fall biomass and nitrogen accumulation into the biomass interactions by cover crop treatment: a) winter rye, b) winter camelina, c) winter wheat, d) oat, and e) radish.

3.3.5. Sugarbeet response after cover crops

There were no significant cover crop by N in any of the environments ($P \geq 0.05$) for NDVI at V7 and V10 stages, plant density, fresh root yield, root dry matter content, and root dry biomass yield (Table 3.13). Plant density of sugarbeet averaged 74,446 plants ha^{-1} across all cover crop treatments. The check treatment had a sugarbeet plant density of 79,408 plants ha^{-1} and winter rye a plant density of 66,125 plants ha^{-1}. Root fresh yield averaged across all cover crops was 57.8 Mg ha^{-1}, while the check treatment root fresh yield was 68 Mg ha^{-1} and that of winter rye 49.9 Mg ha^{-1} (Table 3.14).

The average leaf biomass, root dry matter content, and root dry biomass yield were 2.9 Mg ha^{-1}, 237 g kg^{-1}, and 13.8 Mg ha^{-1}, respectively. In Montana, sugarbeet plant density and root biomass yield were not different between the control and treatments with living mulch on different termination days (Keshavarz et al., 2018). Also, there were no differences in root yield when cover crops were incorporated before sugarbeet planting (Allison et al., 1998).

The interaction between cover crops and the environment was significant for most parameters evaluated (Table 3.13). In Prosper 2018, sugarbeet plant density was less in winter camelina treatments (92,178 plants ha^{-1}) compared with sugarbeet plant density after forage radish in the no cover crop check. Similarly, root fresh weight yield did not show differences among cover crops in Prosper 2018, averaging 79 Mg ha^{-1} (Table 3.15).

Table 3.13. Combined analysis of variance and mean square values of five cover crops (CC) and two N rates (N rate) for sugarbeet evaluations in four environments (Env), Prosper and Hickson, in 2018 and 2019.

SOV	df	NDVI‡ V7	NDVI V10	Plant density ($x10^5$)	Root yield (fresh weight) ($x10^5$)	Leaf biomass	df	Root dry matter content †	Root dry biomass yield †
Env	3	1.2761*	2.0295*	124270*	206724*	236594517*	3	41318.5*	554012769*
Rep(env)	12	0.0169*	0.0348*	15244*	7786*	19397932*	11	1692.2	20917707*
CC	5	0.0555	0.0502	15493	6856	4453667	5	747.9	30168955
Env x CC	15	0.0310*	0.0373*	9001*	4268*	4453667*	15	1413.0	36073871*
Env x rep x CC	60	0.0039*	0.0049*	1755	1880*	3000634*	55	1281.5	8422809
N rate	1	0.1297*	0.1622	5792	38443*	45973182	1	23.3	223123232
Env x N rate	3	0.0111*	0.0239*	1417	3201*	9794619*	3	152.1	24234783
CC x N rate	5	0.0033	0.0018	3272	954	1632067	5	335.4	4860142
Env x CC x N rate	15	0.0027	0.0031	1589	1330	2030222	15	699.6	4878690
Error	72	0.0020	0.0026	1790	821	1714180	66	1551.5	10279935
CV%		11.9060	10.0261	15	16	44		16.6	23

* Significantly different ($P \leq 0.05$).

† Root dry matter content and root dry biomass yield did not include samples for replicate 1 in Prosper 2019, due to the high soil moisture, which affected plant density.

‡Normalized difference vegetative index (NDVI) at 7-leaf-stage (V7) and 10-leaf stage (V10).

Table 3.14. Mean values for sugarbeet evaluations for cover crops and check treatment averaged across two N rates and four environments, Prosper and Hickson, in 2018 and 2019.

Cover crop	NDVI V7	NDVI V10	Plant density	Root yield (fresh weight)	Leaf biomass	Root dry matter content†	Root biomass dry matter yield†
			plants ha^{-1}	------------kg ha^{-1}------------		g kg^{-1}	kg ha^{-1}
Winter rye	0.309	0.438	66125	49867		237.3	12279
Winter camelina	0.349	0.486	64363	55027	2802	236.8	13135
Winter wheat	0.386	0.527	78454	61102	3315	242.8	14541
Oat	0.395	0.510	76693	58772	2525	232.1	13637
Radish	0.422	0.548	81757	60770	2886	231.2	14302
Check	0.406	0.531	79408	61785	3460	242.5	15081
LSD (*P* = 0.05)	NS	NS	NS	NS	NS	NS	NS

† Root dry matter and root biomass yield did not include samples for replicate 1 in Prosper 2019, due to the high soil moisture, which affected plant density.

‡Normalized difference vegetative index (NDVI) at 7-leaf-stage (V7) and 10-leaf stage (V10).

