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Influence of Cover Crop Management Practices on Rainfed Corn Production in Semi-Arid Western Nebraska

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INFLUENCE OF COVER CROP MANAGEMENT PRACTICES ON RAINFED CORN PRODUCTION IN SEMI-ARID WESTERN NEBRASKA

by

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With the increased cover crop (CC) popularity, producers of semi-arid regions of western Nebraska are questioning whether they could successfully incorporate CC into their rainfed winter wheat (*Triticum aestivum L.*)-corn (*Zea mays L.*)-fallow rotations. The major concern is that CCs may deplete soil water affecting the subsequent crop. Therefore, three studies were established under rainfed conditions of western Nebraska to access the effects of CCs on soil water, soil compaction, nutrient cycling, weed demographics, residue coverage, and subsequent corn yield. The first study evaluated the influence of CC planting and termination times prior to corn establishment. Late termination of CCs in the spring reduced weed density and biomass, but also decreased up to 17% of total nitrogen at 0-10 cm soil depth, and up to 26% of soil nitrate at 10-20 cm soil depth at corn V6 development stage. Cover crops planted early and terminated late had the most detrimental impact on corn grain yield. The second study evaluated the effects of different CC species. Cereal rye increased soil penetration resistance from 20-30 cm depth across site-years. Cover crop growth in the spring suppressed weeds during early corn growing season, especially cereal rye. On the other hand, CCs increased N immobilization (except brassicas) during corn growing season and consequently reduced the corn grain yields compared to fallow (except spring oats). The third study combined CCs and WW stubble height management. In Gothenburg and North Platte sites, the residue coverage biomass was increased by CC mixtures in comparison to fallow. Both CC winter-sensitive and winter-hardy mixtures reduced soil water content during CC growth period, especially from 15-45 cm deep and deeper in the soil profile compared to fallow. Consequently, corn grain yields were reduced in about 17% by CC winter-

hardy mixture in all sites, except Gothenburg. The research findings will assist the development of recommendations for CC management in rainfed cropping systems of western Nebraska and Central Great Plains.

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CHAPTER 1: INTRODUCING COVER CROPS IN SEMI-ARID CROPPING SYSTEMS: THE GOOD AND THE BAD

Producers of dryland semi-arid areas rely on proper soil water storage for the success of their cropping systems. The winter wheat (*Triticum aestivum L.*)-corn (*Zea mays L.*)-fallow rotation represents the typical rainfed cropping system of western Nebraska and much of the Great Plains where two crops are grown in three years. In this crop rotation, winter wheat is typically planted in the fall (around September) after a fallow period that starts after corn harvest in the previous year (September-November). Then, winter wheat is harvested in the summer (July) and followed by a second fallow period until corn is planted in the next spring (around May). Therefore, this crop rotation contains two fallow periods that are intended for soil water conservation and soil water recharge by precipitation. However, the sustainability of 2 fallow periods in the cropping system is becoming a major challenge in semi-arid environments because of unstable commodity prices, inefficient land use, herbicide-resistant weeds, and soil degradation through erosion and soil organic carbon reduction (Blanco-Canqui et al., 2011). In this scenario, the inclusion of a cool season crop such as field peas (*Pisum sativum L.*) in the spring after corn harvest (Stepanovic et al., 2018), and cover crops (CCs) following winter wheat harvest are arising as an alternative to intensify crop production and land use in semi-arid regions.

The reduced average precipitation of semi-arid climates (250-500 mm annual precipitation) (Gallart et al., 2002) is a major limiting factor in crop intensification and production. Under those circumstances, no-tillage and proper wheat stubble height (WSH) management are key factors to soil water storage for subsequent crops (Klein, 2012), especially in drier years. Wheat residue management starts at the time of winter wheat harvest. When winter wheat is harvested leaving a short stubble, its residue decomposes at a faster rate (Hagen, 1996), increasing the water evaporation during the fallow period prior to corn planting and also during the corn growing season. A study conducted in semi-arid Colorado found that a short winter wheat stubble height increased the water vapor exchange and radiation absorption, increasing soil water evaporation (McMaster et al., 2000). Hence, with less wheat stubble residue in the soil surface, soil water depletion may increase, which could lead to subsequent corn grain yield loss. However, if only the wheat heads are harvested, a tall stubble is left increasing the snow retention during the winter (Nielsen, 1998). That is possible because the tall stubble can reduce the wind speed of a snow storm, facilitating the snow deposition to the soil (Bilbro and Fryrear, 1994). In semi-arid Kansas, taller winter wheat stubble increased corn grain yield, likely due to soil water conservation (Schlegel, 2015). Therefore, under rainfed semi-arid environments, maintaining or increasing soil residue coverage can help with increasing soil water recharge and reducing water evaporation (Nielsen et al., 2005; Holman et al., 2018) and with increasing subsequent crop yields. However, live CCs transpire water, increasing evapotranspiration, whereas its residues after termination could increase soil residue coverage, reducing water evaporation in semi-arid environments. Thus, it is not well known if including CCs in place of fallow would lead to increments in soil residue coverage and soil water storage.

Lately, CCs have emerged as an alternative conservation tool to cropping systems in the US. Cover crops have numerous documented benefits such as protecting soil from water and wind erosion (Kaspar et al., 2001; Strock and Porter, 2004), reducing nitrogen (N) leaching (Dinnes et al., 2002; Villamil et al., 2006), increasing water infiltration and soil organic carbon (Kaspar and Singer, 2011; Blanco-Canqui et al., 2015) and suppression of weeds (Osipitan et al., 2018; Werle et al., 2018). The aforementioned benefits of growing CCs helped raise their popularity among producers in recent years in Nebraska. The CC planted area doubled in Nebraska going from approximately 145 to 300 thousand hectares from 2012 to 2017 (NASS, 2017). In winter wheat-corn-fallow rotations of western Nebraska, CCs can be planted shortly after winter wheat harvest, replacing one of the fallow periods. A major concern, however, is the impact that these non-cash crops can have on soil water content in water-limited environments. Depending on precipitation amounts, CCs can have different impact on soil water content. Above-average precipitation amounts during CC growing season in semi-arid environments may lead to neutral to positive effects of CCs on the soil water supply (Unger and Vigil, 1998), and consequently the subsequent cash crop grain yield. However, in rainfed semi-arid climates, average and below-average precipitation may lead to negative effects of CCs. The duration of CC growth window in semi-arid environments may result to excessive soil water consumption that could otherwise be available for subsequent cash crops. When CCs are late terminated (close to corn planting time) in the spring, those impacts tend to be more pronounced as typically there is not enough time and precipitation volume to recharge the soil profile to be used by the subsequent crop (Unger and Vigil, 1998). In a study evaluating water use by CCs, Nielsen *et al.* (2015) concluded that CC water use in a semi-arid environment increased 1.78 times, on average, compared to a no-till fallow. Moreover, Holman et al., 2018 reported that in dry years, incorporation of CCs reduced subsequent winter-wheat grain yield by 70%. Thus, one of the major concerns regarding the inclusion of cover crops after winter wheat harvest is the depletion of soil water that can lead to yield and economic penalties in the subsequent corn crop. Yet, the effects of CC on corn grain yield under rainfed semi-arid cropping systems are not well known.

Cover crops can be grown as single or as a mixture of species. Species selection depends on the adaptability to the environment and the producer's main goal(s) with planting the CCs. Cereal rye (*Secale cereale L.*) is one of the most popular CC grown in corn (*Zea mays L.*)-soybean (*Glycine max L. Merr*.) cropping systems in the United States Midwest region (Singer, 2008). Cereal rye has become a popular CC due to its rapid establishment, high biomass production, ability to suppress weeds, winter-hardiness, low cost, and seed availability compared to other CCs (Snapp et al., 2005; Singer, 2008). Other grass species such as oats (*Avena sativa*) and spring-triticale (*Triticosecale*) are also commonly grown as CCs across the United States, and are a potential alternative to cereal rye. However, oats and spring-triticale are not considered a winter-hardy species and if fall seeded will not produce biomass in the spring (Johnson et al., 1998). Besides aboveground biomass, fibrous and extensive root production are an attribute of grass CCs. Leguminous species such as hairy vetch (*Vicia villosa*) (winter-hardy) and balansa clover (*Trifolium michelianum Savi*) (winter-sensitive) have the ability to fix atmospheric nitrogen (N_2) in the soil, potentially supplying nitrogen to the subsequent crops (Blanco-Canqui et al., 2015). Winter-sensitive brassica species like Siberian kale (*Brassica napus*) and purple top turnips (*Brassica rapa*) can reduce soil penetration resistance due to taproot growth (Chen and Weil, 2011; Chen et al., 2014). The taproot system of brassicas can help in loosening the surrounding soil by creating canals with vertical and horizontal growth throughout the soil. These canals may allow for enhanced water infiltration reducing soil erosion.

Cover crops can cycle nutrients in the soil. With mobile soil nutrients such as N, CCs can uptake from deeper in the soil, minimizing N leaching and cycling back to the next crop. However, the timing for this process is critical as the corn N demand starts early in the season (V6 development stage). Cover crop mixtures rich in grass species may lead to N immobilization, especially winter-hardy CCs, as there is not enough time for the CC residues to decompose and cycle N back to be available for the subsequent corn crop (Nevins et al., 2020). Other authors caution for N immobilization issues when adopting CCs. Both CC mixtures (Wortman et al., 2012) and sole CC grass species (Snapp and Surapur, 2018) were found to decrease nitrogen levels in the soil. Therefore, excessive growth of CCs, especially grasses, may increase soil water consumption and extend nitrogen immobilization during the cash crop growing season. A study conducted in Colorado and Nebraska found that legume CCs grown in the spring decreased winter wheat yield by up to 77% (Nielsen and Vigil, 2005) despite possible nitrogen credits provided by legume atmospheric N fixation. Likewise, an irrigated study conducted in eastern Kansas showed that in its third year of implementation, cereal rye reduced corn yields by 9.3% (Kessavalou and Walters, 1997). Conversely, Tollenaar et al. (1993) found that nitrogen fertilization in cereal rye CC minimized the adverse effects on subsequent corn development in Ontario, Canada. However, in a high water stress environment of South Dakota, different CC species (grasses, legumes, and brassicas) grown only in the fall did not reduce subsequent corn grain yield (Reese et al., 2014).

Similar to N, CCs may promote phosphorus (P) and potassium (K) cycling in the soil, where the CC plants take up P and K, and their residue decomposition release those nutrients back to the soil (Nelson and Janke, 2007). The adoption of no-till system keeps the previous crop residue on the soil surface, accumulating nutrients (especially immobile nutrients such as P and K) in the top layers of the soil (Robbins and Voss, 1991; Karlen et al., 1991). Including CCs in the crop rotation can potentially bring P and K from deep soil layers to soil surface, increasing the concentration of those nutrients in the crop root zone (Rosolem and Steiner, 2017). This can be especially positive for early stages of crop growth, as the nutrients (P and K) would be easy accessible by roots. In addition, including CCs in the cropping system has the advantage of minimizing P and K loss by soil erosion and deep percolation, respectively, reducing the risk of water contamination (Hartz, 2006). In a study conducted in southern Brazil, Kepler and Anghinoni (1995) observed higher K levels in the soil during corn grain filling stage following black oats (*Avena strigosa*) CC. However, the synchrony of residue decomposition and nutrient release is not well understood in semi-arid environments. If the nutrient release by CC residue does not pair with subsequent corn nutrient demand, then corn grain yield limitations may occur.

Cover crops can outcompete weeds and provide weed suppression as compared to chemical and mechanical control (Osipitan et al., 2018). A recent survey demonstrated that 93% of the surveyed farmers in Nebraska noticed weed suppression promoted by the incorporation of CCs (Oliveira et al., 2019). Cover crops can help suppress summer annual weeds indirectly through the residue left after termination (Teasdale et al., 1991; Teasdale and Mohler, 2000). Increments in soil coverage residue through CC use can limit the amount of sunlight exposure to the soil, which limits weed emergence. In addition, maintaining or increasing soil coverage residue can help with reducing water evaporation (Nielsen et al., 2005; Holman et al., 2018). With limited water availability, conservational practices such as no-till and CCs can increase the amount of crop residue on the soil surface decreasing the water loss by evaporation. However, in semi-arid environments, it is not well known how CCs can contribute to increasing soil residue coverage, and whether that would result in enhanced summer annual weed suppression and influence soil water storage.

Research Justification and Goals

This dissertation is presented as a series of five chapters. The first chapter is a general overview of the dissertation research. Chapters 2 through 4 are written in a manuscript format and intended to be published. The titles of chapters 2, 3 and 4 are: “Cover crop planting and termination time influenced development and yield of subsequent corn crop under semi-arid rainfed conditions of western Nebraska”, “Cover crop species selection contributions to rainfed cropping systems in semi-arid regions of western Nebraska” and “Influence of winter wheat stubble height and cover crop management on rainfed corn production in the semi-arid Great Plains”. The final chapter (chapter 5) provides general conclusions for the dissertation research.

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CHAPTER 2: COVER CROP PLANTING AND TERMINATION TIME EFFECTS ON DEVELOPMENT AND YIELD OF SUBSEQUENT CORN CROP UNDER SEMI-ARID RAINFED CONDITIONS OF WESTERN NEBRASKA

Abstract

Cover crops (CCs) have the potential to increase soil organic matter, cycle nutrients in the soil, and suppress weeds. However, there is a concern that CCs could use soil water and negatively impact subsequent crops in water-limited environments. Cover crop management practices such as planting and termination time may mitigate detrimental impacts of CCs in semi-arid cropping systems. To determine the effects of CCs under water-limited environments, total CC biomass produced in fall, early and late spring, soil water content during corn growing season, weed density and biomass, and soil residue coverage and fertility at corn V6 development stage, and subsequent corn productivity were evaluated. The study was conducted under a wheat-corn-fallow rotation at two sites (Grant and North Platte, NE) during 2016-2017 and 2017-2018 in a strip-split-plot randomized complete block design with four replications. Treatments consisted of three planting times after winter wheat harvest and four CC termination times prior to corn establishment. Planting CCs shortly after winter wheat harvest increased CC biomass in the fall and early spring compared to late planting. Weed density ($R = -0.24$, $p = 0.0038$) and biomass ($R = -0.39$, $p <.0001$) at corn V6 development stage were negatively correlated with late spring CC biomass. In addition, CCs terminated late in the spring increased soil residue coverage, but decreased total nitrogen at 0-10 cm soil depth up to 17%, and decreased up to 26% of soil nitrate at the 10-20 cm soil depth compared to the control. Cover crops planted early in the fall (August) and terminated late in the spring (May) had the most detrimental impact on corn grain yield. Results from this study indicate that despite enhanced weed suppression and soil residue coverage, CCs decreased nitrogen and corn grain yield, especially when late terminated in the

spring. This study provides important information regarding how planting and termination time of CCs may influence rainfed corn production in semi-arid environments. Our findings suggest that producers in semi-arid regions of the Great Plains willing to incorporate CCs should use caution when selecting management strategies for their CCs in order to minimize corn grain yield and economic losses.

Introduction

Producers throughout the US Midwest are increasing the incorporation of soil conservation management practices in their cropping systems (NASS, 2017). Within the conservation management options, cover crops (CCs) have become popular, particularly as the demand for enhanced sustainability in cropping systems increases (Dunn et al., 2016). Besides the increments towards crop diversity, the benefits provided by CCs to cropping systems are well documented and include: protecting the soil from water and wind erosion (Kaspar et al., 2001; Strock et al., 2004), reducing nitrogen leaching (Dinnes et al., 2002; Villamil et al., 2006), increasing soil organic carbon (Blanco-Canqui et al., 2015; Kaspar and Singer, 2011), and weed suppression (Teasdale, 1996, 2007; Mirsky et al., 2011; Werle et al., 2018; Oliveira et al., 2019). However, some researchers and practitioners caution against CC adoption because of soil water use (Unger and Vigil, 1998; Nielsen and Vigil, 2005) and nitrogen immobilization concerns (Tollenaar et al., 1993; Wortman et al., 2012).

In semi-arid climates (200-700 mm annual precipitation) of the Great Plains (Gallart et al., 2002), the no-till wheat (*Triticum aestivum L.*)-corn (*Zea mays L.*)-fallow is a commonly adopted rotation across rainfed areas (two grain crops in a three year period). This rotation has two fallow periods: one between winter wheat harvest and corn planting, and the other between corn harvest and winter wheat planting (Figure 2-1). Soil water conservation is the main reason for adopting this rotation (Klein, 2012), where the no-till system keeps the winter wheat residue on the soil surface to protect soil water loss through evaporation (Nielsen et al., 2005). Cover crops can be planted after winter-wheat harvest, filling the fallow period before corn planting, whereas a cool-season pulse crop such as field peas (*Pisum sativum L.*) can be grown in the fallow period between corn harvest and winter wheat planting (Stepanovic et al., 2018) (Figure 1). The earlier the CCs are planted, the higher the probability of greater biomass accumulation in the fall because of more growing degree day (GDD) accumulation. This is also true for CC termination time, whereas later termination in the spring (e.g., CCs closer to the corn planting time) could allow more time for CC growth in the spring. However, the duration of the CC growing season is expected to affect several aspects of the cropping system such as soil water content, soil fertility, weed demographics, and subsequent crop yield.

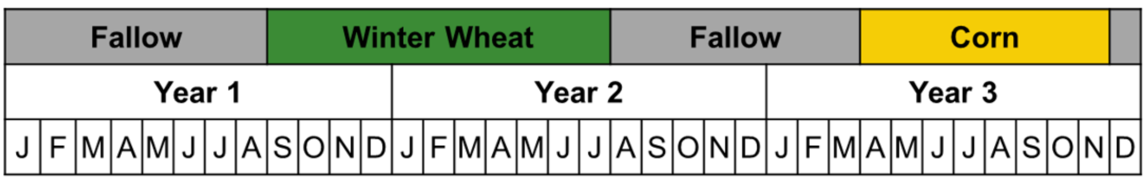

Figure 2-1. Winter wheat-corn-fallow (WCF) rotation commonly adopted in rainfed areas of semi-arid western Nebraska and much of the Great Plains.

Depending on precipitation amounts, CC can have different impact on soil water content. Above-average precipitation amounts during CC growing season in semi-arid environments may lead to neutral to positive effects of CCs on the soil water supply (Unger and Vigil, 1998), and consequently, increase the subsequent cash crop grain yield. However, in rainfed semi-arid climates, average and below-average precipitation may lead to negative effects of CCs on subsequent crop yield. The duration of CC growth window in semi-arid environments may result in excessive soil water consumption that could otherwise be available for subsequent cash crops. When CCs are late terminated (close to corn planting time) in the spring, those impacts tend to be more pronounced as typically there is not enough time and precipitation volume to recharge the soil profile to be used by the subsequent crop (Unger and Vigil, 1998). In a study evaluating water use by CCs, Nielsen *et al.* (2015) concluded that CC water use in a semi-arid environment increased 1.78 times, on average, compared to a no-till fallow. Moreover, Holman et al. (2018) reported that in dry years, incorporation of CCs reduced subsequent winter-wheat grain yields by 70%. Thus, one of the major concerns regarding the inclusion of cover crops after winter wheat harvest is the depletion of soil water that can lead to yield and economic penalties in the subsequent corn crop. Yet, the effects of CC on corn grain yield under rainfed semi-arid cropping systems are not well known.

In wheat-corn-fallow rotation, CCs can grow from July (winter-wheat harvest) through May (corn planting). During this period, CCs can outcompete weeds and provide weed suppression as compared to chemical and mechanical control (Osipitan et al., 2018). A recent survey demonstrated that 93% of the surveyed farmers in Nebraska noticed weed suppression promoted by the incorporation of CCs (Oliveira et al., 2019). Cover crops can help suppress summer annual weeds indirectly through the residue left after termination (Teasdale et al., 1991; Teasdale and Mohler, 2000). The residue of CCs can build soil coverage, limiting light exposure, which consequently limits weed emergence. In addition, maintaining or increasing residue can help with reducing water evaporation (Nielsen et al., 2005; Holman et al., 2018). With limited water availability, conservation practices such as no-till and CCs can increase the amount of crop residue on the soil surface, decreasing the water loss by evaporation, and still be competitive against weeds. However, in semi-arid environments, it is now well known how CCs can contribute to increasing soil residue coverage, and whether that would result in enhanced summer annual weed suppression and influence soil water storage.

Besides increasing crop residue in the soil, legume CCs can fix atmospheric nitrogen, cycle nitrate to prevent its leaching, and provide additional organic matter (Unger and Vigil, 1998; Blanco-Canqui et al., 2015). Cover crops can increase soil carbon, especially if CCs are composed mostly of grass species. Increases in carbon sequestration in the soil may represent an additional source of income for producers if the carbon markets become a reality (Ribaudo et al., 2007). Thus, the adoption of CC could be an advantage for farmers looking into adopting additional conservation practices and enter in the carbon sequestration market. Further, CCs may help nourish soil microbial communities (Finney et al., 2017) increasing their activity in the soil, and consequently improving soil physical and chemical properties (Sanchez et al., 2001). Whether in a single or multiple species mixture, CCs contribute to specific microbial communities (bacteria, fungi or protozoa), leading to soil quality improvement (Finney et al., 2017). On the other hand, the late termination of CCs may induce nitrogen immobilization to the subsequent crop (Dabney et al., 2001; Schomberg et al., 2007). However, due to reduced annual precipitation in semi-arid climates, CC biomass accumulation is limited, restricting the aforementioned advantages and disadvantages. Besides, in dry environments of the Central Great Plains, it is not clear how CCs influence soil nutrient cycling. Finding the best timing for planting and terminating CCs could help to enhance the benefits of CCs to cycle nutrients, reduce their impact on nitrogen immobilization and soil water use, and suppress weeds in the subsequent corn crop. However, it is unclear whether growing CCs in semi-arid rainfed cropping systems is beneficial or detrimental to subsequent corn during early stages of CC adoption.

We hypothesized that (1) planting CC shortly after winter wheat harvest can produce more CC biomass both in the fall and in the spring; (2) CC use soil water, decreasing water availability for corn; (3) CCs can suppress summer annual weeds; (4) CCs decrease nitrogen availability to corn, but can increase soil carbon and microbial activity, enhancing soil quality; and, (5) CC use in semi-arid regions can reduce subsequent corn grain yield. Thus, the objective of this study was to evaluate the impact of CC planting and termination time on CC biomass accumulation, soil water content, residue coverage, soil microbial activity and fertility levels, weed demographics, corn grain yield, and yield components.

Materials and Methods

Field Sites and Experimental Design

Field studies were conducted at two sites in western Nebraska during 2016-2017 and 2017-2018 cover crop-corn growing seasons (four experimental site-years). The studies were located at the University of Nebraska-Lincoln (UNL) Henry J. Stumpf International Wheat Center near Grant, NE (40°51'15.0"N; 101°42'13.9"W) on a Kuma silt loam (fine-silty, mixed, superactive, mesic Pachic Argiustolls) (Soil Science Division Staff, 2017), and at the UNL West Central Research and Extension Center near North Platte, NE (41°03'13.6"N; 100°44'52.8"W) on a Holdrege silt loam soil (fine-silty, mixed, superactive, mesic Typic Argiustolls) (Soil Science Division Staff, 2017). Each site and year was classified as one site-year. Thus, the four site-years are referred to as Grant 2016-2017, Grant 2017-2018, North Platte 2016-2017, and North Platte 2017-2018. Monthly precipitation and average temperature for each site-year are reported in Figure 2-2. The fields used in this study did not have a history of CC use and had been on a winter wheat-corn-fallow rotation and winter wheat was the crop harvested prior to study establishment.

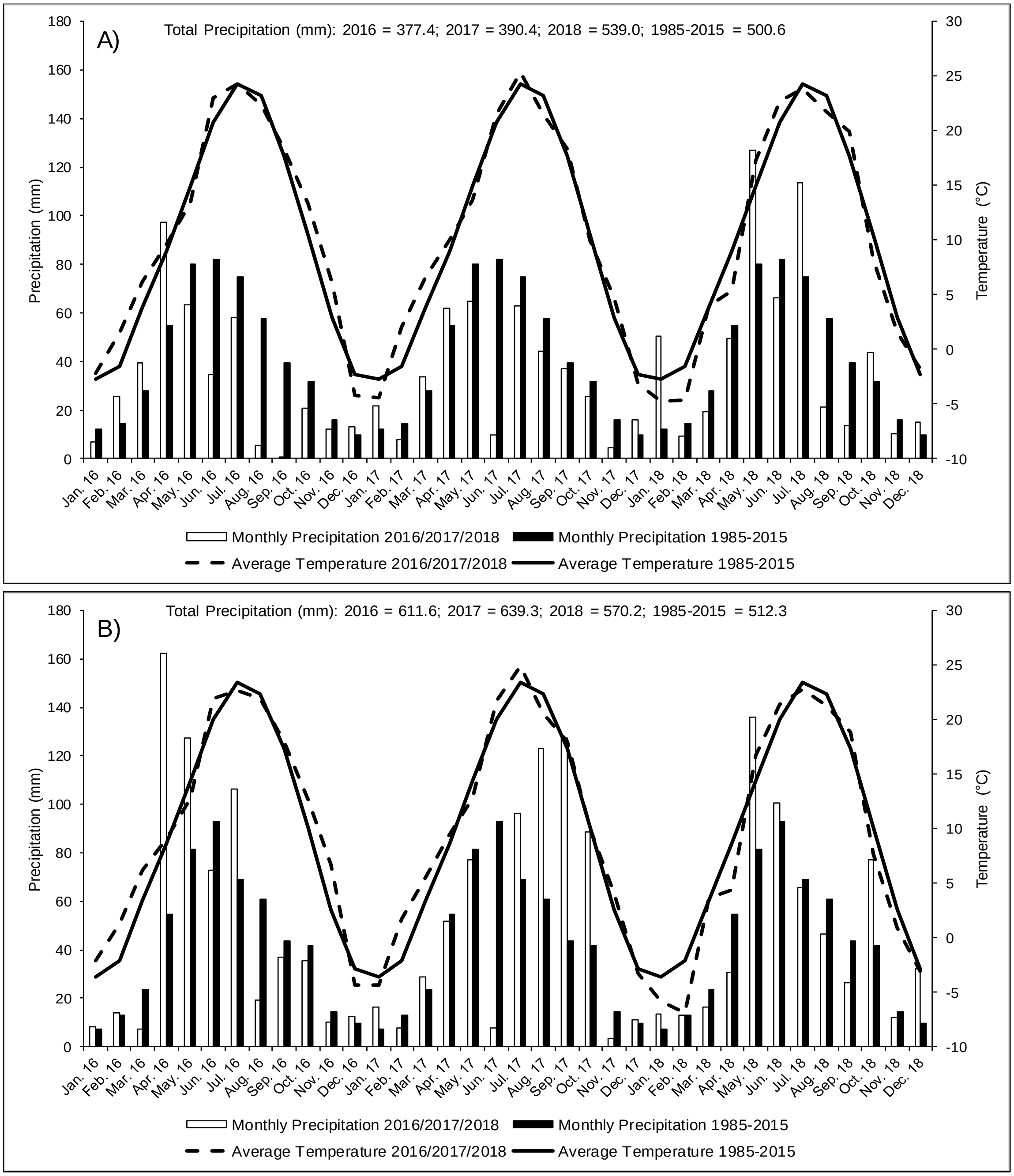

Figure 2-2. Average temperature and monthly precipitation for Grant (A) and North Platte, NE (B) during the years of 2016, 2017, 2018, and the period of 1985-2015. Source: High Plains Regional Climate Center at https://hprcc.unl.edu.

The experimental design was a strip-split-plot randomized complete block with four replications. The CC treatments included three planting times [three (P1), six (P2), and nine weeks (P3) after winter wheat harvest] and four termination times [no cover crop (NCC), winter-sensitive mixture frost-killed (WS), winter-hardy mixture terminated two weeks prior to corn planting (WHET), and winter-hardy mixture terminated at corn planting (WHLT)]. Cover crop planting time was considered the strip-plot, while termination time was the split-plot in the experimental design. The CC mixture species treatments and seeding rates were selected based on popularity (most grown in the region), and to represent a diversity of plant families (Poaceae, Fabaceae, and Brassicaceae) within CC mixtures. The CC winter-sensitive mixture consisted of four species: black oats (*Avena strigosa*), spring barley (*Hordeum vulgare*), spring lentil (*Lens culinaris*), and daikon radish (*Raphanus sativus L. var. longipinnatus*), and was planted at a seeding rate of 70 kg ha^{-1} (28.2 kg ha^{-1} of black oats, 28.2 kg ha^{-1} of spring barley, 11.3 kg ha^{-1} of spring lentil, and 2.3 kg ha^{-1} of daikon radish). The CC winter-hardy mixture also had four species: winter triticale (*Tritico secale*), winter barley (*Hordeum vulgare*), hairy vetch (*Vicia villosa*), and daikon radish (*Raphanus sativus L. var. longipinnatus*), and was planted at a seeding rate of 64 kg ha^{-1} (28.2 kg ha^{-1} of winter triticale, 28.2 kg ha^{-1} of winter barley, 5.3 kg ha^{-1} of hairy vetch, and 2.3 kg ha^{-1} of daikon radish). Cover crops were drilled at 19 cm row spacing and 3 cm seed depth. The individual plot size was 4.6 m wide and 15.2 m long. The CC winter-hardy treatments were terminated in the spring with glyphosate Roundup Powermax® (Bayer Crop Science, Saint Louis, MO) sprayed at 2.34 L ha^{-1} mixed with 453 g ha^{-1} of ammonium sulfate (KALO, Inc, Overland Park, KS), a water conditioner to improve glyphosate efficiency. Corn was planted at 76 cm row spacing and seed depth of 4 cm. The detailed information regarding CC planting and termination dates, corn planting and harvest dates, corn hybrid, and fertilization rates used in each site-year are described in Table 2-1.

Table 2-1. Cover crop (CC) planting and termination, corn planting, and fertilizer information for all research site-years. Cover crops were planted after winter wheat harvest and terminated both in the fall (freeze terminated) and in the spring (herbicide terminated). Corn hybrids, seeding rate, and fertilizer use were selected based on each site-year most common management practice. POST-emergence herbicides were applied to control weeds when corn reached the V6-V7 development stage.

Site-years	CC planting date	First hard freeze date*	CC early termination date	CC late termination date	Corn planting date	Weed control date	Corn hybrid and seeding rate (seeds ha^{-1})	Fertilizer (time, source, rate)	Corn harvest date
Grant 2016-2017	P1: 8/19/2016 P2: 9/8/2016 P3: 9/28/2016	12/09/2016	4/14/2017	5/24/2017	5/15/2017	5/24/2017	DKC52-61 (102 days maturity); 38300	Corn pre-planting, N-K-S, 118-59-5.6 kg ha^{-1}; at corn planting, ammonium polyphosphate (10-34-0), 65 kg ha^{-1}.	10/13/2017
Grant 2017-2018	P1: 8/15/2017 P2: 9/6/2017 P3: 10/13/2017	11/02/2017	5/6/2018	5/24/2018	5/24/2018	6/23/2018	DGVT2PRIB (101 days maturity); 37065	Corn planting, ammonium polyphosphate (10-34-0), 65 kg ha^{-1}; at corn V3 development stage, UAN (32-0-0), 310 kg ha^{-1}.	10/23/2018
North Platte 2016-2017	P1: 8/17/2016 P2: 9/7/2016 P3: 9/26/2016	12/09/2016	4/18/2017	5/2/2017	5/5/2017	6/20/2017	Hoegemayer 7643RR (106 days maturity); 41018	Corn pre-planting (4/6/2017), UAN (32-0-0), 89 kg ha^{-1}; at corn planting, ammonium polyphosphate (10-34-0), 110 kg $ha^{-1.}$	10/27/2017
North Platte 2017-2018	P1: 8/1/2017 P2: 9/22/2017 P3: 9/13/2017	11/01/2017	5/4/2018	5/24/2018	5/23/2018	6/27/2018	Hoegemayer 7643RR (106 days maturity); 41018	Corn pre-planting (4/19/2018), UAN (32-0-0), 112 kg ha^{-1}; at corn planting, ammonium polyphosphate (10-34-0), 110 kg ha^{-1}.	10/17/2018

Abbreviations: P1, P2, and P3 = first, second, and third CC planting time, respectively; UAN, urea ammonium nitrate; N, nitrogen; K, potassium; S, sulfur. *Temperature below 0°C for more than 2 consecutive days.

Data Collection

Cover Crop Aboveground Biomass

Cover crop aboveground biomass were collected in the fall after the first frost event (WS, WHET and WHLT treatments), which occurred in early November for all site-years. In the spring, CC winter-hardy species were harvested at the time of termination, being two weeks prior (WHET treatment only) and at the time of corn planting (WHLT treatment only), according to each site-year (Table 1). Two 0.093 m^{-2} aboveground biomass samples were randomly collected from each plot. After collection in the field, biomass samples were dried in a forced-air oven at 60°C for a minimum of 6 days and weighed when constant dry biomass was achieved.

Soil Water Content

Soil water content readings (m^3 m^{-3}) were performed using a handheld time-domain reflectometry (TDR), FieldScout TDR 300 Meter (Spectrum Technologies, Inc., Aurora, IL) with 0-20 cm waveguides installed vertically to average the water content over the entire soil layer. Six readings were recorded from 0 to 20 cm depth on each plot every other week starting at corn emergence (VE development stage) and ending when corn reached the R2 (blister stage) development stage (Abendroth et al., 2011). The corn development stage upon which the readings were performed varied according to the site-year because of different corn planting dates, selected crop hybrid, and weather conditions (Table 1 and Figure 1).

Calibration tests were conducted to evaluate the accuracy of the FieldScout TDR 300 Meter. Briefly, four undisturbed soil samples, using a round probe (10 cm diameter), were taken from 0 to 20 cm within the area surrounding the sensor reading (within a 50 cm radius) at each site-year four times during the year: late spring, early, mid and late summer. The soil samples were dried in a forced-air oven at 60°C for 8 days until a constant weight was reached. The gravimetric soil water content (Θ_g, grams of water per grams of soil) was quantified as the equation below (Hillel, 1998):

$$\Theta_g = (\text{soil wet weight} - \text{soil dry weight}) / \text{soil dry weight}$$

Where the numerator represents the mass of water (in grams) in the soil. The soil samples were also used to calculate soil bulk density ($\rho_{soil,}$ grams of soil per cubic centimeters, the ratio of soil dry mass to sample volume). Therefore, volumetric water content (Θ_v, cubic centimeters per cubic centimeters) was determined as follows (Hillel, 1998):

$$\Theta_v = (\Theta_g * \rho_{soil}) / \rho_{water}$$

Where ρ_{water} is the density of water (1 g cm^{-3}). The sensor readings were regressed on the volumetric water content measured from soil samples. The linear equations obtained from the regressions were used to adjust the sensor readings. This approach has been used by other researchers (Tarara and Ham, 1997; Song et al., 1998; Werle et al., 2014).

Weed Demographics

Weed species were identified, enumerated, and collected for total aboveground biomass determination when corn reached the V6 (six leaves with collar visible) development stage. Aboveground weed biomass samples were randomly collected from each plot using two 0.093 m^{-2} quadrats. Biomass of the combined weed species collected from each plot was determined after drying the samples in a forced air oven at 60°C (minimum of 6 days) and weighed when constant dry biomass was achieved. Weed assessment was not performed in Grant 2017 due to a pre-emergence herbicide application at corn planting, thus complete early season weed control was achieved across treatments. The other site-years did not receive a pre-emergence herbicide application, allowing early season weed establishment and evaluation. However, a timely post-emergence herbicide application was performed in all site-years at corn V6-V7 development stage to minimize weed impact on corn grain yield while providing enough time to assess weed communities across treatments (Table 2-1).

Residue Coverage

Total residue coverage biomass (kg ha^{-1}) on the soil surface was collected when corn reached the V6 development stage. All plant residues remaining on the soil surface, which mainly consisted of wheat and cover crop residues, were sampled. Two 0.093 m^{-2} aboveground biomass samples were randomly collected from each plot. After collection in the field, the biomass of residue coverage samples was dried in a forced-air oven at 60°C (minimum of 6 days) and weighed when constant dry biomass was achieved.

Soil Sampling

A composite soil sample of eight cores using a straight tube probe (2.5 cm diameter) was collected from 0 to 10 and 10 to 20 cm deep in each plot when corn reached the V6 development stage. Soil samples were sent to Ward Laboratories, Inc. (Kearney, NE) for analyses of pH, soil organic matter, solvita CO_2-C (soil respiration), total nitrogen (organic and inorganic), nitrate, organic carbon, total phosphorus, organic carbon:organic nitrogen (C:N ratio), and soil health score. Soil pH was measured using 1:1 soil:water ratio (Watson and Brown, 1998). Soil organic matter was determined by the loss on ignition method (Hoskins, 2002). The soil respiration represents the amount of CO_2-C released in 24 hours from soil microbes after the soil has been dried and rewetted. Thus, soil respiration is an indicator of soil microbial activity (Doran and Parkin, 1994). Soil respiration was analyzed using an infrared gas analyzer (IRGA) Li-Cor 840A (LI-COR Biosciences, Lincoln, Nebraska). Total nitrogen (organic and inorganic) and organic carbon were analyzed by the water extract using a Teledyne-Tekmar Torch C:N. Nitrate and total phosphorus were determined by the H3A extract on a Lachat 8000 flow injection analyzer (Hach Company, Loveland, Colorado). The C:N ratio was calculated based on the ratio of organic carbon and organic nitrogen, whereas soil health score accounts for the 10:1 C:N ratio and the microbial activity representing the nutrient cycling ability of the soil. Soil health score was determined by the following equation (Haney et al., 2018):

$$\text{Soil Health Score} = \frac{solvita\ \mathrm{CO2{-}C}}{10} + \frac{organic\ carbon}{100} + \frac{organic\ nitrogen}{10}$$

Corn Grain Yield and Yield Components

The two central corn rows in each plot were hand-harvested (2.65 m long per corn row) covering an area of 4.065 m^{-2} (Lauer, 2002). Corn was hand-harvested to enhance sampling and data accuracy. Corn grain yield components were estimated by counting corn plant population, number of kernels per ear, and the total weight of one hundred kernels. The corn plant population was measured by counting the number of plants in three rows of corn in each plot at the whole plot length. The total number of plants was then extrapolated for hectares. Six corn ears were randomly selected from the hand-harvested area for yield component estimations. The number of kernels per ear was determined by counting the number of kernel rows per ear (transversal count) and the number of kernels per row (longitudinal count). After accounting for the yield components, corn ears from the hand-harvested area were all threshed to separate the kernels from the ear using a stationary corn ear sheller (ALMACO, Nevada, IA). After threshing, 100 kernels weight (yield component) and grain yield at each plot was recorded and adjusted to 15.5% moisture using a moisture meter (Model Dickey John GAC 2100 Agri Bench Grain Moisture Tester, Dickey-John Corporation, Auburn, IL).

Statistical Analysis

An analysis of variance (ANOVA) was performed for all plant (CC biomass, soil water at corn VE-V1 development stage, weed density and biomass, residue coverage, corn grain yield, and yield components) and soil variables (organic matter, soil respiration, total N, organic carbon, nitrate, total phosphorus, C:N ratio and soil health score) in this study using the PROC GLIMMIX procedure in SAS 9.2 (SAS Institute, Cary, NC). The CC termination and planting time were considered as fixed factors and the replication blocks nested within site-years were treated as a random factor in the model. We included the no cover crop (NCC) treatment at the first (P1), second (P2) and third (P3) planting times because the drill was ran over these plots (no seeds were drilled). For all variables in the study, the NCC treatment was averaged across planting times P1, P2, P3 according to each replication in order to minimize the potential impact of the drill pass on those plots. The soil water content data measured through the corn growing season were analyzed by site-year as a repeated measure, where the corn development stage was considered as time in the model. Therefore, the soil water content data was analyzed across site-years (site-years treated as random effects) at corn V1-VE development stage, and within site-years (site-years treated as fixed effects) during corn growing season. All variables, except CC early spring biomass, C:N ratio, corn grain yield, and 100-kernel weight were log-transformed before the ANOVA to satisfy the Gaussian assumptions of normality data distribution (back transformed means are presented for ease of interpretation). For all response variables in the study, the separation of means for interactions and main effects was set at a significant level of $\alpha = 0.05$ with Tukey's adjustment for multiple comparisons completed using the LINES function in PROC GLIMMIX. Pearson's linear correlation tests were performed in soil and yield component variables at a 5 % significance level using PROC CORR in SAS 9.2 (SAS Institute, Cary, NC). Pearson's linear correlations were performed to understand the relationship between soil and plant variables, and support the ANOVA results.

A Canonical Discriminant Analysis (CDA) was performed to provide an insight into how the CC planting and termination time treatments cluster according to the plant and soil variables evaluated in this study and the relationships of the variables with the treatment clusters. The higher the relative weight of the variable in the canonical variate (measured by the size and direction of the arrows), the greater the variable contribution to the discriminant power of the function (Villamil et al., 2008). Therefore, the clusters that are in the same direction of the arrow would be positively correlated with the response variable, whereas an opposite direction of the arrow would have a negative canonical correlation with the response variable. In addition, the arrow length approximates the variance of the specific response variable. The CDA plots the canonical variates 1 and 2 (Can1 and Can2) which corresponds to the majority of the total variation within the dataset. The higher the canonical score, the bigger the vector in the plot. Plotting the variables with each other allows a visual representation of how the treatments cluster. All plant and soil variables were plotted in the CDA for both CC planting and termination time with the exception of the soil water during corn growing season, and corn yield components. The CC early and late spring biomass were not used for the CDA in the CC termination time because the CC early spring biomass was collected only for the WHET treatment, whereas the CC late spring biomass was collected only for the WHLT treatment. These two variables were not included to avoid possible CDA data bias. The CDA was performed using the *candisc ()* function (Friendly, 2007) in R (R Development Core Team, 2007).

Results

Weather Data

Some of the differences among treatments found in this study can be justified by the weather patterns (Figure 1). Each site-year was compared to the historical average data of precipitation and temperature for Grant and North Platte from 1985 through 2015. Although the distribution of the precipitation throughout the year is similar among the sites, it is important to note that Grant is historically drier than North Platte, and thus, received less precipitation than North Platte during the years of study (Figure 2-2). Besides the warmer (2017) and cooler spring

(2018) of both sites compared to the 30-year average temperature data, temperatures followed a similar trend in this study when compared to the 30-year average data. Therefore, only precipitation data at each site-year will be discussed hereafter.

Grant 2016-2017

Fall 2016, when cover crops (CCs) were planted after wheat harvest, received less precipitation than the historical average for Grant (Figure 2-2). The cumulative precipitation in fall 2016 (September, October, and November) was 49.8 mm lower than the historical average for Grant. During spring 2017 (March, April, and May) we observed slightly wet conditions, especially in March and April during CC spring growth, but still similar to the historical average for Grant. Summer 2017 (June, July, and August) was dry in Grant. The cumulative precipitation in summer 2017 in Grant was 109.5 mm below the historical average (Figure 2-2).

Grant 2017-2018

Fall 2017 was drier compared to the historical data but still received twice as much precipitation compared to fall 2016 in Grant. September was under the normality in terms of precipitation, but October and November were 19 and 71% below the 30-year average precipitation for the same period. In spring 2018, Grant was below the historical average precipitation until May, when CCs were terminated. May 2018 precipitation was above the historical data, with increased precipitation of 126.7 mm (+ 57%) compared to the historical data for Grant. In addition, spring 2018 precipitation was 22% above spring 2017 in Grant. During summer 2018, Grant received lower precipitation compared to the historical average but registered an increased 50% on the precipitation amount in July, when corn reaches the reproductive development stages. Moreover, the total precipitation for summer 2018 was 72% greater than in summer 2017 in Grant.

North Platte 2016-2017

Fall 2016 received slightly less precipitation than the historical average for North Platte (Figure 2-2). The cumulative precipitation in fall 2016 was 19 mm lower than the historical average, but 2.5 and 1.2 times greater than Grant 2017 and Grant 2018 precipitation amounts. On the other hand, precipitation patterns in spring 2017 were similar to those observed in the historical data for North Platte and Grant 2017. Likewise, in North Platte, the precipitation patterns during summer 2017 were similar to Grant 2017 (dry) until August, when corn development was in the reproductive stages. However, in August 2017, North Platte registered approximately twice the amount of rain expected for the month based on the historical average data.

North Platte 2017-2018

Fall 2017 received above-average precipitation in North Platte with the total precipitation amount greater than 2.2 times compared to the 30-year average and fall 2016 (Figure 2-2). When compared to Grant 2017 and Grant 2018, fall 2017 in North Platte registered approximately 6 and 3 times greater precipitation amounts, respectively. Just like in Grant 2018, in North Platte spring 2018 the precipitation was lower than the 30-year average until May when the total precipitation reached 136.1 mm (67% greater than the historical average). Throughout summer 2018 in North Platte, precipitation amounts were below the historical average, except June, where the precipitation was about 10% higher than the historical average.

Cover Crop Biomass

The predominant species in the CC mixtures varied according to sampling time and site-year. In fall, cool-season grasses were the predominant species (black oats, spring barley, winter triticale, and winter barley) at Grant 2016-2017, whereas radish (daikon radish) was the predominant species growing at North Platte 2016-2017 (data not shown). The predominance of grass species in fall may be due to dry conditions observed in the fall at Grant in 2016-2017 (Figure 2-2). Dry conditions do not favor radishes species (Wan and Kang, 2006). In the second year of the study, both Grant 2017-2018 and North Platte 2017-2018 site-years showed a predominance of radishes in the CC stand in fall. In all site-years, the predominant species in the spring were winter barley and winter triticale. Also, a poor growth was observed from the legumes in the mixes (spring lentil and hairy vetch) both in fall and spring.

Fall Biomass

There were differences in the main effects of CC biomass between CC mixtures (winter-sensitive and winter-hardy) ($p = 0.0141$) and planting time treatments ($p < .0001$). The WS treatment produced, on average, 7% more than the WH mixture (Table 2-2). The CC winter-sensitive species (black oats, spring barley, spring lentil and daikon radish) may be more adapted to higher temperatures that occur in the beginning of fall when compared to winter-hardy species, producing higher fall biomass. Previous studies conducted in Wisconsin showed that early fall (August) planted winter-sensitive cereals produced greater forage biomass than winter-hardy species (Maloney et al., 1999). On the other hand, the P1 (planted 3 weeks after winter wheat harvest) produced the highest biomass among planting time treatments (Table 2-2). The P1 achieved approximately twice the CC biomass than P2 (planted 6 weeks after winter wheat harvest) and eight times more than P3 (9 weeks after winter wheat harvest). Increased biomass in P1 in the fall was expected because of the extended growing window, and consequently more GDD accumulation during fall. No differences in CC biomass were found in the interaction between CC planting and CC mixtures ($p = 0.6513$, Table 2-2).

Table 2-2. Cover crop (CC) biomass during fall, early and late spring, and soil water content at VE-V1 corn development stage according to CC planting and termination time. Site-years were included as random effects in the ANOVA model. Numbers followed by different letters represent significant differences with Tukey adjustment at the $p \leq 0.05$.

	CC Fall Biomass ($kg\ ha^{-1}$)			CC Early Spring Biomass ($kg\ ha^{-1}$)			CC Late Spring Biomass ($kg\ ha^{-1}$)		Soil Water Content VE-V1 ($m^3\ m^{-3}$)		
Treatments	Mean	SE +-		Mean	SE +-		Mean	SE +-	Mean	SE +-	
P1	2470	137	A	1142	145	A	3065	243	0.265	0.012	
P2	1272	67	B	1294	136	A	3525	165	0.260	0.012	
P3	306	27	C	530	38	B	2984	110	0.261	0.012	
NCC	-	-		-	-		-	-	0.266	0.015	A
WS	1428	161	A	-	-		-	-	0.264	0.015	A
WHET	1334	173	B	989	141		-	-	0.263	0.014	A
WHLT	1310	161	B	-	-		3186	206	0.255	0.014	B
					p-values						
Planting Time (P)	**<.0001**			**0.0010**			0.1558		0.2614		
Termination Time (T)	**0.0141**			-			-		**0.0032**		
P x T	0.6513			-			-		0.8101		
					Pearson Correlation Coefficients						
Soil Water Content VE-V1 ($m^3\ m^{-3}$)	R= 0.04 (p = 0.5629)			R= -0.03 (p = 0.6793)			R= -0.03 (p = 0.6301)		1		

Abbreviations: P1, first planting time; P2, second planting time; P3, third planting time; NCC, no cover crop; WS, winter-sensitive; WHET, winter-hardy early termination; WHLT, winter-hardy late termination; VE and V1 corn development stages; SE, standard error of the mean.

Early Spring Biomass

Early in the spring, CC biomass was collected two weeks before corn planting (late-April/early-May). Therefore, only WHET (winter-hardy early termination) treatments were sampled. Early in the spring, the P1 (1142 kg ha^{-1}) and P2 (1294 kg ha^{-1}) planting times achieved similar amounts of CC biomass and were 115 and 144% greater than P3, respectively (Table 2-2).

Late Spring Biomass

Late spring biomass was collected at the time of corn planting (early-May/late-May; Table 2-1). Therefore, only WHLT (winter-hardy late termination) treatments were sampled. There were no differences among CC planting time treatments ($p = 0.1558$) on biomass accumulation late in the spring (Table 2-2).

Soil Water Content

Within site-years, there were no effects of CC planting time on the soil water content. However, the interaction and main effects of CC termination time and corn development stage affected the soil water content (Table 2-2 and Figure 2-3). The interaction between CC termination time and corn development stage was significant only in North Platte 2018 (p <.0001), where the soil water content in the WHLT treatment was similar to NCC and WS but 18% higher than WHET at the corn R2 development stage (Figure 2-3). This result could be attributed to remaining CC residue in the WHLT treatment compared to WHET. Cover crops can facilitate water infiltration through the rooting system by opening channels in the soil profile (Blanco-Canqui, 2018).

Moreover, within site-years, the main effects of CC termination time was significant in Grant 2017 only, where the WS and WHLT treatments decreased up to 8 and 12%, respectively, the soil water content compared to NCC (Figure 2-3). On the other hand, the WHET (0.143 m^3 m^-

^{3}) had similar soil water content as the NCC (0.144 m^3 m^{-3}). Additionally, the main effect of corn development stage was significant in all site-years. Thus, as expected, the soil water content decreased as corn developed from VE (average of 0.246 m^3 m^{-3}) to R2 (average of 0.181 m^3 m^{-3}) development stage (Figure 2-3).

Across site-years, at corn VE-V1 (one leaf with collar visible) development stage, the soil water content decreased up to 5% with the late termination of CCs when compared to NCC (Table 2-2). However, the soil water content measured at corn VE-V1 development stages was not correlated with CC fall (R = 0.04, p = 0.5629), early (R = -0.03, p = 0.6793) or late spring (R = -0.03, p = 0.6301) biomass (Table 2-2). Hence, CCs deplete soil water at corn planting time, especially when late terminated in the spring, increasing the risk of penalizing the subsequent corn crop.

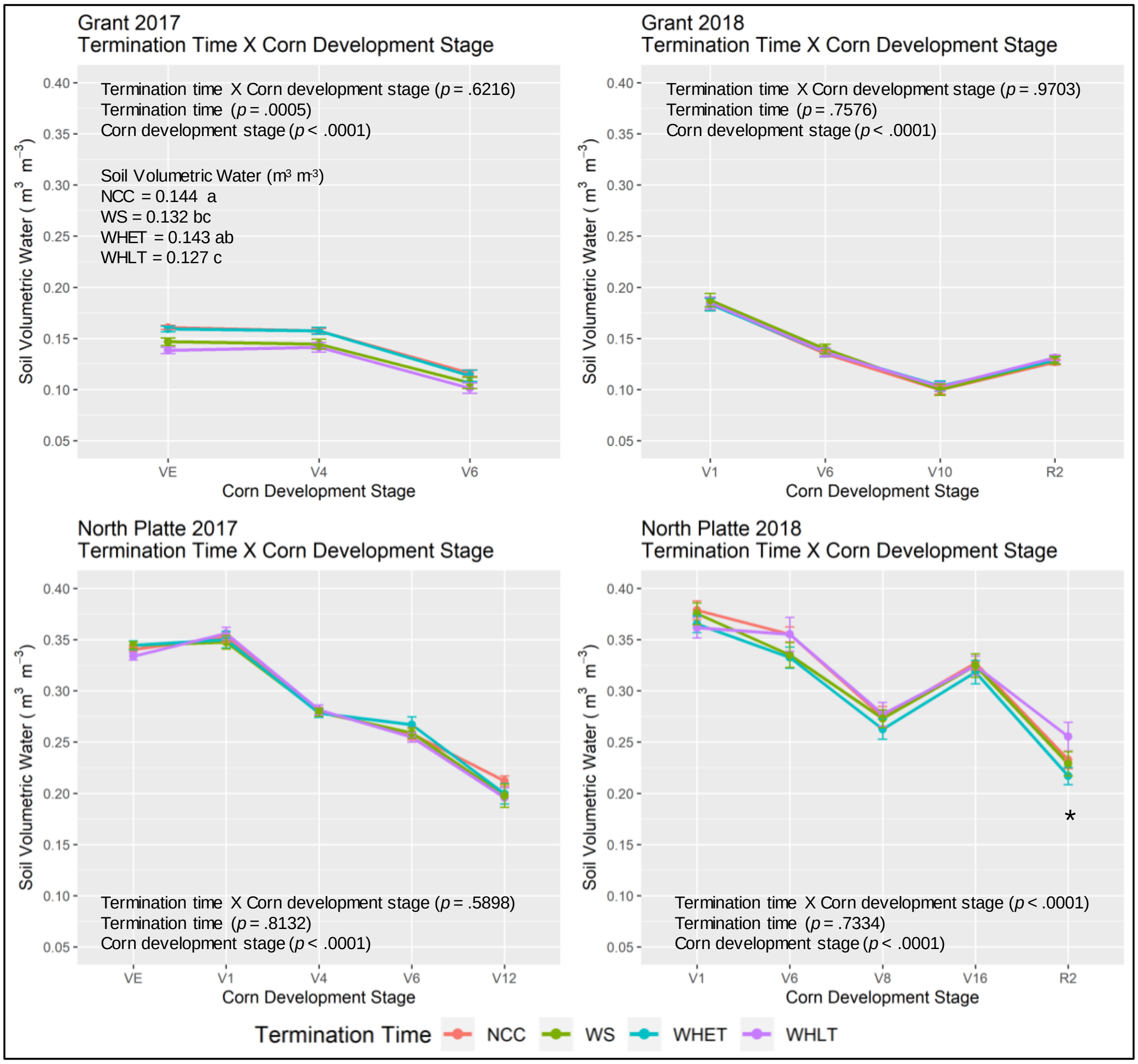

Figure 2-3. Soil volumetric water content at 0-20 cm depth at each site-year according to the interaction of cover crop termination time and corn development stage. Abbreviations: NCC, no cover crop; WS, winter-sensitive; WHET, winter-hardy early termination; WHLT, winter-hardy late termination; VE, V1, V4, V6, V8, V10, V16, R2 corn development stages. * represent significant differences at $p \leq 0.05$.