In Hickson in 2018, plant densities were similar to those in Prosper in 2018 (Table 3.15). Sugarbeet plant density was less in winter-hardy cover crop treatments. Sugarbeet root yield after the winter rye treatment was less than following oat, forage radish, and the check. In addition, plant density after winter camelina and winter wheat were less than after oat, and the check treatment. This lower sugarbeet plant density after certain cover crops is similar to results reported by Petersen and Rover (2005), where sugarbeet emergence was less with winter rye treatments, showing a decrease of 5% compared with no cover crop treatments. Dhima et al. (2006) reported that plant extracts from barley (*Hordeum vulgare* L.) and winter rye (laboratory experiment) reduced sugarbeet emergence and root length. The most important allelopathic secondary metabolites produced by winter rye are phytotoxic benzoxazinones. The allelopathic compounds are stored in the vacuole and then released when the plant tissue is damaged (Barnes and Putnam, 1987). In addition, it has been reported that winter rye allelopathic compounds inhibit weed seed germination in plants from the *Amaranthaceae* family, which is the family that sugarbeet belongs to, so it is important to consider in future research (Barnes and Putnam, 1987; Tabaglio et al., 2013b).

It is important to consider that gravimetric water content was less in winter rye and winter camelina in these environments, which it is the most likely reason for the reduction in root yield observed in sugarbeet following winter-hardy cover crops (Table 3.12). It has been reported that reduced water availability as a result of winter-hardy cover crop growth in the spring can reduce cash crop yields in dry growing seasons, because these cover crops are growing and transpiring, reducing soil water content when rainfall is not sufficient to replenish it (Ewing et al., 1991; Hill et al., 2016).

Table 3.15. Environment by cover crop interaction of sugarbeet plant density and root yield (fresh weight) in Prosper and Hickson, ND, in 2018 and 2019.

	Prosper				Hickson			
	2018		2019		2018		2019	
Cover crop	Plant density	Root yield	Plant density	Root yield	Plant density	Root yield	Plant density	Root yield
	plants ha^{-1}	Mg ha^{-1}	plants ha^{-1}	Mg ha^{-1}	plants ha^{-1}	Mg ha^{-1}	plants ha^{-1}	Mg ha^{-1}
Winter rye	100985	69.8	40805	47.0	48438	49.5	74271	33.2
Winter camelina	92178	78.6	30237	35.8	73684	72.3	61354	33.4
Winter wheat	106563	80.8	43741	50.3	77794	74.6	85720	38.7
Oat	101866	75.6	36402	41.5	99517	85.1	68987	32.8
Radish	114489	74.4	40805	47.7	95114	80.9	76619	40.1
Check	110379	77.0	33466	45.3	100104	88.4	73684	36.4
LSD (P = 0.05)	14215	16.5	14215	16.5	14215	16.5	14215	16.5

In a study conducted in Indiana, USA, Daigh et al. (2014) reported that winter rye growth resulted in yield reduction in maize because the rye was actively growing during drought conditions, decreasing soil water content. Considering that spring 2018 was drier than the 30-yr average in our study, it is likely that the effect of winter-hardy cover crops before sugarbeet planting was mainly due to reduced soil water availability. Even though the spring soil NO_3-N content (0-15 cm depth) was reduced by winter camelina in this study, it probably did not influence sugarbeet root yield since previous reports indicate that winter-hardy cover crops affected sugarbeet yield only when NO_3-N values decreased by 50% in the soil profile, in comparison with no cover crop (Petersen and Röver, 2005).

At Prosper, in 2019, plant density was similar among cover crop treatments, averaging (35,760 plants ha^{-1}) (Table 3.15). At this site, seed germination was affected negatively because of wet and dry periods at the beginning of the respective seasons (Figure 1). Sugarbeet root yield (fresh weight) was similar among cover crops treatments (Table 3.15), averaging (44.6 Mg ha^{-1}).

At Hickson in 2019, plant density was different among treatments, where winter camelina plots had less plant density in comparison with winter wheat and forage radish (Table 3.15). Plant density was not affected by winter rye and winter wheat because the spring growth was less in comparison with winter camelina (Table 3.7).

In 2019, both environments had a wet spring and fall (Figure 1), and the environmental conditions masked the effects of winter-hardy cover crops. Gravimetric water differences at planting date in these environments (Prosper and Hickson, 2019) were similar among treatments. Thus, it is possible to assume that cover crops water use affected sugarbeet yield and plant density in 2018 negatively, while in 2019, results were similar to other sugarbeet research reports where no differences among treatments and the control were reported (Allison et al., 1998; Keshavarz et al., 2018).