Weed Demographics

Weed species community varied across site-years. The most common species found by site-year were prostrate pigweed (*Amaranthus blitoides*) at North Platte 2017; carpetweed (*Mollugo verticillata*) at North Platte 2018; and kochia (*Bassia scoparia*) at Grant 2018. Overall, the weed pressure in the experimental sites was low. Still, weed density was influenced according to CC termination time ($p = 0.0033$). The WHLT reduced weed density by 56 and 54%, respectively, compared to NCC and WS treatments (Table 2-3). Weed density was similar among WHLT and WHET treatments. Moreover, the weed density was negatively correlated with CC late spring biomass (R = -0.24, $p = 0.0038$). Therefore, late termination of CCs had the highest potential to suppress summer annual weeds.

Regarding weed biomass, there was a significant difference among CC termination time treatments ($p < .0001$). The NCC showed the greatest weed biomass among CC termination time treatments. In other words, the WHET and WHLT reduced weed biomass by 70 and 82% compared to NCC, respectively. Besides, there were negative correlations between weed biomass and CC fall (R = -0.24, $p = 0.0035$), early (R = -0.28, $p = 0.0007$) and late spring (R = -0.39, $p < .0001$) biomass, confirming that CCs were effective in reducing weed biomass in this study (Table 2-3).

Table 2-3. Total weed density and biomass, and residue biomass at corn V6 development stage according to CC planting and termination time. Site-years were included as random effects in the ANOVA model. Numbers followed by different letters represent statistically significant differences with Tukey adjustment at the $p \leq 0.05$.

	Weed Density (weeds m^{-2})			Weed Biomass (kg ha^{-1})			Residue Biomass (kg ha^{-1})		
Treatments	Mean	SE +-		Mean	SE +-		Mean	SE +-	
P1	29	4		88	10		7748	519	A
P2	37	6		116	24		7167	377	A
P3	36	7		92	11		6060	300	B
NCC	41	7	A	196	51	A	6398	345	B
WS	39	7	A	105	21	AB	6473	666	B
WHET	37	8	AB	58	9	BC	7055	462	AB
WHLT	18	3	B	36	7	C	8041	356	A
				p-values					
Planting Time	0.9365			0.5587			**0.0097**		
Termination Time	**0.0033**			**<.0001**			**<.0001**		
Planting x Termination Time	0.1285			0.0636			0.6740		
				Pearson Correlation Coefficients					
CC Fall Biomass (kg ha^{-1})	R = -0.12 (p = 0.1303)			**R = -0.24 (p = 0.0035)**			**R = 0.23 (p = 0.0064)**		
CC Early Spring Biomass (kg ha^{-1})	R = -0.15 (p = 0.0731)			**R = -0.28 (p = 0.0007)**			R = -0.02 (p = 0.8361)		
CC Late Spring Biomass (kg ha^{-1})	**R = -0.24 (p = 0.0038)**			**R = -0.39 (p <.0001)**			**R = 0.27 (p = 0.0010)**		

Abbreviations: P1, first planting time; P2, second planting time; P3, third planting time; NCC, no cover crop; WS, winter-sensitive; WHET, winter-hardy early termination; WHLT, winter-hardy late termination; SE, standard error of the mean.

Residue Coverage

The residue coverage biomass was affected by CC planting (p = 0.0097) and termination time (p <.0001) main effects only. The first (P1) and second (P2) CC planting time increased the residue biomass in the soil surface by 28 and 18% compared to the latest CC planting time (P3). Likewise, the latest CC termination time (WHLT) increased the residue biomass in 24 and 26% over WS and NCC, respectively. The WHET reached similar residue coverage biomass as the WHLT treatment. Also, there was a positive correlation between residue coverage and CC fall (R = 0.23, p = 0.0064) and late spring biomass (R = 0.27, p = 0.0010) (Table 2-3). The lack of correlation between CC early spring biomass and residue coverage is justified by the low amount of CC biomass sampled during early spring (Table 2-2). It is possible that most CC residue was degraded when residue coverage biomass was sampled (at corn V6 development stage). In addition, it is important to note that even though NCC did not have any CC planted, the winter wheat straw residue was still present and represented the bulk of the residue collected at corn V6 development stage.

Soil Sampling

The soil variables were analyzed by soil depth to access possible soil nutrient differences caused by CC planting and termination time at each specific soil depth. The mean and standard errors of the soil variables at 0-10 cm soil depth are presented in Table 2-4, whereas the values for 10-20 cm soil depth are in Table 2-5.

At 0-10 cm soil depth, the soil total N (p <.0001), nitrate (p <.0001) and C:N ratio (p = 0.0492) were impacted by CC termination time. Cover crops WHLT reduced the available N in the soil (Table 2-4). Both total N and nitrate levels in the soil were reduced up to 17 and 28%, respectively, by the WHLT compared to the NCC treatment. The WS mixture terminated in the fall also showed lower nitrate levels in the soil compared to the NCC. Consequently, the WHLT and WS increased the C:N ratio compared to NCC. Soil organic carbon was similar among the termination treatments, but the reduction in soil N caused by CCs likely contributed for a higher C:N ratio in the top soil under WHLT and WS treatments. Moreover, both total N (R = -0.28, p = 0.0008) and nitrate (R = -0.29, p = 0.0005) were negatively correlated with residue coverage biomass, and positively correlated [(total N, R = 0.53, p <.0001), (nitrate, R = 0.59, p <.0001)] with corn grain yield (Table 2-4). Thus, CC WHLT had the most negative impact in soil nitrogen levels, probably due to its increased biomass production (fall and spring). Soil carbon and respiration (microbial activity) were not impacted by CCs. Moreover, there were no effects of CC planting time neither interactions on soil variables at 0-10 cm soil depth.

At 10-20 cm soil depth, the soil organic matter (*p* = 0.0175), total N (*p* = 0.0002), nitrate (*p* <.0001) and C:N ratio (*p* = 0.0056) were affected by CC termination time (Table 2-5). The WHLT (2.4 g kg^{-1}) treatment achieved a similar value of soil organic matter compared to NCC (2.3 g kg^{-1}) and WHET (2.3 g kg^{-1}) but higher than WS (2.1 g kg^{-1}). However, there were no correlations of soil organic matter with neither the residue coverage biomass nor the corn grain yield. Cover crops WHLT and WS also reduced the available N at 10-20 cm soil depth (Table 2-5). The soil total N and nitrate levels were reduced up to 14 and 26%, respectively, by the WHLT compared to the NCC treatment. The WS also reduced both soil total N and nitrate levels by 12 and 20%, respectively, compared to NCC. Consequently, the WHLT and WS increased the C:N ratio compared to NCC. Soil organic carbon was similar among the termination treatments, but the reduction in soil N caused by CCs likely contributed for a higher C:N ratio at 10-20 cm soil depth under WHLT and WS treatments. Furthermore, both total N (R = 0.58, *p* <.0001) and nitrate (R = 0.78, *p* <.0001) were positively correlated with corn grain yield (Table 2-5). Thus, CC WHLT also had the most negative impact in soil nitrogen levels at 10-20 cm soil depth, which contributed to reduced corn grain yield. Similarly to 0-10 cm soil depth, there were no effects of CC planting time on soil variables at 10-20 cm soil depth. In addition, soil carbon and respiration (microbial activity) were not impacted by CCs.

Table 2-4. Soil organic matter, soil respiration, total nitrogen, organic carbon, nitrate, total phosphorus, carbon:nitrogen (C:N) ratio, soil health score at 0-10 cm depth collected at corn V6 development stage according to CC planting and termination time. Site-years were included as random effects in the ANOVA model. Numbers followed by different letters represent statistically significant differences with Tukey adjustment at the $p \leq 0.05$.

	Organic Matter ($g\ kg^{-1}$)		Soil Respiration ($mg\ kg^{-1}$ C)		Total Nitrogen ($mg\ kg^{-1}$ N)			Organic Carbon ($mg\ kg^{-1}$ C)		Nitrate ($mg\ kg^{-1}$ NO_3-N)			Total Phosphorus ($mg\ kg^{-1}$ P)		C:N ratio			Soil Health Score	
Planting Time (P)	Mean	SE +-	Mean	SE +-	Mean	SE +-		Mean	SE +-	Mean	SE +-		Mean	SE +-	Mean	SE +-		Mean	SE +-
P1	2.5	0.1	42.4	2.2	29.5	1.1		128	2.6	12.4	1.0		30.2	1.1	10.0	0.2		7.1	0.3
P2	2.5	0.1	45.1	2.9	28.0	1.1		129	2.6	11.5	1.0		29.8	0.9	10.2	0.2		7.1	0.3
P3	2.5	0.1	41.3	2.5	30.2	1.6		125	2.4	13.5	1.4		30.8	0.9	10.3	0.3		6.8	0.3
Termination Time (T)																			
NCC	2.4	0.1	38.8	1.9	31.2	1.0	A	124	2.4	13.7	1.0	A	30.0	0.9	9.7	0.2	B	6.8	0.3
WS	2.4	0.0	47.7	3.7	30.0	1.8	A	129	3.4	13.1	1.6	B	30.9	1.2	10.3	0.3	A	7.4	0.4
WHET	2.4	0.1	41.4	2.2	29.8	1.3	A	127	3.0	13.0	1.4	AB	30.9	1.2	10.1	0.3	AB	6.9	0.3
WHLT	2.6	0.1	43.8	3.5	26.0	1.7	B	130	2.8	9.90	1.3	C	29.3	1.1	10.5	0.3	A	6.9	0.4
p-values																			
P	0.9336		0.4625		0.5343			0.3959		0.3775			0.5072		0.5673			0.3427	
T	0.2009		0.1272		**<.0001**			0.2935		**<.0001**			0.3584		**0.0492**			0.5282	
P x T	0.2328		0.2445		0.7930			0.7950		0.8693			0.9620		0.6479			0.2432	
Pearson Correlation Coefficients																			
Residue Biomass ($kg\ ha^{-1}$)	R= -0.08 (*p* = 0.3490)		R= -0.10 (*p* = 0.2332)		R= -0.28 (*p* = 0.0008)			R= -0.23 (*p* = 0.0066)		R= -0.29 (*p* = 0.0005)			R= -0.32 (*p* <.0001)		R= 0.12 (*p* = 0.1469)			R= -0.23 (*p* = 0.0056)	
Corn Grain Yield ($Mg\ ha^{-1}$)	R= 0.14 (*p* = 0.0546)		R= -0.59 (*p* <.0001)		R= 0.53 (*p* <.0001)			R= 0.27 (*p* = 0.0001)		R= 0.59 (*p* <.0001)			R= -0.42 (*p* <.0001)		R= 0.10 (*p* = 0.1810)			R= -0.50 (*p* <.0001)	

Abbreviations: P1, first planting time; P2, second planting time; P3, third planting time; NCC, no cover crop; WS, winter-sensitive; WHET, winter-hardy early termination; WHLT, winter-hardy late termination; SE, standard error of the mean.

Table 2-5. Soil organic matter, soil respiration, total nitrogen, organic carbon, nitrate, total phosphorus, carbon:nitrogen (C:N) ratio, soil health score at 10-20 cm depth collected at corn V6 development stage according to CC planting and termination time. Site-years were included as random effects in the ANOVA model. Numbers followed by different letters represent statistically significant differences with Tukey adjustment at the $p \leq 0.05$.

	Organic Matter (g kg^{-1})			Soil Respiration (mg kg^{-1} C)			Total Nitrogen (mg kg^{-1} N)			Organic Carbon (mg kg^{-1} C)			Nitrate (mg kg^{-1} NO_3-N)			Total Phosphorus (mg kg^{-1} P)			C:N ratio			Soil Health Score		
Planting Time (P)	Mean	SE +-		Mean	SE +-		Mean	SE +-		Mean	SE +-		Mean	SE +-		Mean	SE +-		Mean	SE +-		Mean	SE +-	
P1	2.3	0.1		22.9	2.0		21.1	0.7		107	2.5		7.6	0.6		9.5	0.7		9.6	0.3		4.6	0.2	
P2	2.3	0.1		22.8	2.2		19.9	0.6		105	2.2		6.9	0.5		9.4	0.3		9.6	0.2		4.6	0.2	
P3	2.3	0.1		21.5	2.0		20.9	0.7		103	2.0		7.8	0.6		9.4	0.3		9.4	0.2		4.5	0.2	
Termination Time (T)																								
NCC	2.3	0.1	AB	18.3	1.0		22.5	1.1	A	101	2.6		8.7	0.5	A	9.1	0.3		8.8	0.2	B	4.4	0.2	
WS	2.1	0.1	B	26.1	3.1		19.8	1.1	BC	105	2.9		7.0	0.7	B	9.3	0.4		9.9	0.3	A	4.7	0.2	
WHET	2.3	0.1	AB	21.7	2.4		21.0	0.9	AB	105	2.5		7.6	0.6	A	9.2	0.4		9.4	0.3	AB	4.6	0.3	
WHLT	2.4	0.1	A	23.7	2.4		19.3	1.0	C	108	2.5		6.4	0.8	B	10.1	0.8		9.9	0.2	A	4.5	0.2	
p-values																								
P	0.9699			0.5463			0.4587			0.2291			0.3094			0.7101			0.8370			0.4481		
T	**0.0175**			0.0789			**0.0002**			0.0585			**<.0001**			0.5057			**0.0056**			0.8212		
P x T	0.1940			0.6034			0.9751			0.8797			0.9632			0.3410			0.9893			0.3653		
Pearson Correlation Coefficients																								
Residue Biomass (kg ha^{-1})	R= 0.01 (*p* = 0.8866)			R= 0.28 (*p* = 0.0007)			R= -0.12 (*p* = 0.1486)			R= -0.14 (*p* = 0.0859)			R= -0.13 (*p* = 0.1306)			R= -0.11 (*p* = 0.1985)			R= 0.03 (*p* = 0.7219)			R= 0.22 (*p* = 0.0068)		
Corn Grain Yield (Mg ha^{-1})	R= 0.09 (*p* = 0.2068)			R= -0.52 (*p* <.0001)			R= 0.58 (*p* <.0001)			R= -0.15 (*p* = 0.0404)			R= 0.78 (*p* <.0001)			R= -0.02 (*p* = 0.8073)			R= -0.14 (*p* = 0.0610)			R= -0.50 (*p* <.0001)		

Abbreviations: P1, first planting time; P2, second planting time; P3, third planting time; NCC, no cover crop; WS, winter-sensitive; WHET, winter-hardy early termination; WHLT, winter-hardy late termination; SE, standard error of the mean.

Corn Grain Yield and Yield Components

Corn grain yield was affected by the CC planting (*p* = 0.0256) and termination time (*p* <.0001) (Table 2-6). The first (P1) and second (P2) planting reduced corn grain yield by up to 5% over the last planting time (P3). On the other hand, the WS, WHET and WHLT decreased corn grain yield by 8, 8, and 20%, respectively, compared to the control treatment (NCC). Therefore, planting CCs early in the fall (P1 and P2) and terminating late (WHLT) caused the most negative effects on corn grain yield (Table 2-6).

Corn yield components were computed to predict which yield components, if any, were mostly affected by CC planting and termination time, and which of those yield components were mostly associated with corn grain yield. The corn plant population was affected by the CC termination time only (*p* = 0.0025) (Table 2-6). Although the corn plant population decreased with the WHLT (approximately 8% fewer corn plants per hectare than the other CC termination treatments), the corn plant population did not influence the corn grain yield (R = 0.03, *p* = 0.7288). Likewise, the number of kernels per ear (*p* = 0.0004) and the 100-kernel weight (*p* <.0001) were affected by CC termination time only (Table 2-6). The WHLT decreased the number of kernels per ear up to 4% compared to NCC, WS, and WHET. Similarly, the WHLT and WHET reduced the 100-kernel weight compared to NCC and WS treatments. Both kernels per ear (R = 0.28, *p* <.0001) and 100-kernel weight (R = 0.78, *p* <.0001) yield components were positively correlated with the corn grain yield (Table 2-6). Thus, the 100-kernel weight was the corn yield component that most affected corn grain yield.

Table 2-6. Corn grain yield and yield components (corn plant population, kernels per ear and 100-kernel weight) according to CC planting and termination time. Site-years were included as random effects in the ANOVA model. Numbers followed by different letters represent statistically significant differences with Tukey adjustment at the $p \leq 0.05$.

	Corn Grain Yield (Mg ha^{-1})			Corn Plant Population (plants ha^{-1})			Kernels per Ear			100-Kernel Weight (g)		
Treatments	Mean	SE +-		Mean	SE +-		Mean	SE +-		Mean	SE +-	
P1	8.2	0.2	B	32434	698		684	10		32.4	0.8	
P2	8.1	0.2	B	32388	680		685	10		31.8	0.8	
P3	8.5	0.2	A	32556	595		696	10		32.5	0.7	
NCC	9.0	0.2	A	32932	606	A	698	10	A	33.3	0.8	A
WS	8.3	0.3	B	33333	556	A	690	12	A	32.6	0.9	B
WHET	8.3	0.2	B	32881	760	A	694	12	A	31.7	0.8	C
WHLT	7.5	0.3	C	30692	993	B	670	13	B	31.4	1.0	C
	p-values											
Planting Time (P)	**0.0267**			0.8249			0.1418			0.0650		
Termination Time (T)	**<.0001**			**0.0007**			**0.0004**			**<.0001**		
P x T	0.1564			0.1247			0.3241			0.5040		
	Pearson Correlation Coefficients											
Corn Grain Yield (Mg ha^{-1})	R = 1			R = 0.03 (p = 0.7288)			**R = 0.28 (p <.0001)**			**R = 0.78 (p <.0001)**		

Abbreviations: P1, first planting time; P2, second planting time; P3, third planting time; NCC, no cover crop; WS, winter-sensitive; WHET, winter-hardy early termination; WHLT, winter-hardy late termination; SE, standard error of the mean.

Canonical Discriminant Analysis

The canonical discriminant analysis (CDA) was performed to visualize the relationships between plant and soil variables with CC planting and termination time treatments. Therefore, the CDA was intended to support the results from the ANOVA. The CDA plot for the CC planting time is presented in Figure 2-4, and the canonical correlation coefficients in Table 2-7. The canonical variates 1 (Can1) and 2 (Can2) correspond to 94.5 and 5.5% of the total variation in the data, respectively. Thus, the Can1 explains most of the variation in the dataset and was the only statistically significant canonical variate *(p* <0.0001). Based on the size of the arrows in the Can1 axis (Figure 2-4) and the high canonical correlation coefficients (Table 2-6), CC fall biomass and residue coverage were the most important variables to characterize differences in planting time (Figure 2-4). Cover crop fall biomass (R = 0.92), residue coverage (R = 0.33), and CC early spring biomass (R = 0.16) were positively correlated to the first CC planting time (P1), and therefore, negatively correlated with the third planting time (P3). However, the corn grain yield was negatively correlated with P1 (R = -0.11) as its arrow is going in opposite direction. Biologically, and according to the ANOVA, the CDA showed that P1 was associated with more CC biomass production in fall and early spring, as well as with residue coverage biomass when compared to the other planting time treatments. On the other hand, the P1 may be associated with lower corn grain yields as compared to P3. The response variables that are more concentrated in the center of the plot were associated with the second planting time (P2), but their canonical correlation coefficients were low. Despite the long arrow and high canonical correlation coefficients for soil total N and nitrate, they were represented by the Can2 which was not significant ($p = 0.4065$).

Table 2-7. Canonical correlation coefficients for plant and soil variables according to cover crop (CC) planting and termination time across site-years in western Nebraska.

	CC Planting Time		CC Termination Time	
Variable	Canonical Variate 1	Canonical Variate 2	Canonical Variate 1	Canonical Variate 2
CC Fall Biomass	0.92	0.03	0.84	0.32
CC Early Spring Biomass	0.16	0.46	NA	NA
CC Late Spring Biomass	0.03	0.14	NA	NA
Weed Density	-0.06	0.19	-0.22	0.40
Weed Biomass	0.15	0.12	-0.49	0.12
Residue Coverage	0.33	0.35	0.25	-0.38
Soil Water VE-V1	0.04	-0.07	-0.04	0.08
Corn Grain Yield	-0.11	-0.32	-0.43	0.44
Organic Matter	-0.04	-0.06	0.08	-0.35
Soil Respiration	0.06	0.19	0.01	0.13
Total Nitrogen (N)	-0.01	-0.35	-0.10	0.19
Organic Carbon (C)	0.10	0.08	0.13	-0.09
Nitrate	-0.04	-0.35	-0.09	0.22
Total Phosphorus	0.01	-0.10	-0.02	0.06
C:N Ratio	-0.02	0.02	0.16	-0.06
Soil Health Score	0.10	0.14	-0.03	0.13
Proportion of Variance (%)	94.5	5.5	72.1	24.8
p values	<.0001	0.4065	<.0001	<.0001

Abbreviations: VE, V1 and V6 corn development stages.

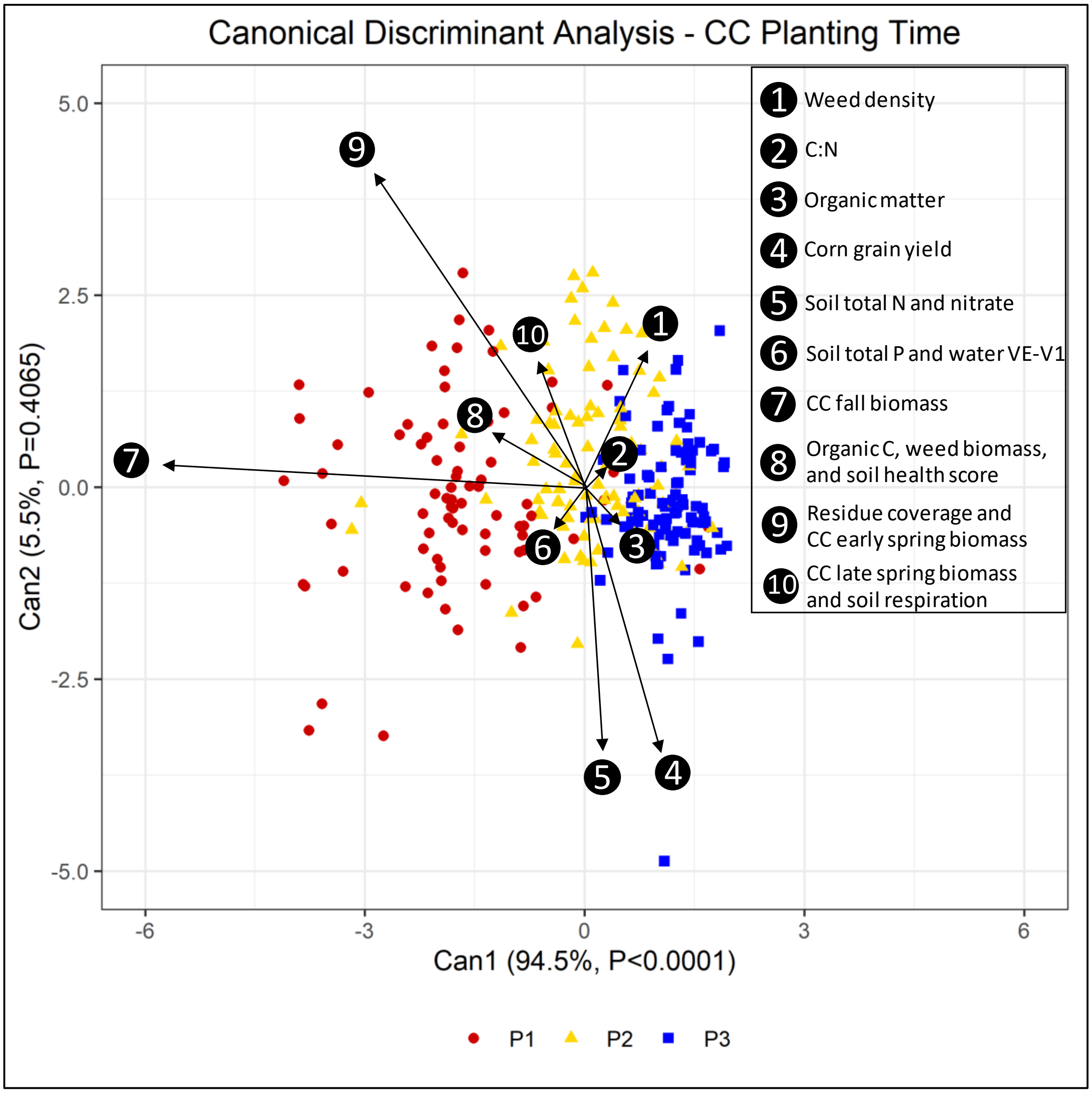

Figure 2-4. Canonical discriminant analysis of plant and soil variables according to cover crop (CC) planting time across site-years in western Nebraska. Abbreviations: P1, P2 and P3 = first, second and third CC planting time, respectively; C, carbon; N, nitrogen; P, phosphorus; VE and V1 corn development stages.

The Figure 2-5 is a plot of the CDA for the CC termination time treatments. The Can1 and Can2 correspond to 72.1 and 24.8% of the total variation, respectively, where both were statistically significant ($p < .0001$). The Can1 explains most of the variation in the data, but the Can2 was also considered for the cluster formation in the Figure 2-5. Based on the size of the arrow (Figure 2-5) and the high canonical correlation value, the CC fall biomass ($R = 0.84$) was the most important variable to characterize the CC termination time, followed by weed biomass ($R = -0.49$), corn grain yield ($R = -0.43$), and residue coverage ($R = 0.25$). For Can2, the most important variables were corn grain yield ($R = 0.44$), weed density ($R = 0.40$), residue coverage ($R = -0.38$), organic matter ($R = -0.35$) CC fall biomass ($R = 0.32$), soil nitrate ($R = 0.22$) and total N ($R = 0.19$). The variables weed density and biomass, and corn grain yield were positively correlated with the NCC treatment, whereas the CC fall biomass is negatively correlated with NCC since its arrow is going in the opposite direction. Therefore, the CDA showed that NCC was associated with higher weed density and biomass, and corn grain yield compared to the other CC termination treatments. On the other hand, the WHLT treatment clustered towards the organic matter, residue coverage, organic carbon, and C:N ratio. At the same time, the WHLT may be associated with lower weed density and biomass, and corn grain yield as their arrows are going in opposite direction.

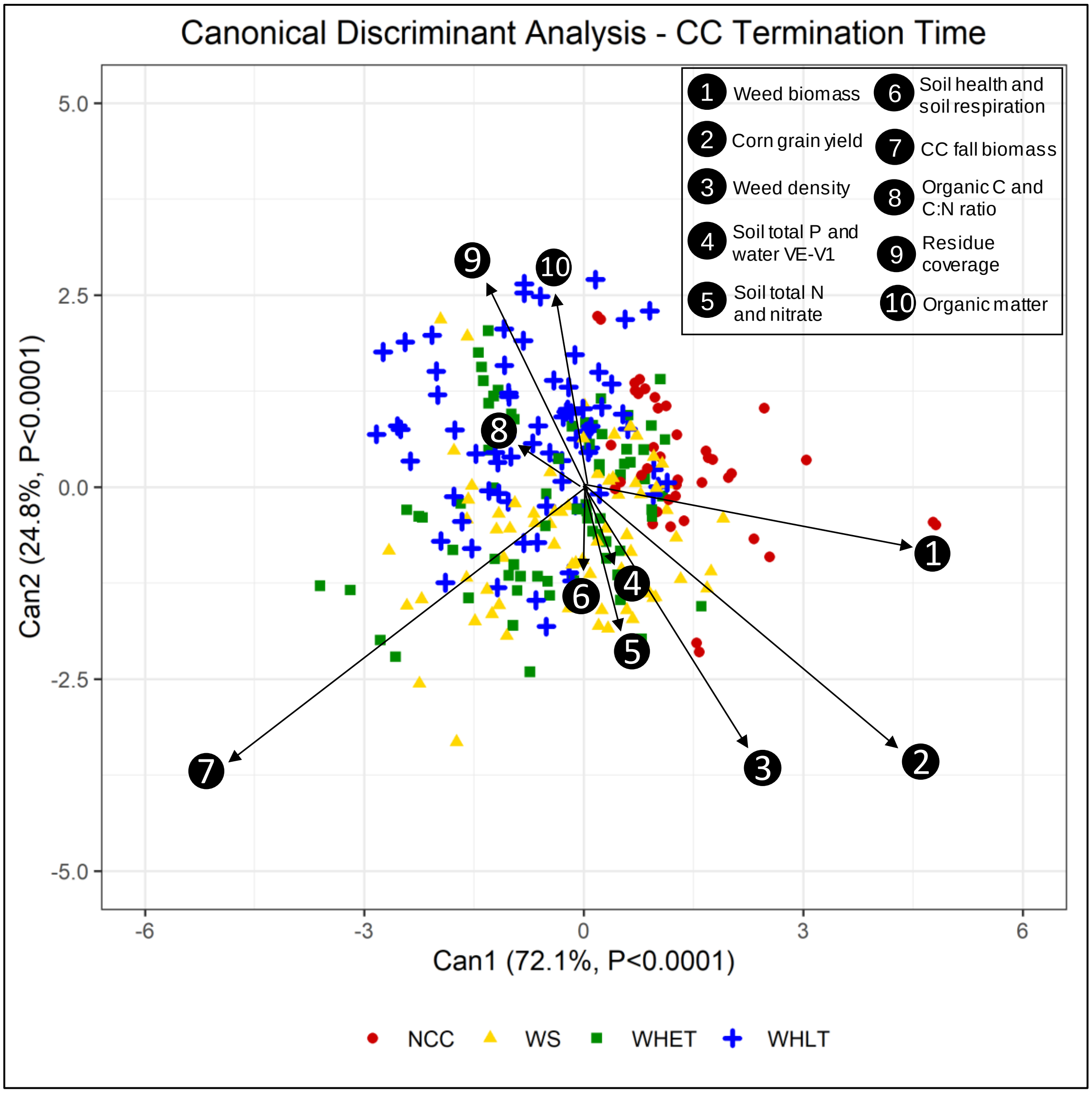

Figure 2-5. Canonical discriminant analysis of plant and soil variables according to cover crop (CC) termination time across site-years in western Nebraska. Abbreviations: NCC, no cover crop; WS, winter-sensitive; WHET, winter-hardy early termination; WHLT, winter-hardy late termination; C, carbon; N, nitrogen; P, phosphorus; VE, V1 and V6 corn development stages.

Discussion

The GDD and precipitation were key for CC growth and development in this study in semi-arid western Nebraska. The earlier CCs were planted, the longer the growth period, and consequently more biomass accumulated in the fall. Early fall presents higher soil and air temperature, which increases the GDD accumulation, and consequently increasing CC biomass (Nielsen et al., 2015b). The CC winter-sensitive mixture reached higher biomass in the fall when compared to CC winter-hardy species. Previous studies conducted in Ohio also reported a similar result, where the increased biomass produced by winter-sensitive species can potentially contribute to grazing in the fall (McCormick et al., 2006). In addition, the CC winter-hardy species planted first in the fall (P1) contributed to higher CC biomass early and late in the spring, taking advantage of the increased precipitation that usually happens in the spring (Figure 2-2). On the other hand, late CC planting dates in the fall (P3) accumulated the least amount of biomass in the fall (winter-sensitive and winter-hardy species) but contributed to increased biomass of CCs late in the spring (winter-hardy species). Thus, the delay in CC planting in the fall limits the CC biomass accumulation, reducing soil protection against erosion, weed suppression, and reducing potential grazing of CCs. However, planting CCs late in the fall may decrease the risk of excessive soil water use by CCs as it reduces their growing window in the fall (Rosa et al., 2019).

Soil water content was precipitation dependent and decreased along the corn growing season (Figures 2-5 and 2-6) except for V16 and R2 corn development stages in North Platte 2018 and Grant 2018, respectively, that were likely sampled shortly after a precipitation event. This result was expected since the corn demand for water keeps increasing, reaching its peak at corn V-T (tassel stage) and R-1 (silking stage). The reduced precipitation in the fall as compared to the spring (Figure 2-1) emphasizes the importance of soil water recharge during the spring. Besides, soil water content at VE-V1 was lower in the WHLT compared to the other CC termination treatments (Table 2), emphasizing the importance of terminating CCs at least two weeks prior corn planting (Sustainable Agriculture Network, 2007). With the adoption of CCs, there is an increased likelihood that the water stored will be used by CC in detriment of being saved for the subsequent crop (Unger and Vigil, 1998; Nielsen et al., 2015a; Holman et al., 2018).

Likewise, the higher biomass accumulation by WHLT treatment in the spring probably induced the increased water consumption affecting soil volumetric water content measured at the corn VE-V1 development stage (Table 2-2). The soil water consumption by CCs can severely affect the subsequent cash crop, especially in drier years. A recent study conducted in Sidney, NE showed that wheat yield was reduced by 22% when grown following CCs as compared to fallow (Nielsen et al., 2016). Although the correlations between soil water content at VE-V1 and CC biomass were not significant, it is possible that the water consumption by CCs went deeper than 20 cm in the soil profile measured in this study (Alvarez et al., 2017). Moreover, previous research showed that for every 125 kg ha^{-1} of CC biomass grown in semi-arid central Great Plains, soil available water was reduced by 1 millimeter (mm) (Holman et al., 2018).

On the other hand, a wetter fall in 2017 compared to 2016 may have increased water infiltration, influencing the results for Grant 2017-2018 and North Platte 2017-2018. This probably explains the lack of response of CC termination time treatments in soil water at corn early development stages at Grant 2017-2018 and North Platte 2017-2018 (Figure 2-3). In a wet year, CCs can increase water storage through living roots that create channels in the soil, promoting soil aggregation, aeration, and water infiltration (De Baets et al., 2011; Blanco-Canqui et al., 2015; Blanco-Canqui, 2018). Increases in water content at 0-20 cm soil depth by the WHLT in North Platte 2017-2018 could be due to root channels promoted by CCs in the soil that allow more water infiltration, and possible reduction in water evaporation promoted by the increased residue coverage biomass. Thus, the impact of CCs in soil water will depend not only on the amount of CC biomass accumulation but also whether the precipitation amounts will replenish the soil water storage used by the CC.

Cover crops growing in the spring (WHET and WHLT treatments) showed potential to suppress weeds, whereas having CC growing in the fall only (WS treatment) did not contribute to decreasing summer annual weed density and biomass. Most of the summer annual weeds start to emerge in April/May/June (Werle et al., 2014b), so having a CC growing at that period (winter-hardy species) may help reduce growth of early-season weeds. Weeds can take advantage of the soil light exposure and water infiltration to germinate earlier. CCs fill the gaps that could otherwise be occupied by weeds (Liebman and Staver, 2001) and exudate chemicals that can interfere with their emergence (Weston, 1996; Bhowmik and Inderjit, 2003). Also, CCs can potentially help the herbicide program by reducing the size and population of herbicide-resistant weeds. Planting CCs early in the fall (P1 treatment) and terminating late in the spring (WHLT treatment) not only increased the amount of CC biomass, but also the residue coverage (Table 2-3). In semi-arid environments, the previous crop residue associated with no-till works as a soil coverage suppressing weeds and decreasing evaporation (Klein, 2012). Therefore, it is important to have CCs growing, especially during the spring, to help reduce summer annual weeds and increase residue coverage. However, growing CCs in the spring (winter-hardy species) demonstrated to be detrimental to soil water content at corn VE-V1 development stages (Table 2-2) and corn grain yield (Table 2-6).

Cover crops negatively affected N availability to subsequent corn. Late termination of CCs in the spring (WHLT) decreased total N and nitrate levels in the soil. The increased biomass accumulation during the spring probably induced N immobilization by late termination of CCs (Wagger and Mengel, 1993; Kaspar and Bakker, 2015). In addition, our results showed higher soil C:N ratio under the WHLT treatment mostly because of reduced N, since there were no differences in the soil organic carbon values (Tables 2-4 and 2-5). Grass rich CCs have higher C:N ratio that contribute for corn early season N immobilization (Kaye and Quemada, 2017). Therefore, CC use in semi-arid environments will likely require adjustments of N fertilization recommendations when growing corn following CCs. Our study did not show any increments on soil carbon or soil microbial activity (soil respiration) with the adoption of CCs. Attributes like organic matter and soil respiration might need more time to show improvements or deterioration with the use of CCs. Soil organic carbon, which is a component of organic matter, was found to increase in the soil after 5 years of CC adoption in a winter-fallow cropping system (Blanco-Canqui et al., 2013). The CDA (Figure 2-5) showed that late termination of CCs (WHLT treatment) were associated with soil organic carbon and organic matter, likely due to its improved soil residue coverage biomass (Table 2-3). A previous study in the northern Great Plains of the US concluded that soil quality can be improved by intensive cropping systems and reduced tillage management (Liebig et al., 2004). Thus, in the long-term, CCs could enhance its contribution to soil quality aspects in semi-arid environments.

In this study, the corn grain yield and yield components results helped to explain the concerns of producers regarding adopting CCs in semi-arid environments. All of the CC treatments reduced corn grain yield, especially the WHLT (Table 2-5). Cover crop termination at corn planting likely reduces corn grain yield (Unger and Vigil, 1998). In dry environments such as western Nebraska, the recommended termination time for CCs is at least 2 weeks prior to subsequent crop planting (Sustainable Agriculture Network, 2007). This recommendation aims to minimize the risk of crop yield loss due to soil water use and nitrogen immobilization by CCs. Moreover, during the spring, grasses composed most of the CC biomass. Cover crop grass species biomass composition has a higher C:N ratio when compared to legume and brassica species increasing the N immobilization during corn early development stages (Appelgate et al., 2017). This study showed that the first (P1) and second (P2) CC planting time, and the latest CC termination time (WHLT) impacted corn grain yield the most. In addition, corn yield components were negatively affected by the WHLT treatment. Thus, the sooner CC are planted in the fall and the longer they are allowed to grow in the spring, the more detrimental their impacts on corn grain yield are expected to be.

Conclusions

The findings from this study emphasize the importance of CC planting and termination time when adopting such soil conservation practice. Under the wheat-corn-fallow rotation of semi-arid environments, CCs have the potential to reduce summer annual weed density and biomass, and increase the soil residue coverage, particularly when CCs are late terminated (WHLT), due to its high biomass production during spring. In addition, CC winter-sensitive can be a potential use for grazing, with reduced soil water use (grows only in the fall), do not require herbicide termination (frost killed) and can possibly compete with winter-annual weeds like horseweed (*Erigeron canadensis*). Despite CC soil water use at the time of corn planting, this study did not find differences in soil water content at 0-20 cm soil depth. Yet, it is possible that CCs used soil water deeper than 20 cm soil depth. In addition, CCs reduced nitrogen availability in the soil for the subsequent corn crop, especially the WHLT. Therefore, CCs did not contribute to any corn grain yield gain. Instead, CCs reduced corn grain yield regardless of its planting and termination time.

It is important to emphasize that this study evaluated the effects of CCs after one wheat-corn-fallow rotation cycle. Yet, the CDA showed trends that soil respiration, organic matter and soil carbon might improve with the long-term adoption of CCs, fostering healthier soils in semi-arid cropping systems. Therefore, future studies should evaluate the long-term effects of CCs, their impact in soil water at deeper soil layers, and N fertilization on subsequent corn performance, as well as which species (grasses, legumes and/or brassicas) would be best suitable to grow in semi-arid environments. Although CCs can help weed management programs and foresee increments in soil carbon and organic matter, it is imperative to say that CCs reduce rainfed corn grain yield in western Nebraska during initial stages of adoption. In this sense, producers should use their best judgment to adopt CCs according to their purposes. Thus, our findings suggest that producers should use caution when incorporating CCs in their cropping systems of semi-arid regions.

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CHAPTER 3: COVER CROP SPECIES CONTRIBUTIONS TO RAINFED CROPPING SYSTEMS IN SEMI-ARID REGIONS OF WESTERN NEBRASKA

Abstract

Cover crop (CC) species selection can contribute to reducing soil compaction (brassicas), cycling nitrogen in the soil (legumes), and suppressing weeds (grasses). However, the impact of different CC species in semi-arid cropping systems is not well known. To determine the effects of CC species selection under water-limited environments, we evaluated CC biomass produced in fall and spring, soil water content and penetration resistance, weed density and biomass during the corn growing season, soil and corn nitrogen status, and corn grain yield. The study was conducted under a winter wheat-corn-fallow rotation at two locations (North Platte and Grant, NE) during 2016-2017 and 2017-2018 (four site-years) in a randomized complete block design with four replications. Treatments consisted of seven CC species, plus a control (no CCs), planted after winter wheat harvest. Spring oats and brassicas produced higher biomass during fall while cereal rye produced the highest amount of biomass in the spring. However, cereal rye reduced soil volumetric water content in North Platte 2016-2017 and increased soil penetration resistance at 20-30 cm soil depth across site-years. Cover crop growth in the spring suppressed weeds during early corn growing season. Due to its aboveground biomass production, cereal rye decreased weed density and biomass by 85 and 89%, respectively, compared to the control plots. On the other hand, CCs increased N immobilization (except brassicas) during corn growing season and consequently reduced corn grain yield up to 30% compared to the control, however spring oats did not decrease corn yield. Results from this study indicate that spring oats can be an alternative to cereal rye as CC species for semi-arid regions. This research provides valuable information on the potential impact of CCs on rainfed corn production, as well as help producers

and agronomists develop better CC management programs for cropping systems in semi-arid regions of the Great Plains.

Introduction

Cover crops (CCs) can provide numerous benefits to cropping systems such as protecting soil from water and wind erosion (Kaspar et al., 2001; Strock et al., 2004), reducing soil penetration resistance (Blanco-Canqui et al., 2011), reducing nitrogen leaching (Dinnes et al., 2002; Villamil et al., 2006), suppressing weeds (Teasdale, 1996; Teasdale et al., 2007; Mirsky et al., 2011), and, in some cases, increasing subsequent crop yield (Marcillo and Miguez, 2017). Because of the aforementioned benefits and the desire to implement more sustainable production practices in cropping systems, CCs are becoming popular among US row crop producers. Recent surveys conducted in Nebraska indicated that 44% of producers are adopting CCs to some extent as part of their cropping systems (Drewnoski et al., 2015), and that 93% observed enhanced weed suppression and 45% reduced soil erosion in fields with CCs (Oliveira et al., 2019).

Cover crops can be grown as single or as a mixture of species. Species selection depends on the adaptability to the environment and the producer’s main goal(s) with planting the CCs. Cereal rye (*Secale cereale L.*) is one of the most popular CC grown in corn (*Zea mays L.*)-soybean (*Glycine max L. Merr*.) cropping systems in the United States Midwest region (Singer, 2008). Cereal rye has become a popular CC due to its rapid establishment, high biomass production, ability to suppress weeds, winter-hardiness, low cost, and seed availability compared to other CCs (Snapp et al., 2005; Singer, 2008). Other grass species such as oats (*Avena sativa*) and spring-triticale (*Triticosecale*) are also commonly grown as CCs across the United States, and are a potential alternative to cereal rye. However, oats and spring-triticale are not considered winter-hardy species and if fall seeded likely will not produce biomass in the spring (Johnson et al., 1998). Besides aboveground biomass, fibrous and extensive root production are an attribute of grass CCs. Leguminous species such as hairy vetch (*Vicia villosa*) (winter-hardy) and balansa clover (*Trifolium michelianum Savi*) (winter-sensitive) have the ability to fix atmospheric nitrogen (N_2) in the soil, potentially supplying nitrogen (N) to the subsequent crops (Blanco-Canqui et al., 2015). Winter-sensitive brassica species like Siberian kale (*Brassica napus*) and purple top turnips (*Brassica rapa*) can reduce soil penetration resistance due to taproot growth (Chen and Weil, 2011; Chen et al., 2014). The taproot system of brassicas can help in loosening the surrounding soil by creating canals with vertical and horizontal growth throughout the soil. These canals may allow for enhanced water infiltration, thus reducing soil erosion.

In semi-arid climates (250-700 mm annual precipitation) of the Great Plains (Gallart et al., 2002), no-till winter wheat (*Triticum aestivum L.*)-corn-fallow is the main crop rotation strategy adopted across rainfed areas (two grain crops in a three year period). This rotation has two fallow periods: one between winter wheat harvest and corn planting, and another between corn harvest and winter wheat planting. Soil water conservation is the main reason for this rotation (Klein, 2012). As such, CCs can be planted after winter wheat harvest occupying the fallow period before corn planting, leaving the other fallow period (between corn harvest and winter-wheat planting) to grow a cool-season cash crop such as field pea (Stepanovic et al., 2018). A major concern is the impact CC species can have on soil water content, which may differ upon CC species selection. Winter-sensitive CCs (e.g., oats, spring triticale, clover, kale, and turnips) growth is limited to the fall, thus, reducing the risk of excessive soil water use by CCs (Reese et al., 2014). On the other hand, winter-hardy species (cereal rye and hairy vetch) have a wider growing window including biomass accumulation in the spring, increasing soil water use (Holman et al., 2018), and likely, the risk of yield reduction of the subsequent crops. However, in a winter wheat-corn-fallow rotation, the effect of different CC species (winter-sensitive vs winter-hardy) on soil water use and subsequent corn grain yield are now well understood.

In the winter wheat-corn-fallow rotation, CCs can grow from August (winter wheat harvest) to May (corn planting), building soil cover on top of the winter wheat residue. During this growth period, CCs can provide direct weed suppression equivalent to chemical or mechanical control (Osipitan et al., 2018). Cover crops can also suppress summer annual weeds indirectly through the residue left after termination (Teasdale et al., 1991; Teasdale and Mohler, 2000). The residue of CCs can provide additional soil coverage reducing light exposure, thus, limiting weed establishment and evapotranspiration (Klein, 2012). Responses of CCs to weed suppression are variable in the literature. Previous research reported no weed suppression by CCs in sweet corn and pumpkin cropping systems (Galloway and Weston, 1996). On the other hand, cereal rye suppressed 90% of winter annual weeds in western Nebraska (Werle et al., 2018). Likewise, rye-vetch CC mixes improved winter annual weed suppression in 98% compared to a control (Hayden et al., 2012). However, the impact of CCs on summer annual weed suppression during the corn growing season in semi-arid environments remains unknown.

Besides soil water use, the inclusion of CCs after winter wheat harvest can induce nitrogen immobilization in the soil, which can lead to yield and economic penalties to the subsequent corn crop. Excessive growth of CCs, especially grasses, may increase soil water consumption and extend nitrogen immobilization during the cash crop growing season. A study conducted in Colorado and Nebraska found that legume CCs grown in the spring decreased winter wheat yield by up to 77% (Nielsen and Vigil, 2005) despite possible nitrogen credits provided by legume atmospheric N fixation. Likewise, an irrigated study conducted in eastern Kansas showed that in its third year of implementation, cereal rye reduced corn yields by 9.3% (Kessavalou and Walters, 1997). Conversely, Tollenaar et al. (1993) found that nitrogen fertilization in cereal rye CC minimized the adverse effects on subsequent corn development in Ontario, Canada. However, in a high water stress environment of South Dakota, different CC species (grasses, legumes, and brassicas) grown only in the fall did not reduce subsequent corn grain yield (Reese et al., 2014). Therefore, the decision to establish a winter-sensitive or winter-hardy CC species in the fallow period between winter wheat harvest and corn planting may influence the subsequent crop soil water balance and nitrogen availability, and consequently, affect the subsequent rainfed corn grain yield. Thus, the objectives of this study were to evaluate the impact of CC species selection on soil water content and penetration resistance, weed demographics, soil and plant nitrogen status, and subsequent corn development and grain yield. The study hypotheses were that (1) CC species differ in soil water use; (2) CCs decrease soil penetration resistance; (3) CCs can suppress weeds; (4) CC species differ in their impact on soil and plant nitrogen status; and, (5) CC species differ in their effects on corn grain yield.

Materials and Methods

Field Sites and Experimental Design

Field studies were conducted at two sites in western Nebraska during 2016-2017 and 2017-2018 cover crop-corn growing seasons (total of four site-years). The studies were located at the University of Nebraska-Lincoln (UNL) Henry J. Stumpf International Wheat Center near Grant, NE (40°51'15.0"N; 101°42'13.9"W) on a Kuma silt loam (fine-silty, mixed, superactive, mesic Pachic Argiustolls), and at the UNL West Central Research and Extension Center near North Platte, NE (41°03'13.6"N; 100°44'52.8"W) on a Holdrege silt loam soil (fine-silty, mixed, superactive, mesic Typic Argiustolls). Hereafter, the four site-years are referred to as: Grant 2016-2017, Grant 2017-2018, North Platte 2016-2017, and North Platte 2017-2018. The monthly precipitation and average temperature for each site-year along with the 30-year historic averages are shown in Figure 3-1. The fields used in this study did not have a history of cover crop (CC) use and had been on a winter wheat-corn-fallow rotation.

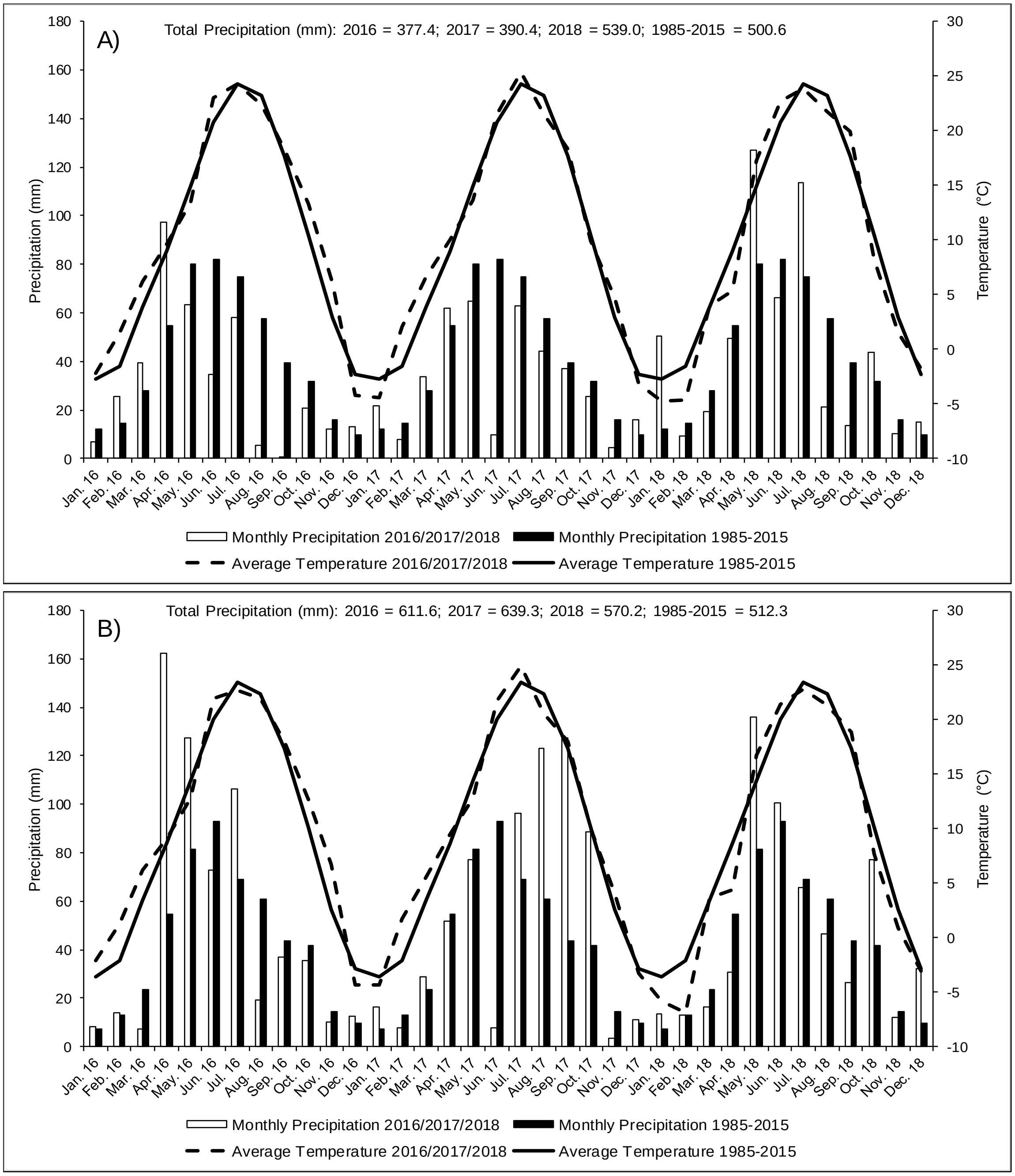

Figure 3-1. Average temperature and monthly precipitation for Grant (A) and North Platte, NE (B) during the years of 2016, 2017, 2018, and the period of 1985-2015. Source: High Plains Regional Climate Center, https://hprcc.unl.edu.

The experimental design was a randomized complete block with four replications. The treatments included seven cover crop species and one control (no cover crop - NCC). The CC species treatments representing a diversity of plant families (Poaceae, Fabaceae, and Brassicaceae) were selected based on the popularity and interest among producers in the region. The seven CC species and seeding rates used in this study were as follows: spring oats (*Avena sativa*) at 67 kg ha^{-1}; spring triticale (*Triticosecale*) at 67 kg ha^{-1}; cereal rye (*Secale cereale*) at 67 kg ha^{-1}; balansa clover (*Trifolium michelianum Savi*) at 22 kg ha^{-1}; hairy vetch (*Vicia villosa*) at 45 kg ha^{-1}; purple top turnip (*Brassica rapa*) at 22 kg ha^{-1}; and Siberian kale (*Brassica napus*) at 22 kg ha^{-1}. Cover crop seeding rates were defined based on the Sustainable Agriculture Research & Education (Sustainable Agriculture Network, 2007) and Green Cover Seed (Green Cover Seed, Bladen, NE) recommendations, and are commonly adopted in Nebraska. Spring oats, spring triticale, balansa clover, purple top turnip, and Siberian kale are winter-sensitive species. Cereal rye and hairy vetch are winter-hardy species. Cover crops were drilled at 19 cm row space and 3 cm seed depth. Individual plot size was 4.6 m wide and 15.2 m long. Cover crops were planted on August 7-14 days after winter wheat harvest. Cover crops were terminated at corn planting in 2017 and two weeks prior to corn planting in 2018 with glyphosate Roundup Powermax® (Bayer Crop Science, Saint Louis, MO) sprayed at 2.34 L ha^{-1} mixed with 453 g ha^{-1} of ammonium sulfate (KALO, Inc, Overland Park, KS) as a water conditioner to improve glyphosate efficacy. Corn was planted at 76 cm row space and seed depth of 3.8 cm. Information regarding CC planting and termination dates, corn planting and harvest dates, hybrid selection, and seeding and fertilization rates in each site-year are described in Table 3-1.

Table 3-1. Cover crop (CC) planting and termination time, corn planting and harvest time, corn hybrid selection and seeding rate, and fertilizer information for all site-years. Cover crops were planted after winter wheat harvest and terminated both in the fall (freezing temperatures) and in the spring (herbicide). Corn was planted 0-2 weeks after CC termination. Corn hybrids, seeding and fertilizer rate followed standard management practices at each site-year. Pre and post-emergence herbicides were applied to control weeds when corn reached the V6-V7 development stage (Abendroth et al., 2011).