3.3.6. Nitrogen rates effect on NDVI index and sugarbeet root yield

The normalized difference vegetation index at V7 stage was different among N rates (0 and 112 kg N ha^{-1}) averaged across environments (Table 3.13). Subplots with 112 kg N ha^{-1} rate had a 0.404 NDVI value, which was greater than the 0 kg N ha^{-1} rate with a 0.352 NDVI value (Table 3.16). Olson et al. (2019) reported that sugarbeet NDVI values were greater with rates of about 140 kg N ha^{-1} than the control. It is important to notice that NDVI indicates the photosynthetic vegetation coverage, where healthy and well-developed plants will have greater chlorophyll content than unhealthy or nutrient-deficient plants. Chlorophyll absorbs wavelengths in the red spectrum and will transmit most of the incident near-infrared light (NIR), given as a consequence higher NDVI values than the NDVI in plants with nutrient deficiency or diseased (Horler et al., 1983; Yang et al., 2017).

Table 3.16. Mean values for sugarbeet NDVI at V7 stage and root yield for two nitrogen rates averaged across cover crops treatments and four environments, Prosper and Hickson, ND, in 2018 and 2019.

Nitrogen rate	NDVI V7†	Root yield (fresh weight)
kg ha^{-1}		Mg ha^{-1}
0	0.352	53.4
112	0.404	62.4
LSD (*P* = 0.05)	0.048	8.2

† Normalized vegetative difference index (NDVI) at 7-leaf-stage (V7).

As expected, sugarbeet fresh weight root yield also was different among N rates (Table 3.13), where the 112 kg N ha^{-1} rate had the greatest root yield (62.4 Mg ha^{-1}) in comparison with 0 kg N ha^{-1} (53.4 Mg ha^{-1}) (Table 3.16). A sugarbeet fertilizer optimization study in the Red River Valley (ND and MN) reported similar results. A 112 kg N ha^{-1} rate resulted in greater sugarbeet root yield than 0 kg N ha^{-1} (Chatterjee et al., 2018).

3.3.7. Sugarbeet chemical composition

Sodium (Na) concentration was the only sugarbeet chemical parameter with significant differences in the interaction between cover crops and N rate (Table 3.17). This is very important because sodium, potassium, and amino-N combined are used to estimate the percentage of sucrose lost to molasses (Campbell, 2002; Campbell and Fugate, 2013). The highest sodium content in sugarbeet was obtained in sugarbeet that followed forage radish with no N applied (Table 3.18).

Table 3.17. Combined analysis of variance and mean square values of five cover crops (CC) and two N rates for sugarbeet variables in four environments (Env), in Prosper and Hickson, in 2018 and 2019.

SOV	df	Na	K	K:Na	Amino-N
Env	3	87349*	6003675*	592.2*	137481*
Rep(env)	12	23047*	115177*	50.8*	51000*
CC	5	3027	16826	6.4	6147
Env x CC	15	4656	57676*	6.4	5122
Env x rep x CC	58	3424	25398	9.8	3896
Nrate	1	8	155998	42.2	146593*
Env x Nrate	3	3296	64744*	39.2*	12524*
CC x Nrate	5	2941*	23058	13.2	3923
ENV x CC x Nrate	15	1004	26462	4.9	3726
Error	69	2831	22144	7.6	2976
CV%		32	6	17.4	15

* Significantly different ($P \leq 0.05$).

It is not very clear why or how radish can affect sodium concentration other than its rapid mineralization once dead might quickly release cations contained in the root. However, it is possible to notice that sugarbeet with reduced sodium values were reported in oat and winter wheat treatments, which are cereals that can establish an association with arbuscular mycorrhizal fungi.

Table 3.18. Sugarbeet Na concentration interaction between cover crop treatments and two N rates averaged across four environments in Prosper and Hickson, ND, in 2018 and 2019.

	Nitrogen rate (kg N ha^{-1})	
Cover crop	0	112
	--------------------------------mg Na kg^{-1}-----------------------------	
Winter rye	167	163
Winter camelina	168	180
Winter wheat	148	163
Oat	141	160
Forage radish	192	155
Check	175	163
LSD_1 (0.05)†	29	29
LSD_2 (0.05)‡	41	41
LSD_3 (0.05)§	43	43

† LSD_1 to compare Na means between different N rates within the same cover crop.
‡ LSD_2 to compare Na means between different cover crops within the same N rate.
§ LSD_3 to compare Na means between different cover crops and different N rates.

This association allows improving mineral nutrient supply in exchange of carbon-rich photosynthates (Jayne et al., 2014; Pellegrino et al., 2015; Lehnert et al., 2017). The root-hyphal association in winter wheat and oat could have increased the absorption of sodium altering the cation exchange capacity of the soil. However, this hypothesis would need to be studied more deeply. Forage radish does not host arbuscular mycorrhizal fungi but can release anti-fungal isothiocyanates which can help reduce disease inoculum in the soil (White and Weil, 2010). Sodium is not a desired element in sugar processing because it reduces the coagulation of impurities on the sugar-lime stream. It is recognized as one of the main impurities responsible for sucrose loss to molasses, considering that 1 kg of impurities prevents the crystallization of 1.5 to 1.8 kg of sucrose, affecting payment to the farmer and sugar company income significantly (Campbell, 2002; Campbell and Fugate, 2013). The remainder of the sugarbeet chemical parameters did not show significant differences with treatment (Table 3.19).