Site-years	CC planting date	First hard freeze date*	CC termination date	Corn planting date	Weed control date	Corn hybrid	Corn seeding rate (seeds ha^{-1})	Fertilizer (time, source, rate)	Corn harvest date
Grant 2016-2017	9/8/2016	12/09/2016	5/24/2017	5/24/2017	5/24/2017	DKC52-61 (102 days maturity)	38300	Corn pre-planting, N-K-S, 118-59-5.6 kg ha^{-1}; at corn planting, ammonium polyphosphate (10-34-0), 65 kg ha^{-1}.	10/13/2017
Grant 2017-2018	8/22/2017	11/02/2017	5/6/2018	5/24/2018	6/23/2018	DGVT2PRI B (101 days maturity)	37065	Corn planting, ammonium polyphosphate (10-34-0), 65 kg ha^{-1}; at corn V3 development stage, UAN (32-0-0), 310 kg ha^{-1}.	10/23/2018
North Platte 2016-2017	9/7/2016	12/09/2016	5/2/2017	5/5/2017	6/20/2017	Hoegemeyer 7643RR (106 days maturity)	41018	Corn pre-planting (4/6/2017), UAN (32-0-0), 89 kg ha^{-1}; at corn planting, ammonium polyphosphate (10-34-0), 110 kg $ha^{-1.}$	10/27/2017
North Platte 2017-2018	8/1/2017	11/01/2017	5/4/2018	5/23/2018	6/27/2018	Hoegemeyer 7643RR (106 days maturity)	41018	Corn pre-planting (4/19/2018), UAN (32-0-0), 112 kg ha^{-1}; at corn planting, ammonium polyphosphate (10-34-0), 110 kg ha^{-1}.	10/17/2018

Abbreviations: UAN, urea ammonium nitrate; N, nitrogen; K, potassium; S, sulfur. *Temperature below 0°C for more than 2 consecutive days.

Data Collection

Cover Crop Aboveground Biomass

Cover crop aboveground biomass samples were collected in the fall after the first hard freeze event (all species) and in the spring at the time of CC termination (winter-hardy species only) in each site-year (Table 1). Balansa clover failed to establish and became an opportunity to study volunteer wheat as a CC. Thus, due to its poor establishment and predominance of volunteer wheat in all site-years, balansa clover plots were considered as a volunteer wheat treatment. Volunteer wheat was not collected in any other CC treatment. Spring triticale was also sampled in the spring because of unexpected winter survival. No CC plots were kept volunteer wheat and weed free during the CC growing season. Two 0.093 m^{-2} aboveground biomass samples were randomly collected from each plot. Biomass samples were dried in a forced air oven at 60°C for a minimum of 6 days (when constant dry biomass was achieved) and weighed.

Soil Water Content

Soil volumetric water content readings (m^3 m^{-3}) were performed using a handheld time domain reflectometry (TDR) FieldScout TDR 300 Meter (Spectrum Technologies, Inc., Aurora, IL) with 0 to 20 cm waveguides installed vertically to average the water content over the entire layer. Six readings were recorded from 0 to 20 cm depth on each plot bi-weekly starting at corn planting and ending when corn reached the R2 (blister stage) development stage (Abendroth et al., 2011). The corn development stage upon which the readings were performed varied according to the site-year. Calibration tests were conducted to evaluate the accuracy of the FieldScout TDR 300 Meter. Briefly, four undisturbed soil samples, using a round probe (10 cm diameter), were taken from 0 to 20 cm soil depth within the area surrounding the sensor reading (within a 2 m radius) at each site-year four times during the year: late spring, early, mid and late summer. The soil samples were dried in a forced-air oven at 60 °C for 8 days until a constant weight was reached. The gravimetric soil water content (Θ_g, grams of water per grams of soil) was quantified as the equation [3] below (Hillel, 1998):

$$\Theta_g = (\text{soil wet weight} - \text{soil dry weight}) / \text{soil dry weight} \quad [3]$$

Where the numerator represents the mass of water (in grams) in the soil. Soil volumetric water content (Θ_v, $cm^3\ cm^{-3}$) was determined as follows (Hillel, 1998):

$$\Theta_v = (\Theta_g \times \rho_{soil}) / \rho_{water} \quad [4]$$

Where ρ_{soil} is the soil bulk density (grams of soil per cubic centimeters, the ratio of soil dry mass to sample volume), and ρ_{water} is the density of water (1 g water cm^{-3}). The sensor readings were regressed on the volumetric water content measured from soil samples. The linear equations obtained from the regressions were used to adjust the sensor readings. Similar calibration methodology has been used in other studies (Song et al., 1998;Tarara and Ham, 1997; Werle et al., 2014).

Soil Penetration Resistance

Soil penetration resistance readings (MPa) were performed using a handheld digital cone-tipped (12.8 mm diameter) soil compaction FieldScout SC 900 Meter (Spectrum Technologies, Inc., Aurora, IL). Six soil penetration readings were recorded from 0 to 30 cm soil depth in each plot at corn planting time. The penetrometer was pushed downward into the soil profile at a constant speed of 1 cm s^{-1}, and the depth of each measurement was in an interval of every 2.54 cm.

Weed Demographics

Weeds were identified, enumerated and collected for total aboveground biomass determination when corn reached V6 (six leaves with collar visible) development stage to evaluate the effects of CCs on summer annual weed suppression on early season corn development. After sampling, weeds were herbicide controlled (Table 1) to avoid any possible effects on corn productivity. Aboveground weed biomass samples were randomly collected from each plot using two quadrats of 0.093 m^{-2}. Biomass of the combined weed species collected from each plot was determined after drying the samples in a forced air oven at 60°C and weighed when constant dry biomass was achieved. Weed assessment was not performed in Grant 2017 due to pre-emergence herbicide application at corn planting. The other site-years did not receive a pre-emergence herbicide application.

Residue Coverage

Total residue coverage biomass on the soil surface was collected when corn reached the V6 development stage to account for possible effects of previous crops (including CCs) on weed suppression. All plant residue remaining on the soil surface, which mainly included winter wheat straw and CC residue, was sampled. Two 0.093 m^{-2} aboveground biomass samples were randomly collected from each plot. Residue samples of each plot were dried in a forced air oven at 60°C and weighed when constant dry biomass was achieved.

Soil and Plant Nitrogen Status

A composite soil sample of eight cores using a straight tube probe (2.5 cm diameter) was collected from 0 to 10 and 10 to 20 cm soil depth at each plot when corn reached the V6 development stage. Soil sampling occurred at corn V6 development stage to allow for CC decomposition, and potentially cycle nitrogen (especially brassica and legume species). Soil samples were sent to Ward Laboratories, Inc. (Kearney, NE) for analyses of organic matter, and inorganic (nitrate and ammonia), organic and total nitrogen (sum of organic and inorganic nitrogen). Soil organic matter was determined by the loss on ignition method (Hoskins, 2002). Inorganic nitrogen (N) is the combination of nitrate (NO_3-N) and ammonium (NH_4-N). Nitrate and ammonium were analyzed by the H3A extract on a Lachat 8000 flow injection analyzer (Hach Company, Loveland, Colorado). Total nitrogen was analyzed by the water extract using a

Teledyne-Tekmar Torch. The organic N was calculated by subtracting the total N from the inorganic N.

In addition, other researchers suggests that crop nitrogen status, leaf chlorophyll content, and leaf greenness can be quickly measured using a chlorophyll meter (Schepers et al., 1992; Varvel et al., 1997; Scharf et al., 2011). Single-Photon Avalanche Diode (SPAD) readings were taken at corn R2 development stage in 30 consecutive corn plants in the two central rows from each experimental plot using a chlorophyll meter (model SPAD 502, Konica Minolta, Osaka, Japan). The chlorophyll reading were taken to account for corn nitrogen status during early reproductive stages (R2 development stage) by sampling the corn ear leaf, and were only measured in Grant 2018 and North Platte 2018.

Corn Grain Yield and Yield Components

The corn plant population was measured by counting the number of plants in three rows of corn in each plot at the whole plot length when corn reached the R2 development stage. The two central corn rows of each plot were hand-harvested (2.65 m long per corn row) covering an area of 4.065 m^{-2} (Lauer, 2002). Six corn ears were randomly selected from the hand-harvested area to estimate the yield components. Corn grain yield components were estimated by counting corn plant population, number of kernel rows per ear, number of kernels per row per ear, number of kernels per ear, and the total weight of one hundred kernels. After accounting for the yield components, all corn ears were threshed using a stationary corn ear sheller (ALMACO, Nevada, IA). After threshing, kernel weight was recorded and grain yield was adjusted to 15.5% moisture content.

Statistical Analysis

All response variables in this study (CC biomass in the fall and spring, soil penetration resistance, soil water content at VE-V1 corn development stage, weed density and biomass, residue coverage, organic matter, total nitrogen, organic nitrogen, ammonium, nitrate, inorganic nitrogen, chlorophyll readings, corn grain yield and yield components) were subjected to analysis of variance (ANOVA) performed using the PROC GLIMMIX procedure in SAS 9.2 (SAS Institute, Cary, NC). Cover crop species treatments were considered as fixed factors whereas replication blocks nested within site-years were treated as a random factor in the model. In addition, the soil water content data measured through the corn growing season was analyzed by site-year (fixed effect) as a repeated measure so that corn development stage was considered as time in the model. Therefore, soil water content was the only variable in this study where site-year was treated as a random effect (evaluated at corn VE-V1 development stage) and as a fixed effect (evaluated throughout corn development as a repeated measure). The variables weed density and biomass, total nitrogen, ammonium, nitrate, inorganic nitrogen, corn plant population, number of kernels per row, kernels per ear, and 100-kernel weight were log transformed prior the ANOVA to satisfy the Gaussian assumptions of normality data distribution. For all variables in the study the separation of means for interactions and main effects was set at a significant level of $\alpha = 0.05$ with Tukey's adjustment for multiple comparisons and completed using the LINES option in PROC GLIMMIX in SAS 9.2. Pearson's linear correlation tests were performed for soil and yield component variables at a 5 % significance level using PROC CORR in SAS 9.2.

The relationship between weed density and biomass with CC biomass in the fall and spring, and residue biomass was established by fitting a quadratic regression model. The quadratic model was chosen because of its best fit in comparison to the linear model, where the adjusted coefficient of determination (R^2) served as an indication of goodness of fit. The quadratic regression analysis was performed using the *nlme* package in R (R Development Core Team, 2007).

Results

Weather Data

Precipitation and air temperature from each site-year was compared to the historical average data for Grant and North Platte during the period of 1985 through 2015 (Figure 3-1). Although precipitation distribution throughout the year followed a similar pattern across the sites, it is important to note that Grant is historically a drier location than North Platte, and similar trend was observed during this study (Figure 3-1). Besides the warmer (2017) and cooler spring (2018) at both sites compared to the 30-year average temperature data, temperatures followed a similar trend in this study when compared to the historical 30-year average data. Precipitation data at each site-year varied and will be further discussed to support the soil water content results.

Grant 2016-2017

Fall 2016 (September, October and November) received 49.8 mm less precipitation than the historical average for Grant (Figure 3-1). Spring 2017 (March, April, and May) had similar precipitation amounts to the historical average for Grant. However, the cumulative precipitation in summer 2017 (June, July, and August) in Grant was 109.5 mm below the historical average (Figure 3-1).

Grant 2017-2018

Fall 2017 was drier compared to the historical data but still received twice as much precipitation compared to fall 2016 in Grant. Precipitation in September was normal, but October and November were 19 and 71% below the 30-year average precipitation for the same period. In the spring 2018, Grant was below the historical average precipitation until May, when CCs were terminated. May 2018 precipitation was above the historical data, with an increased precipitation of 126.7 mm (+ 57%) compared to the historical data for Grant. In addition, spring 2018 precipitation was 22% above spring 2017 in Grant. During summer 2018, Grant received lower precipitation compared to the historical average but registered an increased 50% on precipitation in July, when corn reached the reproductive development stages. Moreover, the total precipitation for the summer 2018 was 72% greater than summer 2017 in Grant.

North Platte 2016-2017

Fall 2016 received slightly less precipitation than the historical average for North Platte (Figure 3-1). The cumulative precipitation in fall 2016 was 19 mm lower than the historical average, but 2.5 and 1.2 times greater than Grant 2017 and Grant 2018 precipitation amounts. On the other hand, precipitation patterns in the spring 2017 were similar to those observed in the historical data for North Platte and Grant 2017. Likewise, in North Platte, the precipitation patterns during summer 2017 were similar to Grant 2017 (dry) until August, when corn development was in the reproductive stages. However, in August 2017, North Platte registered approximately twice the amount of precipitation expected for the month based on the historical average data.

North Platte 2017-2018

Fall 2017 received above average precipitation in North Platte with the total precipitation amount greater than 2.2 times compared to the 30-year average and fall 2016 (Figure 3-1). When compared to Grant 2017 and Grant 2018, the fall 2017 in North Platte registered approximately 6 and 3 times greater precipitation amounts, respectively. Just like in Grant 2018, in North Platte spring 2018 the precipitation was lower than the 30-year average until May when the total precipitation reached 136.1 mm (67% greater than the historical average). Throughout the summer 2018 in North Platte, precipitation amounts were below the historical average, except June, where the precipitation was about 10% higher than the historical average.

Cover Crop Fall Biomass

Cover crop biomass in the fall differed according to species selection ($p < 0.001$). Overall, spring oats, purple top turnips and Siberian kale produced the greatest amount of fall aboveground biomass, whereas volunteer wheat and hairy vetch consistently produced the lowest amount of biomass amongst CCs evaluated (Table 3-2). Among grasses, spring oats produced 50 and 62% more biomass in the fall than cereal rye and spring triticale, respectively. In addition, the brassicas (purple top turnips and Siberian kale) showed significant growth in the fall compared to the other CC species, with biomass equivalent to spring oats.

Table 3-2. Cover crop (CC) biomass in the fall and spring, soil water content at VE-V1 corn development stage, and weed density and biomass collected at corn V6 development stage in western Nebraska according to CC species treatment across site-years[†]. Weed density and biomass were collected at 3 site-years (except Grant 2016-2017). Site-years are included as random effects in the ANOVA model. Numbers followed by different letters within columns represent statistically significant differences with Tukey adjustment at the $p \leq 0.05$.

	CC Fall Biomass (kg ha^{-1})			CC Spring Biomass (kg ha^{-1})			Weed Density (weeds m^{-2})			Weed Biomass (kg ha^{-1})			Soil Water Content VE-V1 (m^3 m^{-3})	
Species	Mean	SE+-		Mean	SE+-		Mean	SE+-		Mean	SE+-		Mean	SE+-
NCC	-	-		-	-		123	35	A	229.6	85.7	A	0.131	0.007
SO	2674	333	A	-	-		58	13	AB	33.3	9.1	ABC	0.133	0.007
ST	1649	177	B	1837	143	B	48	12	AB	65.3	19.3	ABC	0.131	0.007
CR	1784	183	B	4223	333	A	19	5	B	24.4	11.7	C	0.128	0.009
VW	105	27	C	2038	192	B	35	7	AB	70.8	30.0	BC	0.129	0.007
HV	675	103	C	806	181	C	61	16	AB	91.8	25.4	ABC	0.127	0.009
PTT	2157	345	AB	-	-		75	16	AB	91.9	29.8	ABC	0.128	0.009
KS	2151	340	AB	-	-		81	14	A	206.5	57.8	AB	0.128	0.008
							p-values							
Species	**<.0001**			**<.0001**			**0.0064**			**0.0002**			0.8421	

Abbreviations: NCC, no cover crop; SO, spring oats; ST, spring triticale; CR, cereal rye; VW, volunteer wheat; HV, hairy vetch; PTT, purple top turnip; KS, Siberian kale; SE, standard error of the mean. [†]Grant 2016-2017, Grant 2017-2018, North Platte 2016-2017 and North Platte 2017-2018.

Cover Crop Spring Biomass

Only spring triticale, cereal rye, volunteer wheat and hairy vetch overwintered and produced biomass in the spring. During the spring, cereal rye produced the greatest amount of biomass compared to spring triticale (+129%), volunteer wheat (+107%) and hairy vetch (+424%) (Table 3-2). Spring triticale winter survival was a surprise in this study. If a producer plants spring triticale as a CC winter-sensitive and it survives the winter, proper spring termination practices similarly adopted to cereal rye, volunteer wheat and hairy vetch will need to be taken.

Weed Demographics

Weed species distribution changed according to sites. The most common weed species found by site-year were kochia (*Bassia scoparia*) at Grant 2017-2018; prostrate pigweed (*Amaranthus blitoides*) at North Platte 2016-2017; and carpetweed (*Mollugo verticillata*) at North Platte 2017-2018 (data not shown). Both weed density (p = 0.0064) and biomass (p = 0.0002) were impacted by CC species selection (Table 3-2). The no CC treatment showed the highest weed density and biomass among all treatments. Cereal rye reduced weed density (-85%) and biomass (-89%) compared to no CC treatment. Considering both weed density and biomass data, cereal rye was the most efficient CC species in weed suppression. The other CC species influenced neither the weed density nor biomass in comparison to the no CC treatment.

Effects of Cover Crops and Residue on Weed Suppression

One of the objectives of this study was to test the hypothesis that increasing CC biomass and residue coverage would result in enhanced weed suppression. The relationship between weed density and biomass with CC biomass in the fall and spring, and residue biomass are shown in Figure 2. Increased CC biomass in the spring was associated with reduction of weed density (R^2 =

0.16, $p = 0.0025$) and biomass ($R^2 = 0.16$, $p = 0.0029$). However, neither CC biomass in the fall nor residue coverage were predictive of summer weed density or biomass.

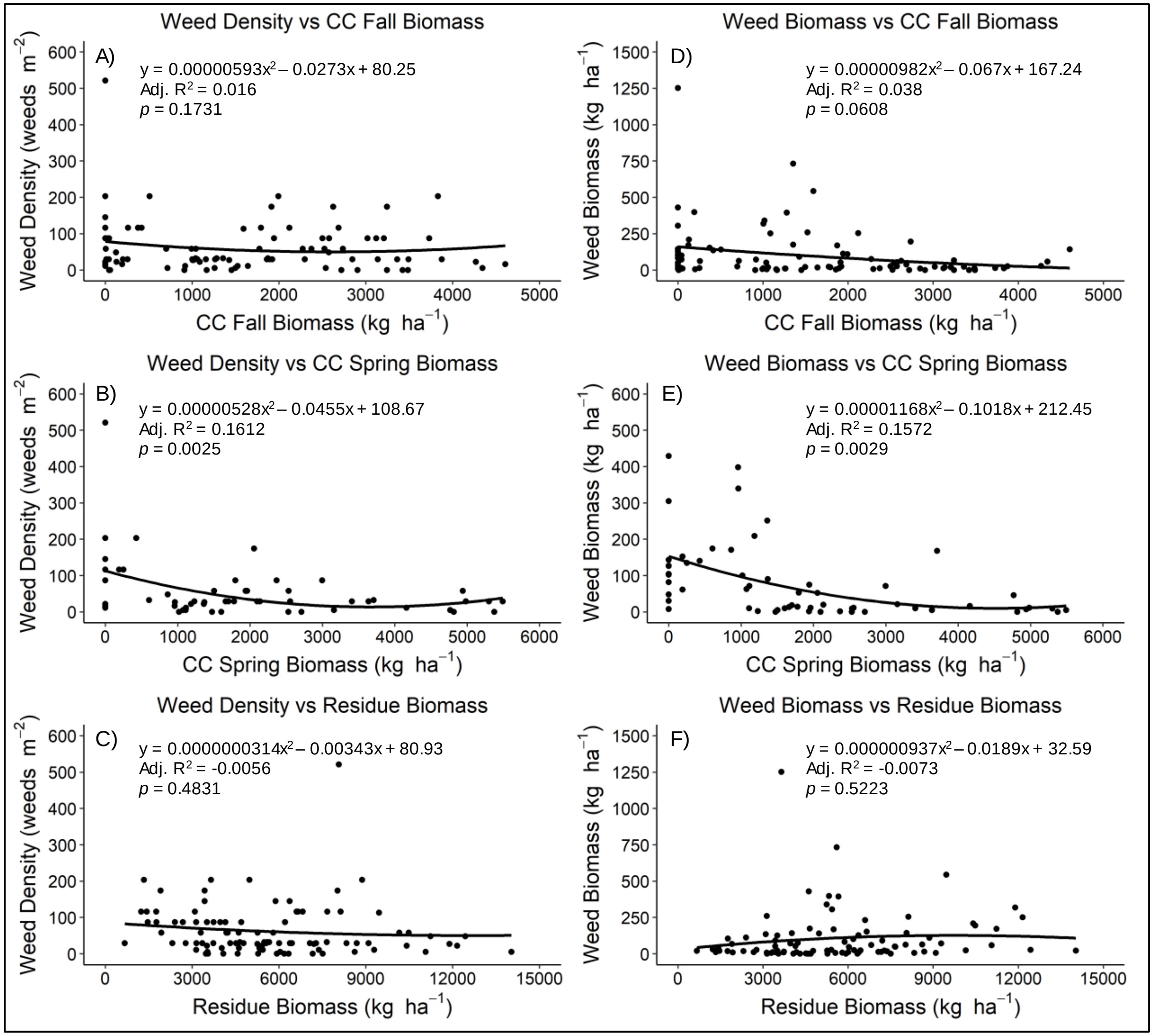

Figure 3-2. Suppression of summer annual weeds by cover crops. Relationship between weed density and cover crop fall (A) and spring biomass (B), and residue biomass (C); and relationship between weed biomass and cover crop fall (D) and spring biomass (E), and residue biomass (F) across site-years in western Nebraska. The quadratic regression model was fitted across data from all treatments and site-years, except Grant 2016-2017. Weed density and biomass, and residue biomass were collected when corn reached the V6 development stage. Residue biomass was all plant residue remaining on the soil surface.

Soil Water Content

Soil volumetric water content (m^3 m^{-3}) measured from 0 to 20 cm soil depth at corn VE-V1 development stage analyzed across site-years did not change among CC species (*p* = 0.8421, Table 3-2). Within site-years, the results indicate that soil water content decreased as corn developed from VE to R2 development stage (Figure 3-3). Cereal rye decreased Θ_v at corn emergence (VE development stage) and V6 development stage in North Platte 2016-2017 only. In all other site-years, there were no differences among CC species regarding Θ_v at 0 to 20 cm soil depth.

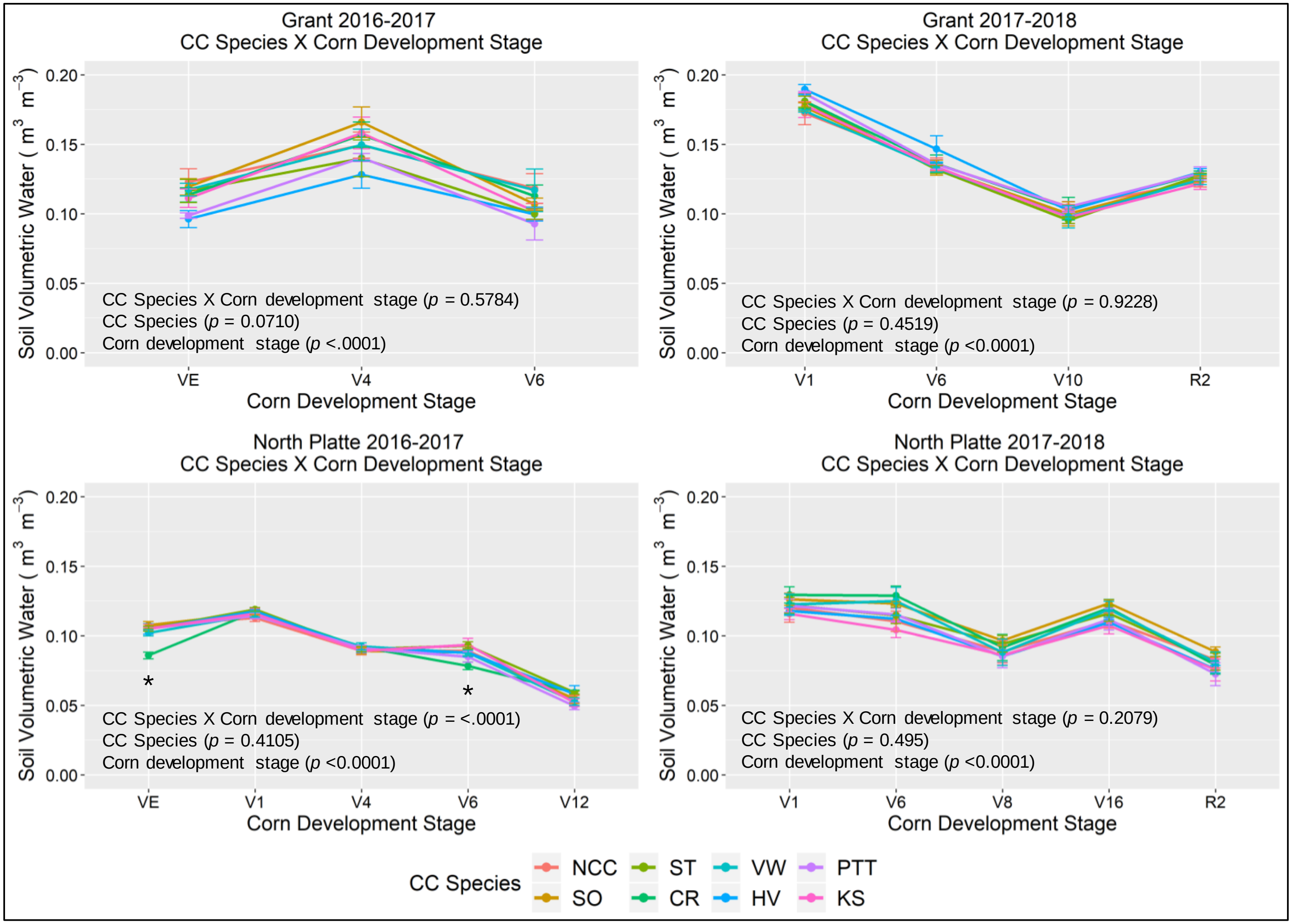

Figure 3-3. Soil volumetric water content at 0 to 20 cm soil depth at each site-year in western Nebraska according to the interaction of cover crop (CC) species and corn development stage. Abbreviations: NCC, no cover crop; SO, spring oats; ST, spring triticale; CR, cereal rye; VW, volunteer wheat; HV, hairy vetch; PTT, purple top turnip; KS, Siberian kale; VE, V1, V4, V6, V8, V10, V16, R2 corn development stage. * represent statistically significant differences at the p ≤ 0.05.

Soil Penetration Resistance

Measured penetration resistance values (Mpa) were plotted against the adjusted measured volumetric water content (Θ_v, m^3 m^{-3}) from 0 to 20 cm soil depth at corn planting time to determine the correlation of penetration resistance with the Θ_v values using a methodology similar to Blanco-Canqui et al. (2006). Exponential equations provided the best fit (R^2 served as an indication of goodness of fit) between the measured penetration resistance values and the adjusted measured Θ_v:

Measured penetration resistance = 3.2361exp(-9.54Θ_v), (R^2= 0.65, p < 0.0001) [Equation 1]

Equation 1 shows that variations in Θ_v explained 65% of the variation in the soil penetration resistance measured indicating high dependency on Θ_v (Figure 3-4A). Thus, the penetration resistance values were adjusted to a common value of Θ_v to reduce the confounding effect of the measured Θ_v on the penetration resistance values.

Adjusted penetration resistance = 2.8342exp(0.0003Θ_v), (R^2= -0.008, p = 0.9949) [Equation 2]

After corrections, the plot in equation 2 showed no relationship between penetration resistance and Θ_v (R^2= -0.008, p < 0.9949) from 0 to 20 cm soil depth (Figure 3-4B). Those equations were used for all site-year's penetration resistance readings to ensure a uniform correction.

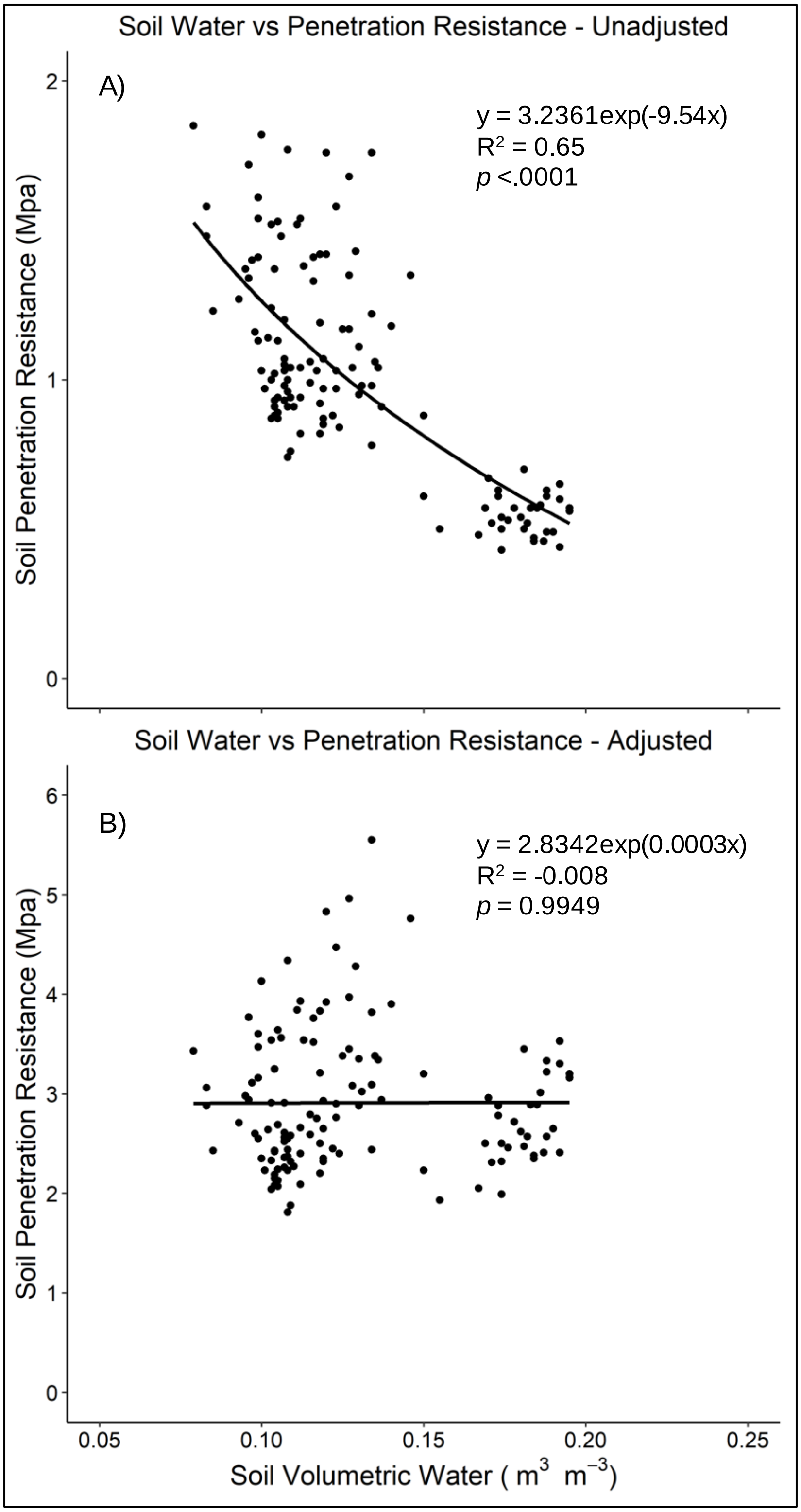

Figure 3-4. Relationship of unadjusted (A) and adjusted (B) data of soil penetration resistance with adjusted soil volumetric water content measured at corn planting time for all data points across site-years in western Nebraska. Unadjusted data is the raw soil penetration resistance whereas the adjusted data is the soil penetration resistance data calibrated through soil moisture content.

The soil penetration resistance results showed an interaction between CC species treatment and depth (Figure 3-5). Thus, the results are presented in megapascal (MPa) at each depth according to the CC species. Soil penetration resistance in the no CC treatment ranged from 0.7 to 3.9 MPa; for spring oats from 0.8 to 3.6 MPa; for spring triticale from 0.7 to 4.1 MPa; for cereal rye from 0.8 to 5.2 MPa; for volunteer wheat from 0.7 to 4.2 MPa; for hairy vetch from 0.7 to 4.1 MPa; for purple top turnip from 0.8 to 3.8 MPa; and, for Siberian kale from 0.7 to 3.8 MPa. (Figure 3-5). Cereal rye and volunteer wheat increased the soil penetration resistance from 20 to 28 cm soil depth among the CC species. At 30 cm soil depth, soil penetration resistance under cereal rye was 0.9 MPa higher than volunteer wheat, the second higher value. Likewise, volunteer wheat increased soil penetration resistance from 28 to 30 cm soil depth compared to no CC. Hairy vetch and spring triticale also increased soil penetration resistance in 27 and 26%, respectively, over no CC at 30 cm soil depth.

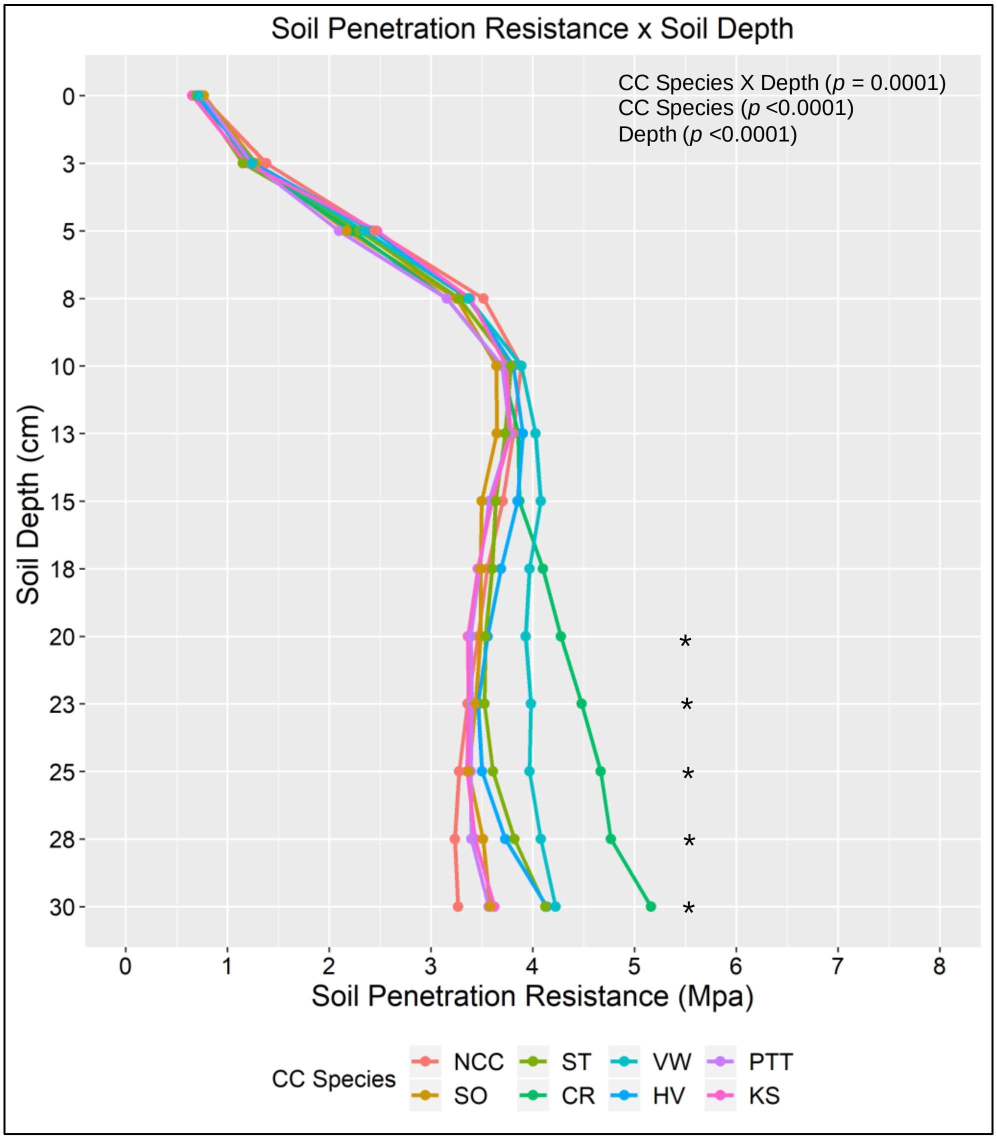

Figure 3-5. Adjusted soil penetration resistance at 0 to 30 cm depth at corn planting time according to the interaction of soil depth and cover crop (CC) species across site-years† in western Nebraska. Abbreviations: NCC, no cover crop; SO, spring oats; ST, spring triticale; CR, cereal rye; VW, volunteer wheat; HV, hairy vetch; PTT, purple top turnip; KS, Siberian kale. Site-years are included as random effects in the ANOVA model. *represent statistically significant differences at the $p \leq 0.05$. †Grant 2016-2017, Grant 2017-2018, North Platte 2016-2017, and North Platte 2017-2018.

Soil and Plant Nitrogen Status

Soil samples were collected from 0 to 10 and 10 to 20 cm soil depth to access the soil nitrogen (N) status through soil organic matter, total N, organic N, ammonium, nitrate, and inorganic N. The mean and standard errors for soil depth and CC species effects on soil N and chlorophyll readings are in Table 3-3. The mean values of all soil variables evaluated were lower from 0 to 10 cm compared to 10 to 20 cm soil depth. Moreover, all soil variables except organic matter (p = 0.7495) and ammonium (p = 0.4775) were impacted by CC species selection.

Table 3-3. Soil organic matter and nitrogen forms (total, organic and inorganic nitrogen, nitrate and ammonium) at 0 to 10 and 10 to 20 cm soil depth collected at corn V6 development stage, and corn leaf chlorophyll readings measured at corn R2 development stage according to cover crops species across site-years[¥] in Western Nebraska. Site-years are included as random effects in the ANOVA model. Numbers followed by different letters within columns represent statistically significant differences with Tukey adjustment at the $p \leq 0.05$.

	Organic Matter ($g\ kg^{-1}$)			Total Nitrogen ($mg\ kg^{-1}$ N)			Organic Nitrogen ($mg\ kg^{-1}$ N)			Ammonium ($mg\ kg^{-1}$ NH_4-N)			Nitrate ($mg\ kg^{-1}$ NO_3-N)			Inorganic Nitrogen ($mg\ kg^{-1}$ N)			chlorophyll readings		
Depth (D)	Mean	SE+-		Mean	SE+-		Mean	SE+-		Mean	SE+-		Mean	SE+-		Mean	SE+-		-	-	-
0 to 10 cm	2.4	0.1	A	31.3	1.6	A	13.2	0.2	A	4.6	0.4	A	13.9	1.4	A	18.5	1.7	A	-	-	-
10 to 20 cm	2.2	0.0	B	20.6	0.7	B	11.4	0.2	B	2.1	0.1	B	7.1	0.5	B	9.2	0.6	B	-	-	-
Species (S)																					
NCC	2.3	0.1	NS	30.7	3.0	A	13.4	0.6	A	4.0	0.8	NS	14.4	2.4	A	17.7	3.0	A	56.3	0.4	AB
SO	2.3	0.1		23.3	1.7	B	12.4	0.5	AB	2.6	0.3		8.2	1.3	B	10.8	1.5	B	54.3	0.5	B
ST	2.3	0.1		26.6	3.3	B	12.2	0.5	AB	3.5	0.7		11.3	2.9	B	14.8	3.5	B	55.5	0.8	AB
CR	2.4	0.1		24.4	2.7	B	12.1	0.4	AB	3.2	0.6		9.4	2.3	B	12.6	2.8	B	53.8	0.8	B
VW	2.3	0.1		24.4	2.2	B	12.1	0.5	AB	3.2	0.5		8.9	1.8	B	12.4	2.1	B	54.1	0.7	B
HV	2.2	0.1		23.5	1.9	B	12.4	0.4	AB	3.0	0.4		8.6	1.6	B	11.4	1.9	B	54.6	0.5	AB
PTT	2.3	0.1		28.0	3.1	AB	12.4	0.5	AB	3.6	0.6		12.2	2.8	AB	15.7	3.4	AB	56.0	0.8	AB
KS	2.2	0.1		26.4	2.8	AB	11.4	0.5	B	3.5	0.6		13.3	2.5	AB	15.3	3.1	AB	56.8	0.5	A
											p-values										
D	**<.0001**			**<.0001**			**<.0001**			**<.0001**			**<.0001**			**<.0001**			-		
S	0.7495			**0.0011**			**0.0269**			0.4775			**<.0001**			**<.0001**			**0.0008**		
D x S	0.7159			0.8256			0.7899			0.5429			0.8434			0.8235			-		
											Pearson Correlation Coefficients										
chlorophyll readings	0.15 (p = 0.0963)			0.23 (p = 0.0085)			0.14 (p = 0.1160)			0.11 (p = 0.2270)			0.25 (p = 0.0048)			0.22 (p = 0.0107)			1.0		

Abbreviations: NCC, no cover crop; SO, spring oats; ST, spring triticale; CR, cereal rye; VW, volunteer wheat; HV, hairy vetch; PTT, purple top turnip; KS, Siberian kale; SE, standard error of the mean. [¥]Grant 2016-2017, Grant 2017-2018, North Platte 2016-2017, and North Platte 2017-2018.

Cover crop species (except brassicas) reduced the total N in the soil compared to no CC treatment (Table 3-3). Spring oats, spring triticale, cereal rye, volunteer wheat and hairy vetch reduced total N in the soil by 24, 13, 21, 21 and 23%, respectively, compared to no CC. Similar results were found for nitrate and inorganic nitrogen, where CC species reduced N levels in the soil. On the other hand, the organic N was similar among no CC (13.4 mg kg^{-1} N) and the CC species, except Siberian kale. Siberian kale presented the lower amount of organic N in the soil (11.4 mg kg^{-1} N).

Chlorophyll readings from the corn leaf at the R2 development stage indicated that Siberian kale (56.8) showed the higher value among CC species (Table 3-3). On the other hand, spring oats, cereal rye and volunteer wheat presented 4, 5 and 5% lower values of chlorophyll readings than Siberian kale, respectively. The no CC treatment presented similar values of chlorophyll readings compared to all other CC species. In addition, there were positive correlations of chlorophyll readings with total N (R = 0.24, $p = 0.0085$), nitrate (R = 0.25, $p = 0.0048$) and inorganic N (R = 0.22, $p = 0.0107$) (Table 3-3). In this study, organic N corresponds to approximately 40% of total N, whereas inorganic N (nitrate and ammonium) corresponds to 60% of the total N (Table 3-3). However, organic N must break down into inorganic forms to be available for plant uptake (Havlin et al., 2005). This helps to explain the lack of correlation between organic N and chlorophyll readings (R = 0.14, $p = 0.1160$).

Corn Grain Yield and Yield Components

Corn grain yield was affected by CC species selection ($p < 0.0001$, Table 3-4). In general, CC species decreased corn grain yield compared to no CC, except spring oats. Cereal rye had the most detrimental effects on corn grain yield among all CC species in this study, decreasing corn grain yield up to 30% compared to no CC.

Table 3-4. Corn grain yield and yield components (corn population, number of kernel rows per ear, number of kernels per row, number of kernels per ear, and 100 count kernel weight) according to cover crop species across site-years[†] in western Nebraska. Site-years are included as random effects in the ANOVA model. Numbers followed by different letters represent statistically significant differences with Tukey adjustment at the $p \leq 0.05$.

	Corn Grain Yield (Mg ha^{-1})			Corn Plant Population (plants ha^{-1})		Number of Kernel Rows per Ear			Number of Kernels per Row			Kernels per Ear			100-Kernel Weight (g)		
Species	Mean	SE+-		Mean	SE+-	Mean	SE+-		Mean	SE+-		Mean	SE+-		Mean	SE+-	
NCC	8.7	0.2	A	33920	1082	16.4	0.2	A	43.3	0.8	A	713	20	A	32.8	1.4	A
SO	7.5	0.4	AB	33869	1037	16.3	0.2	AB	43.1	0.8	AB	703	21	A	30.0	1.6	B
ST	7.0	0.5	BC	32982	1314	15.7	0.2	AB	42.3	1.3	AB	668	26	AB	30.6	1.6	AB
CR	6.1	0.6	C	31645	1154	15.6	0.4	B	40.3	1.9	B	635	40	B	31.1	1.9	AB
VW	7.0	0.5	BC	33490	1306	15.9	0.2	AB	42.6	1.5	AB	680	28	AB	31.0	1.7	AB
HV	7.2	0.5	BC	33414	1424	15.6	0.3	B	43.1	1.2	AB	678	29	AB	30.6	1.8	B
PTT	7.1	0.6	BC	33198	1090	15.9	0.3	AB	42.9	1.3	AB	684	28	AB	30.2	1.8	B
KS	7.2	0.6	BC	33931	1032	16.2	0.2	AB	41.3	1.5	AB	671	29	AB	30.8	1.5	AB
p-values																	
Species	**<.0001**			0.2241		**0.0055**			**0.0326**			**0.0025**			**0.0134**		
Pearson Correlation Coefficients																	
Corn Grain Yield (Mg ha^{-1})	1			R = -0.34 (p < 0.0001)		R = 0.38 (p < 0.0001)			R = 0.54 (p < 0.0001)			R = 0.54 (p < 0.0001)			R = 0.61 (p < 0.0001)		

Abbreviations: NCC, no cover crop; SO, spring oats; ST, spring triticale; CR, cereal rye; VW, volunteer wheat; HV, hairy vetch; PTT, purple top turnip; KS, Siberian kale; SE, standard error of the mean. [†]Grant 2016-2017, Grant 2017-2018, North Platte 2016-2017, and North Platte 2017-2018.

The Pearson's linear correlation showed that most of the yield components affected corn grain yield, especially the number of kernels per row (R = 0.54), kernels per ear (R = 0.54) and 100-kernel weight (R = 0.61) (Table 3-4). No effects of CC species on corn plant population were detected in this study (p = 0.2241). On the other hand, the number of kernel rows per year (p = 0.0055), number of kernels per row (p = 0.0326), kernels per ear (p = 0.0025), and 100-kernel weight (p = 0.0134) were affected by CC species selection (Table 3-4). Overall, cereal rye and hairy vetch showed the lowest number of kernel rows per ear. Cereal rye reduced the number of kernels per row and kernels per ear by 7 and 11%, respectively, compared to no CC (Table 3-4). Likewise, spring oats, hairy vetch, and purple top turnip reduced the 100-kernel weight by 9, 9 and 8%, respectively, compared to no CC. Thus, just like for corn grain yield, cereal rye treatment negatively affected the majority of the corn yield components.

Discussion

Cover crop biomass production was dependent whether CCs were winter-sensitive or winter-hardy. The CC winter-sensitive species spring oats, purple top turnip, and Siberian kale reached the highest biomass in the fall. Due to its increased biomass in the fall, those species might have good potential for grazing, reducing costs of CC implementation. On the other hand, winter-hardy species grew in the fall and spring bringing the opportunity to enhance soil residue coverage, and suppress summer annual weeds. In this study, cereal rye was the most consistent CC species in terms of biomass, especially in the spring. Cereal rye had the highest spring biomass among CC species. Cereal rye's winter hardiness contributes to more soil residue coverage, potential soil nutrient scavenging, and grazing opportunity (Snapp et al., 2005; Kaspar and Singer, 2011; Appelgate et al., 2017). This finding justifies the popularity of cereal rye over other CC species.

Soil water content decreased during the corn growing season (Figure 3). This result was expected since precipitation amounts decrease from summer to fall, and the corn demands for water keeps increasing, reaching its peak at corn VT (tassel stage) and R1 (silking stage) (Westgate et al., 2004; Abendroth et al., 2011). The increased biomass production by cereal rye in the spring probably induced the increased water consumption impacting the Θ_v at North Platte 2016-2017. In a previous study, cereal rye decreased Θ_v from 0 to 20 cm soil depth among sole CCs at corn planting (Appelgate et al., 2017). Grant 2016-2017 did not show differences in Θ_v among CC species likely due to low CC biomass during the spring (data not shown by site-years). For Grant 2017-2018 and North Platte 2017-2018, the lack of differences among CC species regarding soil water may be due to the above average precipitation during the spring in those site-years. Our study suggests that the 2018 spring precipitation probably minimized the effect of CCs in Θ_v. Although the TDR sensor measurements do not show Θ_v differences in 0 to 20 cm soil depth, the precipitation patterns especially during fall 2016 and summer 2017 may help explain the severe drop in yields from CC treatments.

Soil penetration resistance was not affected from 0 to 20 cm soil depth, which is a critical layer for corn establishment and root growth (Figure 3-5). Approximately 45% of the corn rooting system is at 0 to 20 cm soil depth (Yamaguchi et al., 1990). Thus, in their first year of implementation, CCs did not affect positively or negatively the soil penetration resistance. However, from 20 to 30 cm soil depth, CCs such as volunteer wheat, hairy vetch, spring triticale and especially cereal rye increased soil penetration resistance compared to other CC treatments. In dry years, the increased soil penetration resistance can be a challenge for corn root growth to scavenge water and nutrients in deeper soil layers (Unger and Kaspar, 1994). Besides, the increments in soil penetration resistance can limit water infiltration in the soil (Chen et al., 2014) affecting soil water recharge. As shown by equation [1] and Figure 3-4, the soil penetration resistance values were associated with soil water. Since the TDR sensor could only measure Θ_v from 0 to 20 cm soil depth, the adjustment for soil penetration resistance was limited to the same depth as the TDR sensor. In a previous study, Blanco-Canqui et al. (2006) found that soil penetration resistance was highly correlated with soil water. Therefore, cereal rye could be using soil water up to 30 cm soil depth increasing soil penetration resistance, and consequently contributing to reduced corn grain yield.

Cover crop species with high biomass can suppress weed populations (Teasdale and Mohler, 2000; Blanco-Canqui et al., 2015; Osipitan et al., 2018). In semi-arid environments, the previous crop residue (winter wheat) associated with no-till works as a physical barrier suppressing weeds (Klein, 2012). In addition to previous crop residue, CCs fill the gaps that could otherwise be occupied by weeds (Liebman and Staver, 2001). This study showed that spring oats and cereal rye produced the highest aboveground biomass in the fall and spring, respectively, where cereal rye was responsible for the greatest summer annual weed biomass reduction among all other CC species tested (Table 3-2). In addition, cereal rye reduced summer annual weed populations (weed density) being an effective tool for weed management control. A recent study published by Pittman et al. (2020) in Virginia revealed that increased CC biomass, especially with higher carbon:nitrogen (C:N) ratio like cereal rye, increment soil coverage duration increasing summer annual weed suppression. Most of the summer annual weeds start emerging in April/May/June (Werle et al., 2014b), so either having a CC growing or increasing the amount of crop residue during that period will help corn early-season competition against weeds. Besides, cereal rye CC residues can release allelochemicals that may inhibit weed emergence (Weston, 1996). Our results showed that CCs grown in the spring were more effective to reduce weed density and biomass (Figure 2) as compared to CC fall biomass. Thus, it is important to have CCs growing in the spring if the goal is to reduce summer annual weeds.

Cover crops, especially grasses, likely induced N immobilization during the corn growing season (Table 3-3). Grass residue decomposition is known to be slow in comparison to legumes (Blanco-Canqui et al., 2015) because of their higher C:N ratio. Since the soil samples were collected at the corn V6 development stage most of the grass CCs residue was still visible in the soil surface. Therefore, we speculate that there was not enough time for grass CCs to complete N cycling by corn V6 development stage. Lower nitrogen values in grass CC plots could potentially reduce nitrate prone to leaching (White et al., 2017), however, it also means less nitrogen available for corn uptake. Therefore, it is difficult to estimate nitrogen mineralization and associate with the crop N requirements (Snapp and Fortuna, 2003). Biotic or abiotic stresses at corn V6 development stage can compromise the potential number of kernels per ear (Abendroth et al., 2011), and consequently, increase the risk of yield penalty to corn. Although hairy vetch is a winter-hardy legume CC, its plots presented considered amounts of volunteer wheat growth in the spring which probably increased the total C:N ratio of this treatment inducing N immobilization. In addition to soil N sampling, chlorophyll readings were collected to estimate in real time N status in the corn plant. The positive correlation of the chlorophyll readings with total N, nitrate and inorganic N demonstrate that the measurement was efficient to inform N status in the plant later in the corn growing season (Table 3-3). Thus, based on the chlorophyll readings, spring oats, cereal rye and volunteer wheat treatments likely extended N immobilization further during corn growing season.

The corn grain yield and yield component results help explain the concerns of producers about adopting CCs in semi-arid environments. Most of the CC species reduced corn grain yield and yield components, especially cereal rye (Table 3-4). Although not measured deeper than 20 cm soil depth, we hypothesize that soil water depletion likely happened from 20 to 30 cm soil depth under cereal rye, volunteer wheat, spring triticale and hairy vetch based on the soil penetration resistance results. In addition, cereal rye remarkably decreased N levels in the soil. Therefore, both soil water and N were limiting factors for corn grain yield. Other studies documented that cereal rye reduce soil water and N availability due to excessive growth (Campbell et al., 1984; Nevins et al., 2020), decreasing corn grain yield in water-limited regions (Ruis and Blanco-Canqui, 2017). Moreover, cereal rye's potential to become a weed in winter wheat cropping systems due to its seed production and long seed dormancy (Lyon and Klein, 2007) is a concern for producers in western Nebraska. Similarly, allowing volunteer wheat grow during the spring will likely induce nitrogen immobilization, and introduce a potential host of wheat streak mosaic disease (Wegulo et al., 2008). Volunteer wheat needs to be monitored in both fall and spring when growing CCs in a winter wheat-corn-fallow rotation. Volunteer wheat can establish especially under a poor CC stand in the fall, or in the spring if planting winter-sensitive CC species as they may not survive the winter.

Since our studies were conducted in rainfed semi-arid environments, the precipitation during spring and early summer plays an important role regarding the success of the crops cultivated. In this sense, water storage is important to mitigate stresses in the subsequent crop. The conservation of crop residue at the soil surface aims to reduce weed populations and evapotranspiration in semi-arid environments (Klein, 2012). In addition, considering dry environments such as western Nebraska, the recommended termination time for CCs is at least two weeks prior to subsequent crop planting (Sustainable Agriculture Network, 2007) due to water conservation (USDA/NRCS, 2013) and nitrogen immobilization (Appelgate et al., 2017). Thus, the reduced precipitation during spring and early summer of 2017 plus the CC termination near corn planting time likely contributed to increased nitrogen immobilization, soil water depletion and consequently lower corn grain yield under CC treatments (Table 3-4).

Conclusions

Our findings emphasize the importance of species selection when adopting cover crops (CCs). This study shows that under the winter wheat-corn-fallow rotation of semi-arid environments, CCs have the potential to suppress summer annual weeds, particularly with cereal rye, due to its increased biomass production during fall and especially spring. Cover crops can potentially help the herbicide program by reducing the size and population of weeds, decreasing herbicide-resistant plants. On the other hand, our study did not find any positive or negative effect of CC species in soil water from 0 to 20 cm soil depth and penetration resistance, except of cereal rye. Cereal rye increased soil penetration resistance from 20 to 30 cm soil depth likely because of soil water use beyond 0 to 20 cm soil depth. Likewise, CCs did not contribute to any gain in corn grain yield. Instead, the majority of the CC species reduced corn grain yield except spring oats, which had no effect on corn grain yield. Corn grain yield reduction by CCs was probably related to soil water use below 20 cm soil depth and N immobilization during corn growing season. Thus, future studies should evaluate not only soil water content deeper in the soil, but N mineralization by different CC species, calibrating N requirements for corn as a subsequent crop.