Table 3.19. Mean values for sugarbeet Na, K, K:Na, and amino-N for cover crops treatments averaged across two N rates and four environments (Env), Prosper and Hickson, in 2018 and 2019.

Cover crop	Na	K	K:Na	Amino-N
	------------mg kg^{-1}--------------			mg kg^{-1}
Winter rye	163	2349	16.4	353
Winter camelina	174	2359	15.8	365
Winter wheat	155	2360	16.2	333
Oat	150	2308	16.1	343
Radish	171	2311	15.6	351
Check	168	2305	15.2	369
LSD (*P* = 0.05)	NS	NS	NS	NS

Sucrose loss to molasses and amino-N concentration were different between N rates averaged across environments (Table 3.20 and 3.17). When sugarbeet was not fertilized with N, it resulted in less loss of sucrose to molasses and amino-N concentration in comparison with sugarbeet fertilized with 112 kg N ha^{-1} rate (Table 3.22).

Fertilized treatments had greater higher yield than those not fertilized. Consequently, sugarbeet plants were larger and it is likely that the taproot was longer which could have taken up N deeper in the soil profile, increasing amino-N content in sugarbeet, and in consequence sucrose loss to molasses, (Campbell and Fugate, 2013).

Table 3.20. Combined analysis of variance and mean square values of five cover crops (CC) and two N rates treatments for sugarbeet parameters in four environments (Env), Prosper and Hickson, in 2018 and 2019.

SOV	df	SLM	Sucrose	Sucrose purity	Recoverable sucrose
Env	3	46.26*	15094.8*	93.89*	630835595*
Rep(env)	12	17.97*	621.0*	15.31*	5718691*
CC	5	1.66	65.3	2.14	13785170
Env x CC	15	3.17*	52.9	2.16	12582700*
Env x rep x CC	58	1.28	47.4*	1.42*	2710590*
Nrate	1	13.35*	594.0	0.76	89184363*
Env x Nrate	3	0.69	134.3*	1.32	4870900*
CC x Nrate	5	0.84	12.1	0.34	2009274
ENV x CC x Nrate	15	1.38	21.4	0.98	2771163
Error	69	0.89	23.8	0.63	1706166
CV%		7.09	3.3	0.87	16

* Significantly different ($P \leq 0.05$). Sucrose lost to molasses (SLM).

Table 3.21. Mean values for sugarbeet variables for cover crops and no cover crop check averaged across two N rates and four environments (Env), Prosper and Hickson, 2018 and 2019.

SOV	SLM	Sucrose	Sucrose purity	Recoverable sucrose
	g kg^{-1}	%	%	Mg ha^{-1}
Winter rye	1.3	15.0	91.0	7.24
Winter camelina	1.6	14.6	90.5	7.67
Winter wheat	1.3	14.9	91.1	8.59
Oat	1.3	14.7	91.0	8.27
Radish	1.3	15.1	61.1	9.12
Check	1.3	14.7	60.7	8.81
LSD (*P* = 0.05)	NS	NS	NS	NS

Sucrose lost to molasses (SLM).

Table 3.22. Sugarbeet amino-N, sucrose lost to molasses (SLM) and recoverable sucrose (RS) means between two nitrogen rates and averaged across cover crop treatments and four environments, Prosper and Hickson, ND, in 2018 and 2019

Nitrogen rate	Amino-N	SLM	RS
kg ha^{-1}	mg kg^{-1}	g kg^{-1}	Mg ha^{-1}
0	324	1.30	7.55
112	380	1.35	9.02
LSD (*P* = 0.05)	52	0.04	1.03

Recoverable sucrose was higher at the 112 kg N ha^{-1} rate compared with no N application averaged across environments (Table 3.20 and 3.22). Recoverable sugar is a function of sucrose purity and sugarbeet root yield. Consequently, if the root yield is higher, so is the recoverable sugar, with the highest N rate the sucrose lost to molasses was also significantly higher, decreasing sucrose purity. Overall, recoverable sucrose was higher in the higher N rate. Recoverable sucrose was significant for the interaction between cover crops and environment (Table 20). In Prosper in 2018, recoverable sucrose was not affected by treatments, and the average was 11.58 Mg ha^{-1} (Table 23).

Recoverable sucrose was the lowest in sugarbeet following winter rye (7.01 Mg ha^{-1}). In Prosper in 2019, recoverable sucrose was different among cover crops (Table 3.23). Sugarbeet had the lowest recoverable sucrose (4.07 Mg ha^{-1}) when following winter camelina compared with radish (7.51 Mg ha^{-1}).