Additionally, our findings reflect the transition period (1st year of CC adoption as part of the winter wheat-corn-fallow rotation), thus, suggesting that producers should use caution when incorporating CCs in their cropping systems of semi-arid regions. It is important to consider the purpose of growing CCs where weed suppression, reduced soil erosion, and increased fall biomass for grazing may work well in semi-arid environments. If the goal is to promote N cycling then it will require a calibration to determine when N will be available for the subsequent crop uptake. However, if the producer aims to increase corn grain yield then growing CCs may not work at least for a short-term (1 year of crop rotation) in winter wheat-corn-fallow rotations of western Nebraska. Long-term CC adoption investigations are necessary to provide a conclusive answer about CC use in western Nebraska and its effects on cash crops in rotation, and soil chemical and physical properties (particularly those enhancing water infiltration in the soil). Producers must consider CC planting and termination timing, precipitation amounts, and fertilization, which are key factors to the success of CCs in dry environments. Due to cereal rye's potential of becoming a weed in winter wheat and its detrimental impacts on corn yield, spring oats might be the best CC species option for producers to grow under water-limited environments.

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CHAPTER 4: WINTER WHEAT STUBBLE HEIGHT AND COVER CROP MANAGEMENT ON RAINFED CORN PRODUCTION IN THE SEMI-ARID GREAT PLAINS

Abstract

Soil water storage during fallow periods is crucial for the success of cropping systems in semi-arid environments. Because of their benefits to soil conservation, water infiltration and nutrient cycling, the incorporation of cover crops (CCs) has gained notoriety. Conjointly, proper winter wheat stubble height (WSH) management during grain harvest can decrease subsequent soil water loss, potentially minimizing the effects of water consumption by cover crops (CCs). Thus, the objectives of this study were to evaluate the effects of WSH management and CCs on soil water content during CC and subsequent corn growing season, residue coverage and soil nutrient levels at corn V6 development stage, chlorophyll readings at corn blister development stage (R2), and corn grain yield. The study was conducted in a winter wheat-corn-fallow rotation at four locations (Gothenburg, Grant, North Platte, and Sidney, NE) during 2017-2018 and 2018-2019 in a strip-split-plot randomized complete block design with four replications. Treatments consisted of two WSH [short (26 cm) and tall (58 cm)] and three CC treatments [winter-sensitive CC mixture, winter hardy CC mixture and fallow (no CC)]. Cover crop winter-sensitive mixture aboveground biomass was 16% higher than winter-hardy in the fall, whereas only winter-hardy species survived the winter producing biomass in the spring. In Gothenburg and North Platte, the residue coverage biomass was increased by CC mixtures (especially by the CC winter-hardy mixture) in comparison to fallow. Both CC winter-sensitive and winter-hardy mixtures reduced soil water content during CC growth period (fall and spring). The soil water depletion was more evident from 15-45 cm soil depth and below compared to fallow. In addition, the soil phosphorus and chlorophyll readings were reduced by CCs, likely because of the predominance of grasses in

both CC mixtures. Consequently, corn grain yields were reduced by CC winter-hardy mixture in all sites (average of 17% reduction), except Gothenburg. Likewise, CC winter-sensitive mixture reduced corn grain yields in North Platte and Grant only (average of 12% reduction). The WSH did not influence the variables evaluated in this study. Hence, producers should use caution when incorporating CCs in semi-arid environments due to increased risk of soil water depletion and nitrogen immobilization to subsequent corn crop. This study will aid in the development recommendations for WSH and CC management that optimize soil water use and overall productivity of rainfed cropping systems of semi-arid environments of the Great Plains region of the United States.

Introduction

Producers of dryland semi-arid areas rely on proper soil water storage for the success of their cropping systems. The winter wheat (*Triticum aestivum L.*)-corn (*Zea mays L.*)-fallow rotation represents the typical rainfed cropping system of western Nebraska and much of the Great Plains where two crops are grown in three years. In this crop rotation, winter wheat is typically planted in the fall (around September) after a fallow period that starts after corn harvest in the previous year (September-November). Then, winter wheat is harvested in the summer (July) and followed by a second fallow period until corn is planted in the next spring (around May). Therefore, this crop rotation contains two fallow periods that are intended for soil water conservation and soil water recharge by precipitation. However, the sustainability of two fallow periods in the cropping system is becoming a major challenge in semi-arid environments because of unstable commodity prices (especially winter wheat), inefficient land use, herbicide-resistant weeds, and soil degradation through erosion and soil organic carbon reduction (Blanco-Canqui et al., 2011). In this scenario, the inclusion of a cool season crop such as field peas (*Pisum sativum L.*) in the spring after corn harvest (Stepanovic et al., 2018), and cover crops (CCs) following winter wheat harvest are arising as an alternative to intensify crop production and land use in semi-arid regions.

The reduced average precipitation of semi-arid climates (250-700 mm annual precipitation) (Gallart et al., 2002) is a major limiting factor in crop intensification and production. Under those circumstances, no-tillage and proper wheat stubble height (WSH) management are key factors to soil water storage for subsequent crops (Klein, 2012), especially in drier years. Wheat residue management starts at the time of winter wheat harvest. When winter wheat is short harvested, its residue decomposes at a faster rate (Hagen, 1996), increasing the water evaporation during the fallow period prior corn planting and also during the corn growing season. A study conducted in semi-arid Colorado found that a short winter wheat stubble height increased the water vapor exchange and radiation absorption, increasing soil water evaporation (McMaster et al., 2000). Hence, with less wheat stubble residue in the soil surface, soil water depletion may increase which could lead to subsequent corn grain yield loss. However, if only the wheat heads are harvested, a tall stubble is left increasing the snow retention during the winter (Nielsen, 1998). That is possible because the tall stubble can reduce the wind speed of a snow storm, facilitating the snow deposition in the soil (Bilbro and Fryrear, 1994). In semi-arid Kansas, taller winter wheat stubble increased corn grain yield, likely due to soil water conservation (Schlegel, 2015). Therefore, under rainfed semi-arid environments, maintaining or increasing soil residue coverage can help with increasing soil water recharge and reducing water evaporation (Nielsen et al., 2005; Holman et al., 2018) and with increasing subsequent crop yields. However, live CCs transpire water increasing evapotranspiration, whereas its residues after termination could increase soil residue coverage reducing water evaporation in semi-arid environments. Thus, it is not well known if including CCs in place of fallow would lead to increments in soil residue coverage and soil water storage.

Lately, CCs have emerged as an alternative conservation tool to cropping systems in the US. Cover crops have numerous documented benefits such as protecting soil from water and wind erosion (Kaspar et al., 2001; Strock and Porter, 2004), reducing nitrogen (N) leaching (Dinnes et al., 2002; Villamil et al., 2006), increasing water infiltration and soil organic carbon (Kaspar and Singer, 2011; Blanco-Canqui et al., 2015) and suppress weeds (Osipitan et al., 2018; Werle et al., 2018). The aforementioned benefits of growing CCs helped raise their popularity among producers in recent years in Nebraska. The CC planted area doubled in Nebraska going from approximately 145 to 300 thousand hectares from 2012 to 2017 (NASS, 2017). In winter wheat-corn-fallow rotations of western Nebraska, CCs can be planted shortly after winter wheat harvest replacing one of the fallow periods. A major concern, however, is the impact that these non-cash crops can have on soil water content in water-limited environments. Thus, by replacing fallow with CCs, the soil water storage will likely reduce affecting negatively the subsequent corn yield.

Different strategies to minimize the effects of CCs on soil water levels can be implemented in semi-arid cropping systems. Cover crop planting and termination time are important management practices that define the amount of biomass produced by CCs, and consequently, the amount of water used by them. Since winter wheat is harvested in July, there is a wide window to plant CCs in the summer/fall. Similarly, terminating CCs in the fall can allow enough time for soil water recharge in the spring. Winter-sensitive CCs growth is limited to the fall (frost-killed during the winter), thus, reducing the risk of excessive soil water use by CCs (Reese et al., 2014). On the other hand, winter-hardy species have a wider growing window including biomass accumulation in the spring, increasing soil water use (Holman et al., 2018), and likely, the risk of yield reduction of the subsequent crops. Winter-hardy species require either a mechanical or herbicide termination method which should be done at least two weeks prior planting the subsequent crop to leave enough time for soil water recharge and minimize nitrogen (N) immobilization (USDA/NRCS, 2013).

Cover crops can cycle nutrients in the soil. With soil mobile nutrients such as N, CCs can uptake from deeper in the soil minimizing N leaching and cycling back to the next crop. However, the timing for this process is critical as the corn N demand starts early in the season (V6 development stage). Cover crop mixtures rich of grass species may lead to N immobilization, especially winter-hardy CCs, as there is not enough time for the CC residues to decompose and cycle N back to be available for subsequent corn (Nevins et al., 2020). Moreover, other authors caution for N immobilization issues with CC mixtures (Wortman et al., 2012) and sole CC grass species (Snapp and Surapur, 2018). Similar to N, CCs may promote phosphorus (P) and potassium (K) cycling in the soil, where the CC plants take up P and K, and their residue decomposition release those nutrients back to the soil (Nelson and Janke, 2007). The adoption of no-till system keeps the previous crop residue in the soil surface, accumulating nutrients (especially immobile nutrients such as P and K) in the top layers of the soil (Robbins and Voss, 1991; Karlen et al., 1991). Including CCs in the crop rotation can potentially bring P and K from deep soil layers to soil surface, increasing the concentration of those nutrients in the crop root zone (Rosolem and Steiner, 2017). This can be especially positive for early stages of crop growth, as the nutrients (P and K) would be easy accessible by roots. In addition, including CCs in the cropping system has the advantage of minimizing P and K loss by soil erosion and deep percolation, respectively, reducing the risk of water contamination (Hartz, 2006). In a study conducted in southern Brazil, Kepler and Anghinoni (1995) observed higher K levels in the soil during corn grain filling stage followed by black oats (*Avena strigosa*) cover crop. However, the synchrony of residue decomposition and nutrient release is not well understood in semi-arid environments. If the nutrient release by CC residue does not pair with subsequent corn nutrient demand, then corn grain yield limitations may occur.

The decision to establish a winter-sensitive or winter-hardy CC species replacing the fallow period between winter wheat harvest and corn planting may influence the soil water and fertility to subsequent corn, and consequently, affect the corn grain yield. Moreover, it is not well understood if WSH management could improve soil water retention minimizing the drawback effects of CCs in semi-arid environments. Hence, the objectives of this study were to evaluate the effects of WSH management and CCs on soil water content during CC and corn growing season, residue coverage, soil and plant nitrogen levels, and corn grain yield and yield components. The study hypotheses were that (1) tall WSH will increase soil water retention; (2) WSH and CCs contribute to increased soil residue coverage; (3) CCs decrease soil water, soil P and K, and soil N levels leading to N immobilization; and (4) CC winter-hardy mixtures decrease corn grain yield and yield components compared to CC winter-sensitive mixture and fallow.

Materials and Methods

Field Sites and Experimental Design

Field studies were conducted at four sites in western Nebraska during 2017-2018 and 2018-2019 cover crop-corn growing seasons (total of eight site-years). The studies were located at the Bayer Crop Science Gothenburg Water Utilization Learning Center (Bayer Crop Science, St. Louis, MO) near Gothenburg, NE (40°88'20.9"N; 100°16'60.1"W; 788 m elevation) on a Hord silt loam soil (fine-silty, mixed, superactive, mesic Cumulic Haplustolls); at the University of Nebraska-Lincoln (UNL) West Central Research and Extension Center near North Platte, NE (41°03'13.6"N; 100°44'52.8"W; 854 m elevation) on a Holdrege silt loam soil (fine-silty, mixed, superactive, mesic Typic Argiustolls); at the UNL Henry J. Stumpf International Wheat Center near Grant, NE (40°51'15.0"N; 101°42'13.9"W; 1040 m elevation) on a Kuma silt loam (fine-silty, mixed, superactive, mesic Pachic Argiustolls); and at the UNL High Plains Agricultural Laboratory near Sidney, NE (41°22'89"N; 103°02'05.8"W; 1246 m elevation) on a Keith loam soil (fine-silty, mixed, superactive, mesic Aridic Argiustolls). The study sites are represented in Figure 4-1. The sites were strategically chosen to represent different precipitation regimes within rainfed semi-arid western NE. The historic precipitation amounts across sites decrease from east (Gothenburg) to west (Sidney). The monthly precipitation and temperature for each site-year along with the 30-year historic average for each site are shown in Table 4-1. The fields used in this study did not have a history of cover crop (CC) use and had been on a winter wheat-corn-fallow rotation.

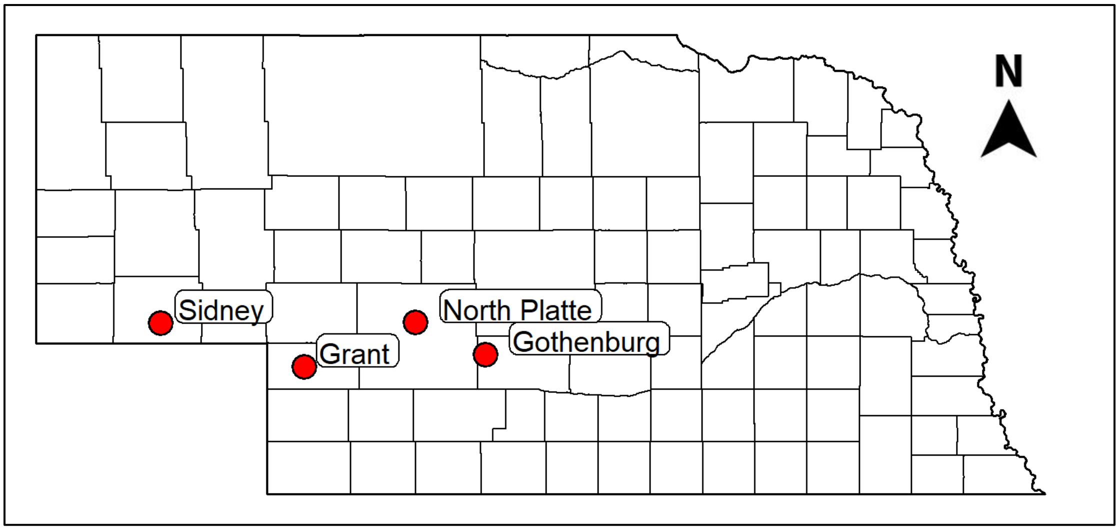

Figure 4-1. Study sites across western Nebraska during the 2017-2018 and 2018-2019 growing seasons.

Table 4-1. Average temperature (T) and monthly precipitation (P) for Gothenburg, North Platte, Grant and Sidney from cover crop planting to corn harvest during the years of 2017, 2018 and 2019, and the 30-year averages (Tavg, Pavg) for period of 1986-2016. Source: High Plains Regional Climate Center, https://hprcc.unl.edu.

		Gothenburg				North Platte				Grant				Sidney			
Year	Month	T	P	Tavg	Pavg	T	P	Tavg	Pavg	T	P	Tavg	Pavg	T	P	Tavg	Pavg
2017	September	19.1	93.2	17.8	44.7	17.9	127.5	17.4	41.1	18.3	36.8	17.8	37.3	17.2	41.9	16.4	43.4
2017	October	11.2	84.8	10.8	42.7	10.0	88.4	10.3	41.7	9.9	25.7	10.6	31.5	9.3	31.2	9.5	27.4
2017	November	4.8	4.6	3.3	18.3	4.1	3.3	2.9	14.2	4.7	4.6	3.1	15.5	5.3	5.3	2.7	12.7
2017	December	-2.9	8.9	-2.2	11.2	-3.3	10.9	-2.8	9.4	-3.1	16.0	-2.3	9.7	-1.9	22.1	-2.4	10.2
	Avg. T, Total P	11.1	686.3	10.4	590.8	10.1	639.3	9.6	517.7	10.5	390.4	10.4	497.1	10.2	438.9	9.9	451.1
2018	January	-4.3	28.7	-2.7	8.4	-5.8	13.5	-3.3	7.4	-4.7	50.3	-2.8	11.4	-1.9	14.0	-2.3	7.1
2018	February	-	18.5	-1.1	16.5	-6.9	13.2	-1.8	13.5	-4.6	9.4	-1.3	15.2	-3.3	11.2	-1.3	12.2
2018	March	5.2	8.6	4.4	25.1	3.6	16.5	3.5	23.1	3.9	19.3	3.9	29.5	4.3	19.3	3.5	22.9
2018	April	6.4	45.5	9.8	64.8	4.3	30.5	8.6	58.4	5.4	49.3	8.9	56.1	5.3	48.8	7.3	42.7
2018	May	18.2	154.7	15.7	97.5	16.7	136.1	14.3	82.8	17.3	126.7	14.8	79.5	15.2	140.0	12.8	75.2
2018	June	23.4	96.3	21.3	100.1	21.4	100.8	20.2	94.5	22.7	66.3	20.9	80.5	20.7	55.6	18.8	83.8
2018	July	23.2	136.1	24.1	80.3	22.8	65.8	23.4	70.6	23.8	113.5	24.3	74.9	22.5	126.5	22.6	60.5
2018	August	-	36.3	22.8	81.3	21.3	46.5	22.4	61.0	21.8	21.1	23.2	55.9	20.7	34.0	21.4	53.1
2018	September	-	77.0	17.8	44.7	18.9	26.2	17.4	41.1	19.9	13.5	17.8	37.3	18.4	20.1	16.4	43.4
2018	October	9.6	83.3	10.8	42.7	7.7	77.0	10.3	41.7	8.3	43.9	10.6	31.5	7.8	32.3	9.5	27.4
2018	November	2.1	14.5	3.3	18.3	0.8	11.9	2.9	14.2	1.5	10.4	3.1	15.5	1.9	28.7	2.7	12.7
2018	December	-1.7	67.8	-2.2	11.2	-3.1	32.3	-2.8	9.4	-1.7	15.2	-2.3	9.7	-0.8	13.7	-2.4	10.2
	Avg. T, Total P	9.1	767.3	10.4	590.8	8.5	570.2	9.6	517.7	9.4	539.0	10.4	497.1	9.2	544.1	9.9	451.1
2019	January	-1.7	3.8	-2.7	8.4	-3.1	2.5	-3.3	7.4	-1.7	1.0	-2.8	11.4	-1.7	5.1	-2.3	7.1
2019	February	-6.9	16.8	-1.1	16.5	-8.1	11.9	-1.8	13.5	-7.1	9.9	-1.3	15.2	-5.6	10.4	-1.3	12.2
2019	March	1.3	80.5	4.4	25.1	-0.8	63.2	3.5	23.1	0.0	61.2	3.9	29.5	0.6	66.0	3.5	22.9
2019	April	10.8	52.6	9.8	64.8	8.8	36.8	8.6	58.4	9.8	31.2	8.9	56.1	9.1	49.5	7.3	42.7
2019	May	13.1	180.6	15.7	97.5	10.4	167.6	14.3	82.8	11.5	140.7	14.8	79.5	10.0	150.6	12.8	75.2
2019	June	20.6	126.2	21.3	100.1	18.7	122.7	20.2	94.5	20.5	64.3	20.9	80.5	18.1	92.5	18.8	83.8
2019	July	24.1	162.3	24.1	80.3	22.8	138.2	23.4	70.6	24.4	53.3	24.3	74.9	22.7	137.9	22.6	60.5

2019	August	22.2	177.0	22.8	81.3	21.0	89.2	22.4	61.0	22.8	89.9	23.2	55.9	21.6	101.6	21.4	53.1
2019	September	21.6	18.8	17.8	44.7	19.9	15.0	17.4	41.1	20.4	54.9	17.8	37.3	19.1	41.9	16.4	43.4
2019	October	7.4	32.8	10.8	42.7	6.2	27.9	10.3	41.7	6.3	3.6	10.6	31.5	6.1	7.4	9.5	27.4
	Avg. T, Total P	9.7	900.9	10.4	590.8	8.0	707.9	9.6	517.7	9.1	542.3	10.4	497.1	8.6	690.6	9.9	451.1

The experimental design was a strip-split-plot randomized complete block with four replications. The treatments included two CC mixtures (winter-sensitive mixture frost killed during the winter, and winter-hardy mixture chemically terminated two weeks before corn planting) and a control (fallow = no cover crop), and two winter wheat stubble height management (short and tall). Winter wheat stubble height management was considered the strip-plot, while CC mixtures was the split-plot in the experimental design. The WSH treatment was applied at the time of winter wheat harvest. The WSH treatment was established by harvesting winter wheat with a stripper header combine that cuts only the winter wheat heads, leaving the majority of the stubble standing (approximately 58 cm high on average). To apply the short stubble treatment (approximately 26 cm high on average), a draper header combine was ran through the strip-plots cutting the winter wheat stubble by half of the size of the tall stubble treatment.

Cover crops were planted in August, 7-14 days after winter wheat harvest (except Gothenburg where CCs were planted in mid-September). The CC mixture treatments were selected based on the popularity and interest among producers in the region, and represent a diversity of plant families (Poaceae, Fabaceae, and Brassicaceae). The CC winter-sensitive mixture had four species: black oats (*Avena strigosa*), spring barley (*Hordeum vulgare*), spring lentil (*Lens culinaris*) and daikon radish (*Raphanus sativus L. var. longipinnatus*), and was planted at a seeding rate of 70 kg ha^{-1} (28.2 kg ha^{-1} of black oats, 28.2 kg ha^{-1} of spring barley, 11.3 kg ha^{-1} of spring lentil, and 2.3 kg ha^{-1} of daikon radish). The CC winter-hardy mixture also had four species: winter triticale (*Triticosecale*), winter barley (*Hordeum vulgare*), hairy vetch (*Vicia villosa*) and daikon radish (*Raphanus sativus L. var. longipinnatus*), and was planted at seeding rate of 64 kg ha^{-1} (28.2 kg ha^{-1} of winter triticale, 28.2 kg ha^{-1} of winter barley, 5.3 kg ha^{-1} of hairy vetch, and 2.3 kg ha^{-1} of daikon radish). Cover crop seeding rates were defined based on the Sustainable Agriculture Research & Education (Sustainable Agriculture Network, 2007) and Green Cover Seed (Green Cover Seed, Bladen, NE) recommendations, and are commonly adopted in Nebraska. Cover crops were drilled at 19 cm row space and 3 cm seed depth. The individual plot size was 4.6 m wide and 15.2 m long. The CC winter-sensitive mixture was frost-killed during the winter, while the CC winter-hardy mixture was terminated two weeks prior corn planting with glyphosate Roundup Powermax® (Bayer Crop Science, Saint Louis, MO) sprayed at 2.34 L ha^{-1} mixed with 453 g ha^{-1} of ammonium sulfate (KALO, Inc, Overland Park, KS). Also two weeks prior to corn planting, the CC winter-sensitive mixture and the fallow plots were kept clean of volunteer wheat by spraying glyphosate using the same rate as previously described. Corn was planted at 76 cm row space and seed depth of 4 cm. The detailed information regarding soil texture, CC planting and termination dates, corn planting and harvest dates, corn hybrid, seeding rate, and fertilization rates used in each site-year are described in Table 4-2.

Table 4-2. Soil texture, cover crop (CC) planting and termination time, corn planting and harvest time, corn hybrid selection and seeding rate, and fertilizer information for all site-years. Cover crops were planted after winter wheat harvest and terminated both in the fall (freezing temperatures) and in the spring (herbicide). Corn was planted approximately 2 weeks after CC termination (except Sidney in 2018). Corn hybrids, seeding and fertilizer rate followed standard management practices at each site-year. Pre and post-emergence herbicides were applied to control weeds when corn reached the V6-V7 development stage (Abendroth et al., 2011).

Site	Year	Soil texture (0-165 cm soil depth)	CC planting date	First hard freeze date[¥]	CC termination date	Corn planting date	Corn hybrid	Corn seeding rate (seeds ha^{-1})	Fertilizer (time, source, rate)	Corn harvest date
Gothenburg	2018	19.8% clay; 58.4 % silt; 21.8% sand	9/7/2017	11/3/2017	5/4/2018	5/17/2018	DKC60-69RIB (110 days maturity)	59405	At corn V3 development stage, 168 kg ha^{-1} N, 45 kg ha^{-1} P, 19 kg ha^{-1} S and 0.6 kg ha^{-1} Zn.	10/22/2018
	2019		9/11/2018	11/9/2018	4/29/2019	5/15/2019	DKC63-55 (113 days maturity)	59405	Corn pre-planting (4/23/2019), 168 kg ha^{-1} N, 67 kg ha^{-1} P, and 21 kg ha^{-1} S	10/18/2019
North Platte	2018	21.8% clay; 66.5% silt; 11.7% sand	8/1/2017	11/1/2017	5/4/2018	5/23/2018	Hoegemayer 7643RR (106 days maturity)	41018	Corn pre-planting (4/19/2018), UAN (32-0-0), 112 kg ha^{-1}; at corn planting, ammonium polyphosphate (10-34-0), 110 kg ha^{-1}.	10/17/2018
	2019		7/18/2018	10/15/2018	5/5/2019	5/17/2019	Hoegemayer 7556RR (106 days maturity)	39851	Corn pre-planting (4/9/2019), UAN (32-0-0), 112 kg ha^{-1}; at corn planting, ammonium polyphosphate (10-34-0), 110 kg ha^{-1}.	10/19/2019
Grant	2018	23% clay; 62.9% silt; 14.1% sand	8/22/2017	11/2/2017	5/6/2018	5/24/2018	DGVT2PRIB (101 days maturity)	37065	Corn planting, ammonium polyphosphate (10-34-0), 65 kg ha^{-1}; at corn V3 development stage, UAN (32-0-0), 310 kg ha^{-1}.	10/23/2018
	2019		7/21/2018	10/16/2018	5/5/2019	5/17/2019	DGVT2PRIB (101 days maturity)	37128	Corn planting, ammonium polyphosphate (10-34-0), 65 kg ha^{-1}.	10/21/2019
Sidney[*]	2018	19.9% clay; 46.2% silt; 33.9% sand	8/22/2017	11/2/2017	5/5/2018	5/8/2018	Croplan 3337 RR (93 days maturity)	37128	Corn pre-planting (4/26/2018), UAN (32-0-0), 56 kg ha^{-1}.	10/3/2018
	2019		8/10/2018	10/16/2018	5/5/2019	5/15/2019	Croplan 3337 RR (93 days maturity)	37128	Corn planting, ammonium polyphosphate (10-34-0), 46 kg ha^{-1}.	10/21/2019

Abbreviations: UAN, urea ammonium nitrate; N, nitrogen; P, phosphorus; S, sulfur; Zn, zinc. [*]Soil texture from 0-105 cm soil depth. [¥]Temperature below 0°C for more than 2 consecutive days.

Data Collection

Cover Crop Aboveground Biomass

Cover crop aboveground biomass samples were collected in the fall after the first frost event (for both winter-sensitive and winter-hardy mixtures), and in the spring at the time of CC termination time (winter-hardy mixture only). Two 0.093 m^{-2} aboveground biomass samples were randomly collected from each plot. Plants within each sample were separated according to families (grass, legume and brassica) to evaluate their contribution to each mix in fall and spring. After collection in the field, biomass samples separated by CC family were dried in a forced-air oven at 60°C for a minimum of six days and weighed when constant dry biomass was achieved.

Soil Water Content

Soil volumetric water content (m^3 m^{-3}) readings were performed in 30 cm soil depth intervals centered at 15, 45, 75, 105, 135, and 165 cm using a neutron gauge (Model 503 Hydroprobe, CPN International, Martinez, CA). At Sidney, the deepest soil water measurement was 105 cm due to presence of a restricting calcium carbonate layer that limited the access tube installation depth. The neutron gauge was thermo-gravimetrically calibrated ($R^2 > 0.96$) for each site. The aluminum neutron access tubes were installed in three replications from each treatment at each site after CC germination in the fall, removed at the time of corn planting (due to the tractor and planter pass in the plots), and re-installed in the same location within each plot after corn emergence. Wet conditions promoted by precipitation events during May and June combined with rapid corn growth did not permit re-installation of neutron tubes in Gothenburg during corn growing season in 2019. The volumetric water content measurements were taken seven times during the CC and corn growing season: early and late fall (during CC winter-sensitive and winter-hardy mixture growth); early and late spring (during CC winter-hardy mixture growth); early and mid-corn growth, and by corn harvest.