There were no differences in recoverable sugar among cover crops or N rates at Hickson, 2019 (Table 3.23). This environment did not experience a dry spring, and gravimetric soil water was not a limiting factor. Gravimetric soil moisture was less at planting in winter rye plots, which affected sugarbeet stand establishment and, consequently, root yield and recoverable sugar.

Table 3.23. Recoverable sucrose (RS) means per environment averaged across two N rates, in Prosper and Hickson, ND, in 2018 and 2019

	Prosper		Hickson	
Cover crop	2018	2019	2018	2019
	--------------------------Mg ha^{-1}	----------------------		
Winter rye	10.60	6.99	7.01	4.19
Winter camelina	12.05	4.07	10.45	4.13
Winter wheat	12.38	6.11	11.10	4.78
Oat	11.36	4.89	12.95	3.87
Radish	11.30	7.51	12.26	4.87
Check	11.78	5.78	12.83	4.38
LSD (0.05)†	------------------------------2.08	---------------------------		

3.3.8. Recoverable sugar and NDVI relationship

Normalized difference vegetation index has been used as a good predictor of crop yield for an extended period (Tucker, 1978; Rutan and Steinke, 2017b). The NDVI is an early indicator of biomass and vigor in the early stages of sugarbeet (Chatterjee et al., 2018; Olson et al., 2019). Healthy sugarbeet plants will cover more soil surface, that will absorb light in the wavelength in the red spectrum and will transmit most of the incident near-infrared light (NIR), given as consequence higher NDVI values (Horler et al., 1983; Yang et al., 2017).

Figure 3.4 shows the relationship between recoverable sucrose and NDVI at sugarbeet growth stage V10 for cover crop treatments. The V10 stage was chosen because it has been used with good results in other research estimations in the USA Upper Midwest (Olson et al., 2019). In Figure 3.4, all the relationships between recoverable sucrose and NDVI are positive; in other words, a higher NDVI value resulted in the highest recoverable sucrose. The determination coefficient in Figure 4 allows us to explain recoverable sucrose prediction by NDVI measured at the V10 stage of sugarbeet. In this scenario, winter camelina (r^2 = 0.89) and the check (r^2 = 0.89) were the treatments that presented the highest determination coefficients between sugarbeet NDVI and recoverable sucrose, whilst oat (r^2 = 0.64) relationship was lowest. Nevertheless, it is important to consider that all r^2 values were greater than 0.71, resulting in an excellent prediction tool for recoverable sucrose in these four environments. This prediction is critical because payment to farmers is based on recoverable sucrose yield (Gehl and Boring, 2011).

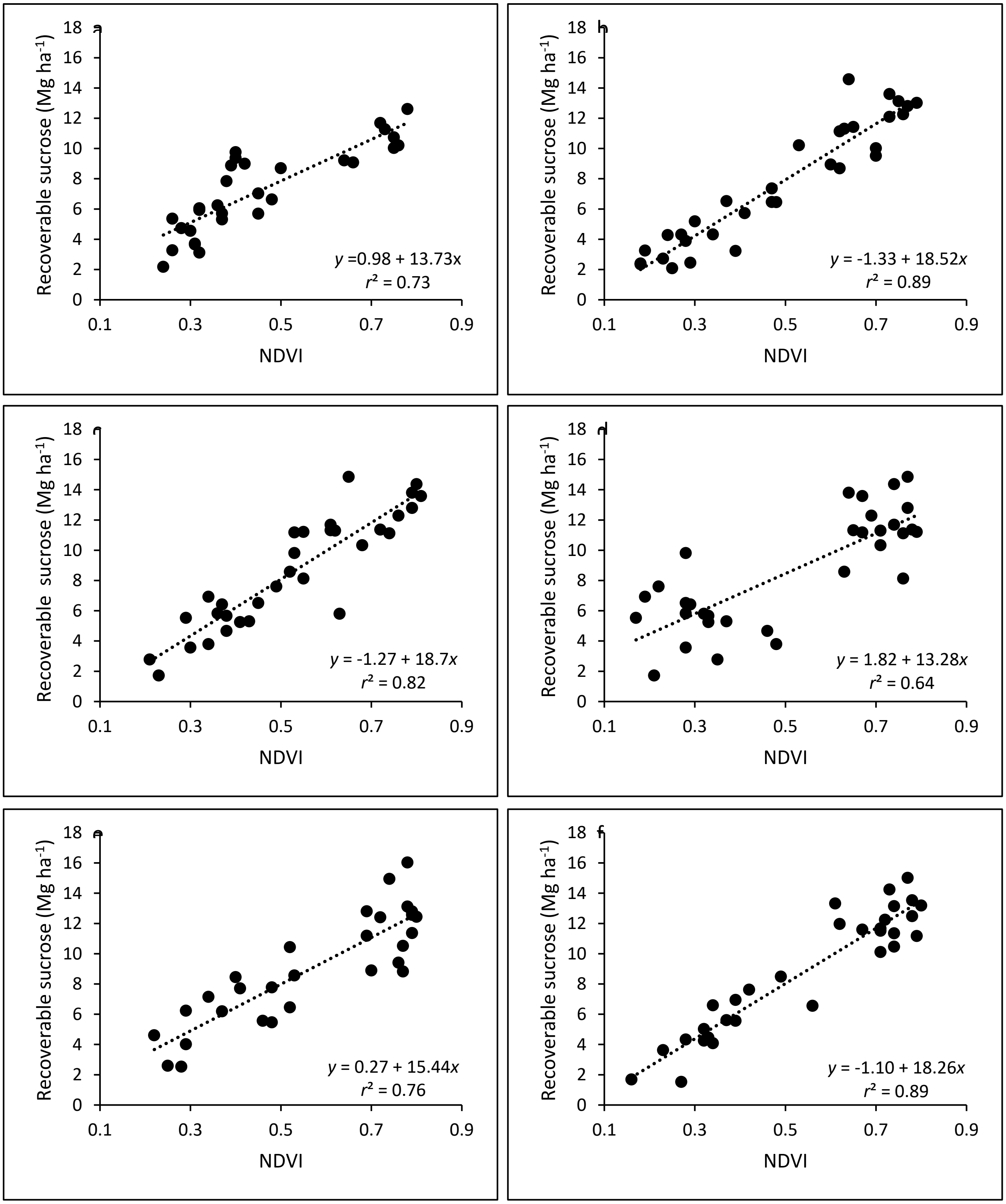

Figure 3.4. Recoverable sugar and normalized difference vegetation index (NDVI) interactions from sugarbeet following cover crops: a) winter rye, b) winter camelina, c) winter wheat, d) oat, e) radish, and f) check, without cover crop.

3.3.9. Soil residual NO_3-N

Soil residual NO_3-N was not different between cover crops treatments, nitrogen rate, or their interactions. These results were observed in both sampling depths (0-15 and 15-60 cm depth) in all cover crops averaged across four environments ($P \geq 0.05$) (Table 3.24). The samples were taken 30 days after sugarbeet planting date attempting to determine nutrients released from the cover crop biomass and possible N credits to sugarbeet. However, any N obtained from cover crop growth was not observed even when significant biomass production and N accumulation was measured (Table 3.7).

The biomass mineralization process is positively related to the cover crop residue composition and C/N ratio. Cover crops with a C/N ratio less than 20 expect usually indicate release of N through mineralization during the cash crop growing period, giving in theory extra N as a 'credit' to the following cash crop (Jensen et al., 2005; Lawson et al., 2012). Cover crops and cover crops mixture with a C/N ratio less than 20 did not increase maize yield or result in extra N (Ruark and Franzen, 2020), and in Wisconsin, forage radish did not supply N credits to the following maize crop (Ruark et al., 2018). In this research, we can see similar results which might be related to similar causes.

Lack of N release from cover crops biomass, suggests that the mineralization process did not occur or was not great enough to produce a significant difference in sugarbeet root yield. The same lack of N release from cover crops has also been observed in other no-till experiments, where the N mineralization from cover crops was not consistent with what might be expected from residues with C:N ratios less than 20 (Parr et al., 2011b).

Organic matter mineralization is a temperature-dependent process, with an ideal range between 20 and 30°C (Davidson and Janssens, 2006; Lawson et al., 2012), but average temperatures on April (2017 and 2018) and May (2018) were less than the 30-year average at Prosper and Hickson, probably reducing early season organic matter mineralization from cover crop biomass. This could be one of reasons why the N credits were not observed in this study.

North Dakota soils in the Red River Valley generally have a high smectite:illite ratio (higher than 3.5). The majority of 2:1 smectite clay minerals tie-up or ‘fix’ potassium (K^+) in considerable amounts, especially in dry seasons, and similarly can tie-up or ‘fix’ ammonium (NH_4^+), because both cations have a similar ionic radius (Franzen and Bu, 2018; Breker et al., 2019). In preliminary studies, soils following a winter rye and forage radish, the soil that had cover crops tended to have an increase in non-exchangeable NH_4^+ (Franzen et al., 2019a). Smectitic clay minerals (2:1) might be fixing NH_4^+ coming from cover crop biomass mineralization directly into their interlayers in dry seasons, adding more complexity to the understanding of N released from cover crop mineralization and the N credits that might be provided in a transitional no-till system and the short North Dakota growing season.

Table 3.24. Combined analysis of variance and mean square values for cover crop treatments and two N rates for spring and fall soil nitrate tested in four environments, Prosper and Hickson, ND, in 2018 and 2019.

		Spring		Fall		
SOV	df	Soil NO_3-N (0-15 cm)	Soil NO_3-N (15-60 cm)	Soil NO_3-N (0-15 cm)	df	Soil NO_3-N (15-60 cm)
Env	3	8819*	25069*	1357*	1	2793.24*
Rep(env)	12	968*	1113*	120*	6	106.71*
CC	5	834	734	19	5	14.32
Env x CC	15	671*	464*	28	5	11.78
Env x rep x CC	60	197	166	17*	30	12.30
N rate	1	20499	28281	7	1	<0.01
Env x N rate	3	4167*	8518*	10	1	4.24
CC x N rate	5	681	574	4	5	14.13
Env x CC x N rate	15	506*	203	7.4	5	17.24
Error	72	236	169	11	36	14.99
CV%		68	50	32.6		38.93

* Significantly different ($P \leq 0.05$).

† Fall soil NO_3^--N (15-60 cm) included only 2018 Prosper and Hickson environments in the analysis. 2019 Prosper and Hickson environments were not included, due to the excess of soil moisture conditions.

Table 3.25. Mean of soil nitrate for cover crops and check treatments across two N rates and four environments, Prosper and Hickson, ND, in 2018 and 2019.

	Spring		Fall	
Cover crops	Soil NO_3-N (0-15 cm)	Soil NO_3-N (15-60 cm)	Soil NO_3-N (0-15 cm)	Soil NO_3-N † (15-60 cm)
	kg ha^{-1}			
Winter rye	17.2	30.0	10.1	9.3
Winter camelina	27.2	27.0	9.7	11.4
Winter wheat	20.9	20.9	9.4	10.2
Oat	16.7	19.0	10.5	9.9
Forage radish	26.0	30.8	11.6	8.6
Check	28.2	26.9	10.0	10.3
LSD (P = 0.05)	NS	NS	NS	NS

† Fall soil NO_3-N (15-60 cm) included only 2018 Prosper and Hickson environments in the analysis. Prosper and Hickson (2019) environments were not included, due to the excess of soil moisture conditions.

The interaction of cover crops and the spring soil NO_3-N environments at both depths was significant (Table 3.24). In Prosper and Hickson 2019, soil with winter rye and winter wheat had lower NO_3-N than the check (Table 3.26). Similar results have been reported in several studies, where winter rye scavenged soil nitrate because it was actively growing in early spring (Staver and Brinsfield, 1998; O'Reilly et al., 2011b; Basche et al., 2016a; Peterson et al., 2019b). In Prosper 2019, radish and oat treatments resulted in reduced soil NO_3-N values compared with the no cover-crop check. This might be related to slow biomass mineralization, considering that temperatures in April and May 2019 were less than average (Table 3.3), affecting this temperature-dependent process (Davidson and Janssens, 2006; Lawson et al., 2012). In addition, these results agree with those of Ruark et al. (2018), where radish did not release N for use in the following crop. After sugarbeet harvest, there were no differences in soil residual NO_3-N due to cover crop, N rate, and their interaction at both sampling depths (0-15 and 15-60 cm depth) averaged across four environments ($P \geq 0.05$) (Table 3.24). These results were observed in both sampling depths (0-15 and 15-60 cm depth) among cover crops across four environments ($P \geq 0.05$) (Table 3.25).

After sugarbeet harvest, there were no differences in soil residual NO_3-N for cover crops, N rates, and their interactions in both sampling depths (0-15 and 15-60 cm depth) averaged across four environments ($P \geq 0.05$) (Table 3.24). These results were observed in both sampling depths (0-15 and 15-60 cm depth) among cover crops across four environments ($P \geq 0.05$) (Table 3.25).

Table 3.26. Environment by cover crop interaction for spring soil nitrate averaged across two N rates, at Prosper and Hickson, ND, 2018 and 2019.

	Prosper				Hickson			
	2018		2019		2018		2019	
Cover crop	NO_3-N (0-15 cm)	NO_3-N (15-60 cm)	NO_3-N (0-15 cm)	NO_3-N (15-60 cm)	NO_3-N (0-15 cm)	NO_3-N (15-60 cm)	NO_3-N (0-15 cm)	NO_3-N (15-60 cm)
	----------kg ha^{-1}----------							
Winter rye	9.4	8.8	28.6	55.1	19.8	41.6	11.2	14.3
Winter camelina	8.8	7.6	42.5	65.1	13.6	24.4	43.9	10.9
Winter wheat	8.4	8.0	42.5	49.6	12.6	16.8	20.0	9.2
Oat	9.4	8.0	21.9	48.8	8.3	8.4	27.2	10.9
Radish	10.9	10.5	33.5	77.3	14.0	17.7	45.4	17.7
Check	8.5	11.8	57.9	59.7	12.5	16.4	33.9	19.8
LSD_1 (0.05)†	23							
LSD_2 (0.05)‡	15.1							

† LSD_1 to compare of means of NO_3-N at 0-15 cm for both locations and any year combination.

‡ LSD_2 to compare of means of NO_3-N at 15-60 cm for both locations and any year combination.

3.4. Conclusions

Fall cover crop biomass and soil cover were greater in radish and oat, than that of winter-hardy cover crops. Soil residual NO_3-N (15-60 cm) in the fall immediately after termination of cover crops by freezing was greater in the check with no cover crop compared with all cover crop treatments. This result indicates that cover crops serve as a NO_3-N catch crop, reducing the risk of N loss from leaching and denitrification.

Winter rye had greater biomass than winter camelina and winter wheat in early spring. All winter-hardy cover crops resulted in reduced soil NO_3-N compared with the check, reducing the risk spring N losses.

Spring in Prosper and Hickson in 2018 was abnormally dry. Winter-hardy cover crops resulted in reduced soil gravimetric water content compared with forage radish, and oat treatments which had winter killed, or the check. Likewise, in 2018 at Prosper winter camelina decreased sugarbeet plant density compared with the check and radish treatments due to reduced soil moisture from the spring-growing cover crop. Under similarly dry conditions at Hickson, sugarbeet plant density was significantly reduced with winter rye, winter camelina, and winter wheat compared with oat, radish, and the check plots. Also, at Hickson in 2018, sugarbeet yield was reduced following winter camelina and winter rye, probably due to dry conditions.

Normalized difference vegetation index, measured using an active-optical sensor, is a powerful tool to predict recoverable sucrose in sugarbeet. This research demonstrated that NDVI predicts recoverable sucrose when measured at the V10 stage regardless of cover crop or N rate treatment. These results have considerable potential when cover crops are included in the cropping systems, allowing farmers to correct deficient N status early in the season to achieve target sugarbeet root yield and quality parameters.

There are multiple advantages to using winter rye, winter camelina, winter wheat, oat, and forage radish as cover crops in the sugarbeet crop rotation. Winter-hardy cover crops can reduce soil water content allowing earlier sugarbeet planting in high clay soils during wet springs. However, disadvantages need to be considered such as excessive water use under dry spring conditions, and slow cover crop biomass N mineralization.

3.5. References

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CHAPTER 4. COVER CROPS OVERALL CONCLUSIONS

The benefits of cover crops are manifold. In both experiments, it was possible to see significant differences in late-fall season, where averaged overall cover crop fall biomass was 1.51 Mg ha^{-1} and soil coverage was greater in all cover crops than in the check. Fall soil residual NO_3-N (15-60 cm) was greater in the check plot without cover crops when compared with each cover crop treatment in the sugarbeet experiment. This result indicates that cover crops serve as a NO_3-N catch crop, reducing the risk of N loss from leaching and denitrification. However, this phenomenon was not observed in the corn experiment, where legumes cover crops and camelina did not give significant differently soil residual NO_3-N to check plots.

In early spring, all winter-hardy cover crops resulted in reduced soil NO_3-N compared with the check, reducing the risk of spring N losses in the sugarbeet experiment. However, reduced soil NO_3-N was not observed in early spring for winter-hardy camelina in the corn experiment, related with of lack of camelina stand population.

Spring in Prosper and Hickson 2018 was abnormally dry. Winter-hardy cover crops resulted in reduced soil gravimetric water content compared with winter-killed cover crops, and the check. In 2018 at Prosper, winter camelina decreased sugarbeet plant stand compared with the check and radish plots, due to reduced soil moisture from the spring-growing cover crop. Under similarly dry conditions at Hickson, sugarbeet plant density was significantly reduced with winter rye, winter camelina, and winter wheat compared with oat, radish, and the check plots. Also, at Hickson in 2018 sugarbeet yield was reduced following winter camelina and winter rye, again likely due to dry conditions. Likewise, in the corn experiment winter camelina negatively affected maize grain yield in comparison with the other cover crop treatments averaged across environments. Grain yield reduction could be related to the late termination of the cover crop and a dry spring in 2018.

Normalized difference vegetation index, measured using an active-optical sensor, is a powerful tool to predict corn grain yield at V8 corn stage and recoverable sucrose in sugarbeet at V10 stage. This research showed that NDVI readings can predict accurately both crops yield parameters, regardless of cover crop or N rate treatment. These results have considerable potential when cover crops are included in the cropping systems, allowing farmers to correct deficient N status early in the season to achieve target yield and quality parameters.

Overall, these experiments have demonstrated the potential for cover crops to improve soil health in two relevant cash crops in North Dakota, particularly with regards to maintaining N content in the soil and decreased nitrate leaching. However, these experiments have also shown that the choice of cover crop to complement the cash crop is vital, since there is a risk of negatively affecting crop yield through water use under dry conditions and/or competition with the cash crop, and because of that, many factors should be considered to achieve framing success.