Residue Coverage

Total residue coverage biomass on the soil surface was collected when corn reached the V6 development stage to account for possible contribution of previous crops (including CCs) and WSH (short versus tall stubble) to increased water storage. All plant residue remaining on the soil surface, which mainly included winter wheat stubble and cover crop residue, was sampled. Two 0.093 m^{-2} aboveground biomass samples were randomly collected from each plot. Residue samples of each plot were dried in a forced air oven at 60°C until constant dry biomass was achieved and weighed.

Soil Fertility and Chlorophyll Readings

A composite soil sample (eight cores per depth) using a straight tube probe (2.5 cm diameter) was collected from 0 to 10 and 10 to 20 cm soil depth at each plot when corn reached the V6 development stage. Soil sampling occurred at corn V6 development stage to allow time for CCs decomposition, and potentially cycle nitrogen (especially brassica and legume species). Soil samples were sent to the Ward Laboratories, Inc. (Kearney, NE) for analyses of soil nitrate, total phosphorus (P) and total potassium (P). Soil nitrate and soil P were analyzed by the H3A extract on a Lachat 8000 flow injection analyzer (Hach Company, Loveland, Colorado). The soil K was also analyzed using the H3A extract but on an Inductively Coupled Plasma-Optical Emission Spectrometry instrument (Thermo Fisher Scientific Inc., Waltham, MA).

Chlorophyll readings were performed by sampling the corn ear leaf to access corn plant nitrogen levels (Schepers et al., 1992; Varvel et al., 1997; Scharf et al., 2011), and complement soil nitrogen measurements. The readings were taken during corn early reproductive stages (R2 development stage) in 30 consecutive corn plants in the two central rows from each experimental plot using a chlorophyll meter (model SPAD 502, Konica Minolta, Osaka, Japan).

Corn Grain Yield and Yield Components

The two central corn rows of each plot were hand-harvested (2.65 m long per corn row) covering an area of 4.065 m^{-2} (Lauer, 2002). The corn plant population was estimated by counting the number of plants in three rows of corn in each plot at the whole plot length when corn reached the R2 development stage. Six corn ears were randomly selected from the hand-harvested area to estimate the yield components. The number of kernels per ear was determined by counting the number of kernel rows per ear (transversal count) and the number of kernels per row (longitudinal count). After accounting for the yield components, all corn ears were threshed using a stationary corn ear sheller (ALMACO, Nevada, IA). After threshing, 100-kernel weight (yield component) and grain yield at each plot was recorded and adjusted to 15.5% moisture content.

Statistical Analysis

All plant (CC biomass in the fall and spring, residue coverage, chlorophyll readings, corn grain yield, and yield components) and soil (soil nitrate, P and K) variables in this study were subjected to analysis of variance (ANOVA) using the PROC GLIMMIX procedure in SAS 9.2 (SAS Institute, Cary, NC). The CC mixtures, WSH, and sites were considered as fixed factors and the replication blocks nested within years were treated as a random factor in the model. The soil variables (soil nitrate, P and K) were analyzed by soil depth (0-10 and 10-20 cm) to account for possible soil nutrient differences within the top soil profile across treatments. The soil water content data measured throughout the CC and corn growing seasons were analyzed by site and soil depth (replication blocks nested within years were treated as random effect whereas soil depth was a fixed effect) as a repeated measure in time, where the time in season (early fall, late fall, early spring, late spring, early corn growth, mid corn growth, and corn harvest) was considered as time in the model. Years were treated as random in all variable analysis because the precipitation patterns during the growing seasons 2017-2018 and 2018-2019 were similar (above

30-year average) within the sites (Table 4-1). On the other hand, sites were considered fixed because the main goal was to identify possible differences on soil water content within the sites as their precipitation patterns (precipitation decrease from east to west in Nebraska) and soil textures differ (i.e. soil water holding capacity). The variables CC biomass in the fall and spring, soil nitrate, soil P, soil K, corn grain yield, and corn plant population were log-transformed before the ANOVA to satisfy the Gaussian assumptions of normality data distribution (back transformed means are presented for ease of interpretation). For all response variables in the study, the separation of means for interactions and main effects was set at a significant level of $\alpha = 0.05$ with Tukey's adjustment and completed using the LINES option in PROC GLIMMIX. Pearson's linear correlation tests were performed in soil variables, chlorophyll readings and corn grain yield at a 5% significance level using PROC CORR in SAS 9.2, and were plotted using the *ggscatter* function in R (R Development Core Team, 2007).

Results

Weather Data

Precipitation and air temperature from each site were compared to their historical average data (30-year period, 1986-2016; Table 4-1). Although precipitation distribution throughout the year followed a similar pattern across the sites, it is important to note that Sidney is historically a drier site than all other sites, followed by Grant, North Platte, and Gothenburg. The years which the study was conducted registered above normal precipitation amounts as compared to the 30-year historical average for all sites, except for Grant and Sidney in 2017 where the annual precipitation was lower than the 30-year historical average. All sites registered average temperatures slightly below the historical average. However, comparing the sites, the temperature patterns are similar, with North Platte (9.6 °C) and Sidney (9.9 °C) registering the lower, and Gothenburg (10.4 °C) and Grant (10.4 °C) the higher 30-year average temperatures. Therefore, temperatures followed a similar trend in this study when compared to the historical 30-year average data. Since the precipitation data at each site differed from each other, they will be further discussed in order to support the soil water content results.

Gothenburg

Precipitation amounts at Gothenburg were above the 30-year average for the 3 years of the study (Table 4-1). The 30-year average precipitation amounts in Gothenburg is 590.8 mm of rain per year. Throughout the study, Gothenburg registered 686.3 mm in 2017 (+ 95.5 mm), 767.3 mm in 2018 (+ 176.5 mm), and 900.9 mm in 2019 (+ 310.1 mm). During fall 2017 and 2018 (September, October and November), when CCs were planted, the average precipitation was 1.7 times above the 30-year historical average. Likewise, in spring 2018 and 2019 (March, April and May), when only CC winter-hardy mixtures were growing, the average precipitation was 11 and 67% higher, respectively, compared to the 30-year historical average. Similarly, in summer 2018 and 2019 (June, July and August), when corn was actively growing, the average precipitation was 3 and 78% higher, respectively, compared to the 30-year historical average.

North Platte

Precipitation amounts at North Platte were above the 30-year average for the 3 years of the study (Table 4-1). The 30-year average precipitation amounts in North Platte is at 517.7 mm of rain per year. Throughout the study, North Platte registered 639.3 mm in 2017 (+ 121.6 mm), 570.2 mm in 2018 (+ 52.5 mm), and 707.9 mm in 2019 (+ 190.2 mm). During fall 2017 and 2018, the average precipitation was 2.3 times and 18% greater, respectively, than the 30-year historical average. Likewise, in spring 2018 and 2019, the average precipitation was 11 and 63% higher, respectively, than the 30-year historical average. On the other hand, in summer 2018 and 2019, the average precipitation was 6% lower and 55% higher, respectively, compared to the 30-year historical average.

Grant

Precipitation amounts at Grant were above the 30-year average (497.1 mm), with 539 mm in 2018 and 542.3 mm in 2019 (Table 4-1). In 2017, the average precipitation was 390.4 mm (-106.7 mm) the only year of the study that registered below average precipitation. During fall 2017 and 2018, the average precipitation was 20% below the 30-year historical average. In contrast, spring 2018 and 2019 average precipitation was 18 and 41% higher, respectively, compared to the 30-year historical average. In summer 2018 and 2019, the average precipitation was 5 and 2% below, respectively, compared to the 30-year historical average.

Sidney

Precipitation amounts at Sidney were above the 30-year average (454.1 mm), with 544.1 mm in 2018 and 690.6 mm in 2019 (Table 4-1). In 2017, the average precipitation was 438.9 mm (-12.2 mm), the only year of the study that registered below average precipitation. During fall 2017 and 2018, the average precipitation was only 6 and 3% below the 30-year historical average. In contrast, spring 2018 and 2019 average precipitation was 48 and 89% higher, respectively, compared to the 30-year historical average. Likewise, in summer 2018 and 2019, the average precipitation was 10 and 68% higher, respectively, than the 30-year historical average.

Cover Crop Biomass

Fall Biomass

Cover crop winter-sensitive and winter-hardy mixtures followed similar trends in terms of species composition. In both CC mixtures, there was a predominance of grass species (77 to 89%) in the CC fall biomass at all sites, followed by brassicas (5 to 16%) and then legumes (0 to 2%) (Table 4-3). Cover crop biomass in the fall differed among CC mixture treatments (p = 0.0315) where the winter-sensitive mix reached 16% more biomass than the winter-hardy mix in the fall. This is likely due the winter-sensitive species adaptability to higher temperatures of late summer and early fall as compared to winter-hardy species that grow more after the vernalization period (triticale). In addition, CC biomass differed according to site (p <.0001). North Platte achieved the highest CC biomass (average of 1934 kg ha^{-1}, winter-sensitive and winter-hardy mix combined), followed by Grant (1879 kg ha^{-1}), Sidney (1384 kg ha^{-1}) and Gothenburg (1181 kg ha^{-1}). The differences in sites can be justified by the earlier planting time and increased precipitation in North Platte compared to the other sites (Tables 4-1 and 4-2). The WSH was neither significant in any interaction nor as a main effect in CC fall biomass.

Table 4-3. Cover crop (CC) biomass and percentage of each species families (grass, legume and brassica) in cover crop winter-sensitive (WS) and winter-hardy (WH) mixtures in the fall and spring, and residue biomass at corn V6 development stage according to CC mixtures, winter wheat stubble height (WSH)†, and interaction sites with CCs. Sites in western Nebraska include Gothenburg, North Platte, Grant and Sidney. Years were included as random effects in the ANOVA model. Numbers followed by different uppercase letters represent statistical differences among main effects of CC and WSH, whereas lowercase letters represent statistical differences among main effects of sites with Tukey adjustment at the $p \leq 0.05$.

	CC Fall Biomass (kg ha^{-1})						CC Spring Biomass (kg ha^{-1})						Residue Biomass (kg ha^{-1})		
Cover Crops (CC)	Grass	Legume	Brassica	Mean total	SE +-		Grass	Legume	Brassica	Mean total	SE +-		Mean	SE +-	
Fallow	-	-	-	-	-		-	-	-	-	-		6259	390	B
WS	1753 (88.7%)	14 (0.8%)	209 (10.5%)	1976	120	A	-	-	-	-	-		6732	358	AB
WH	1436 (84.6%)	17 (1.1 %)	244 (14.3%)	1697	97	B	1519 (99.7%)	4 (0.3%)	0 (0%)	1523	149		7529	397	A
Winter Wheat Stubble Height (WSH)															
Short	-	-	-	1859	101		-	-	-	1610	121		6781	330	
Tall	-	-	-	1815	77		-	-	-	1449	123		6899	301	
Sites (S) x CC															
Gothenburg	*1181 (83.9%)*	*17 (1.4%)*	*208 (14.7%)*	*1406*	*92*	*c*	3186 (99.9%)	5 (0.1%)	0 (0%)	*3191*	*163*	*a*	*6513*	*414*	
Fallow	-	-	-	-	-		-	-	-	-	-		5845	565	B
WS	1307 (89.4%)	17.8 (1.4%)	160 (9.2%)	1485	150		-	-	-	-	-		5487	463	B
WH	1056 (85.5%)	16.1 (1.2%)	256 (13.2%)	1327	171		3186 (99.9%)	5 (0.1%)	0 (0%)	3191	163		8206	885	A
North Platte	*1934 (84%)*	*12 (0.6%)*	*356 (15.4%)*	*2302*	*118*	*a*	964 (99.8%)	3 (0.2%)	0	*967*	*49.3*	*b*	*6494*	*356*	
Fallow	-	-	-	-	-		-	-	-	-	-		4880	414	B
WS	2136 (88.8%)	6 (0.2%)	323 (10.9%)	2464	203		-	-	-	-	-		7177	643	A
WH	1672 (77.9%)	17.1 (0.9%)	389 (16.2%)	2139	205		964 (99.8%)	3 (0.2%)	0	967	49.3		7426	585	A
Grant	*1879 (90.2%)*	*16 (0.8%)*	*188 (9%)*	*2083*	*161*	*ab*	942 (99%)	3 (1%)	0 (0%)	*945*	*103*	*b*	*7194*	*605*	
Fallow	-	-	-	-	-		-	-	-	-	-		6934	1142	NS

WS	2093 (94.5%)	14.1 (0.4%)	167 (5.1%)	2275	337					-	-		6915	969	
WH	1664 (91%)	18.2 (0.7%)	209 (8.3%)	1891	207		942 (99%)	3 (1%)	0 (0%)	945	103		7734	1081	
Sidney	*1384 (88.9%)*	*17 (1.2%)*	*155 (9.9%)*	*1556*	*75.4*	*bc*	983 (96.8)	32 (3.2%)	0	*1015*	*49*	*b*	*7159*	*364*	
Fallow	-	-	-	-	-		-	-	-	-	-		7375	710	NS
WS	1475 (88%)	19.8 (1%)	185 (11%)	1680	140		-	-	-	-	-		7351	663	
WH	1295 (89.4%)	13.5 (1.1%)	124 (9.5%)	1433	116		983 (96.8)	32 (3.2%)	0	1015	49		6752	534	
							p-values								
S	-	-	-	**<.0001**			-	-	-	**<.0001**			0.371		
CC	-	-	-	**0.0315**			-	-	-	-			**0.0239**		
S x CC	-	-	-	0.9815			-	-	-	-			**0.0459**		
WSH	-	-	-	0.7353			-	-	-	0.2228			0.7636		
S x WSH	-	-	-	0.4119			-	-	-	0.9849			0.8378		
CC x WSH	-	-	-	0.6100			-	-	-	-			0.5046		
S x CC x WSH	-	-	-	0.8825			-	-	-	-			0.7985		

Abbreviations: WS, cover crop winter-sensitive mixture; WH, cover crop winter-hardy mixture; SE, standard error of the mean. †winter wheat short (26 cm) and tall (58 cm) stubble height.

Spring Biomass

Only the CC winter-hardy mixture survived the winter and produced biomass in the spring. Similar to fall, the CC winter-hardy mix had a predominance of grass species (96 to 99%) in the total CC biomass at all sites, followed by legumes (0 to 3%) (Table 3). As expected, brassicas did not survive the winter. Cover crop spring biomass was influenced by sites only (p <.0001) (Table 4-3). Cover crop winter-hardy biomass in the spring was approximately 3 times higher in Gothenburg (3186 kg ha^{-1}) than Grant (942 kg ha^{-1}), North Platte (964 kg ha^{-1}) and Sidney (983 kg ha^{-1}). The higher soil fertility (N, P and K values; Tables 4 and 5), higher average temperature and the increased precipitation amounts during the spring (especially in 2019) probably contributed for the higher biomass accumulation in Gothenburg compared to the other sites. In addition, planting winter-hardy species later in the fall (Gothenburg planting time was about one month later compared to the other sites; Table 4-2) could help the survival of winter-hardy species through the spring (Rosa and Werle, 2017). The WSH was neither significant in any interaction nor as a main effect in CC spring biomass.

Residue Coverage

The residue coverage biomass measured at corn V6 development stage was affected by the interaction among CC mixtures and sites (p = 0.0459) (Table 4-3). In Gothenburg, the CC winter-hardy mixture increased the residue biomass by approximately 2700 and 2400 kg ha^{-1} over CC winter-sensitive and fallow, respectively. In North Platte, both the CC winter-sensitive and winter-hardy mixture increased the residue biomass when compared to fallow (+47 and +52%, respectively). On the other hand, Grant and Sidney did not show effects of CC mixtures on the residue coverage biomass. The WSH was neither significant in any interaction nor as a main effect in the residue coverage biomass.

Soil Water Content

The soil water measurements analyses were separated by sites due to their different soil texture and precipitation patterns (Table 4-1 and 4-2). The interaction of CC mixtures and time in the season (early fall, late fall, early spring, late spring, early corn growth, mid corn growth, and corn harvest) affected the soil water content differently according to the sites and soil depths. However, the WSH was not significant in any interaction nor as a main effect in the soil water content at any site (Figures 4-2, 4-3, 4-4 and 4-5).

Gothenburg

In the late spring, the CC winter-hardy mixture reduced the soil water by approximately 25% compared to fallow and CC winter-sensitive mixture at 15 cm soil depth, and by 11% at 45 cm (Figure 4-2). However, in the first reading during the corn growing season (early corn growth), the CC winter-sensitive mixture increased soil water content by 20% in comparison to fallow at 45 cm soil depth. In the deeper soil layers (75, 105, 135, and 165 cm) the soil water values were not different throughout the CC and corn growing season, although there was a trend of higher values for fallow treatment compared to CC winter-sensitive and winter-hardy mixtures.

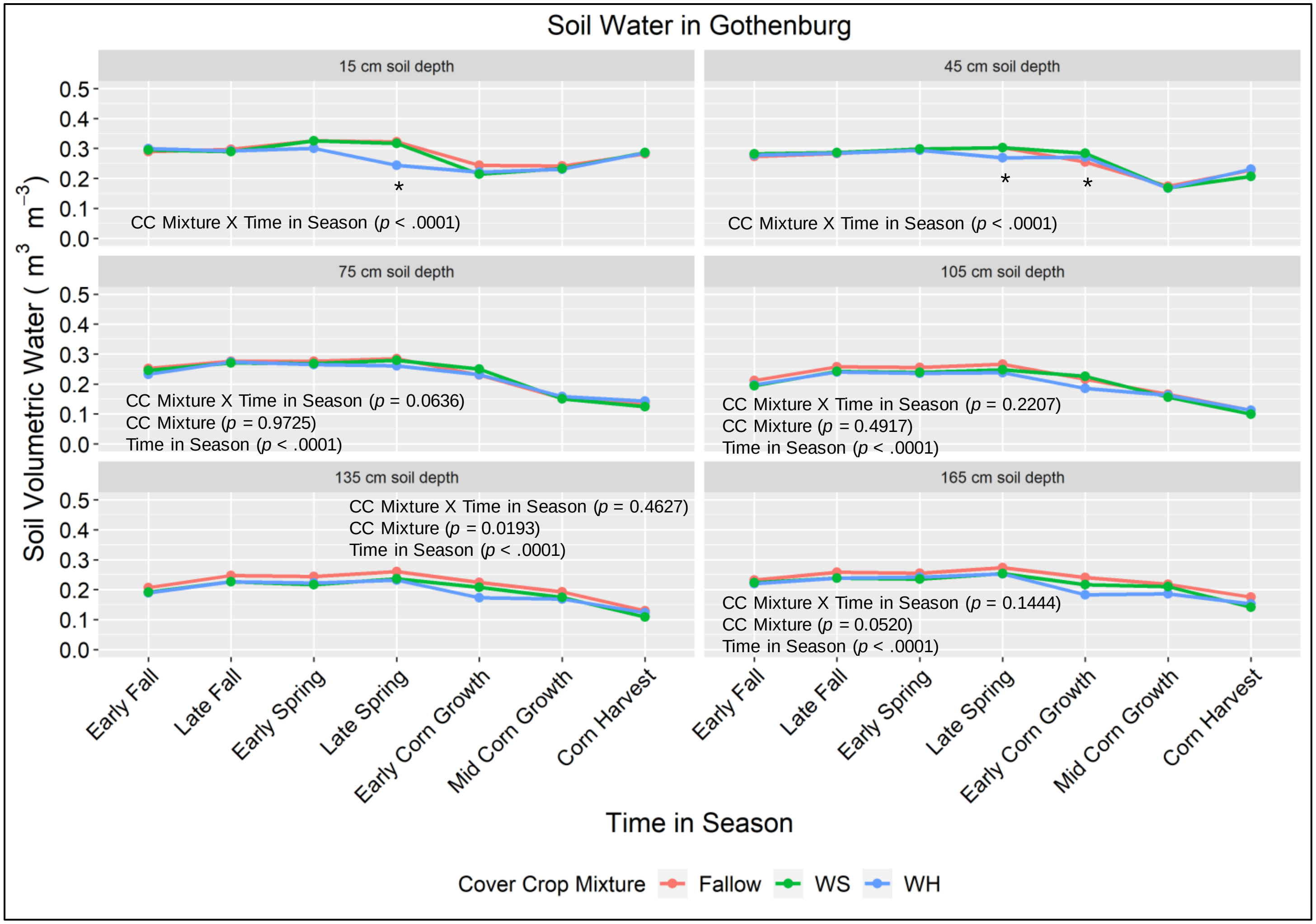

Figure 4-2. Soil volumetric water content (m^3 m^{-3}) at different soil depths (15, 45, 75, 105, 135, and 165 cm) in Gothenburg, NE pooled between years according to the interaction of cover crop (CC) mixtures and time during CC and corn growth season. Abbreviations: WS, cover crop winter-sensitive mixture; WH, cover crop winter-hardy mixture. * represents significant differences ($p \leq 0.05$) between CCs in that specific time in season.

North Platte

In the early fall, the CC winter-sensitive and winter-hardy mixture reduced the soil water at 15 cm soil depth by 37 and 27%, respectively, compared to fallow (Figure 4-3). In addition, at 45 cm soil depth, the soil water content under the CC winter-sensitive and winter-hardy mixtures was 20 and 15% lower, respectively, related to fallow. The CC winter-hardy mixture also reduced soil water content in 16% compared to fallow at 75 cm soil depth. In the late fall, the soil water differences among CC treatments showed up at deeper layers in the soil, with an incremented reduction especially by the CC winter-hardy mixture (Figure 4-3). At 75 cm soil depth, both the CC winter-sensitive and winter-hardy mixtures reduced soil water content in 18 and 22% as related to fallow. At 105 cm soil depth, only the CC winter-hardy mixture reduced soil water content (-20%) compared to fallow. Similarly, at 165 cm soil depth, the CC winter-hardy mixture reduced the soil water content (-19%) when compared to the fallow treatment.

Likewise, in the early spring, the soil water differences were found at 105 cm soil depth and deeper in the soil profile (Figure 4-3). At 105 cm soil depth, both the CC winter-sensitive and winter-hardy mixtures reduced soil water content in 15 and 20% as related to fallow. At 135 cm soil depth, only the CC winter-hardy mixture reduced soil water content (-18%) compared to fallow. Besides, at 165 cm soil depth, both the CC winter-sensitive and winter-hardy mixtures reduced soil water content in approximately 22% compared to fallow. In the late spring, the CC winter-sensitive and winter-hardy mixtures reduced soil water content by 21 and 25% compared to fallow at 165 cm soil depth (Figure 4-3). However, when measured at the time of corn harvest, the soil water content increased by 31% under CC winter-hardy mixture as compared to fallow treatment at 165 cm soil depth (Figure 4-3). Therefore, the effects of CCs on soil water could potentially impact the following crop in the rotation (e.g. field pea or winter wheat).

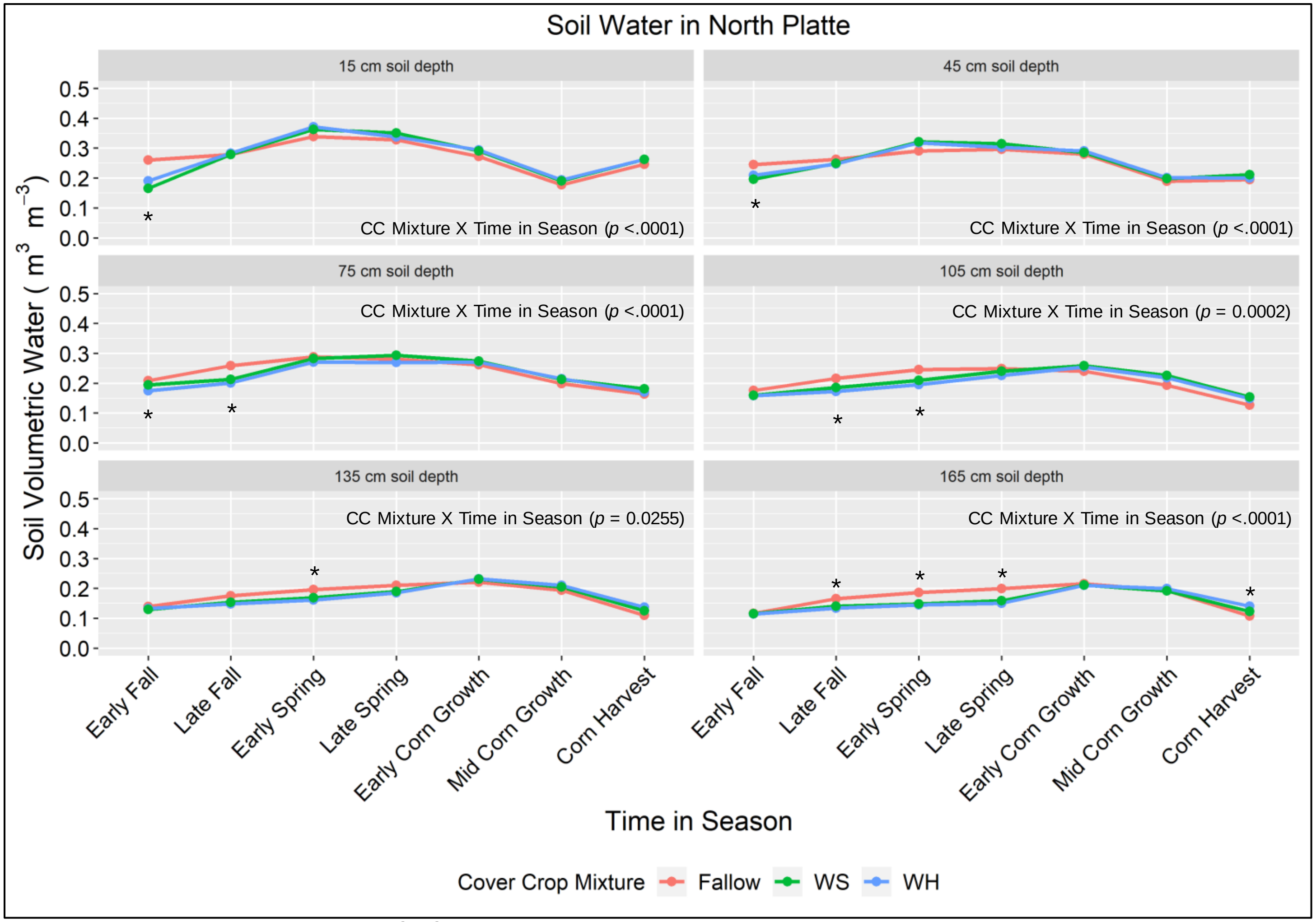

Figure 4-3. Soil volumetric water content (m^3 m^{-3}) at different soil depths (15, 45, 75, 105, 135, and 165 cm) in North Platte across years according to the interaction of cover crop (CC) mixtures and time during CC and corn growth season. Abbreviations: WS, cover crop winter-sensitive mixture; WH, cover crop winter-hardy mixture. * represent statistically significant differences ($p \leq 0.05$) between CCs in that specific time in season.

Grant

Differences in soil water content among CC treatments were observed only during CC growth (early fall, late fall, early spring, and late spring) in Grant (Figure 4-4). In the early fall, both CC winter-sensitive and winter-hardy mixtures reduced the soil water by 26 and 29%, respectively, compared to fallow at 15 cm soil depth, and by 15 and 20% at 45 cm soil depth. Likewise, in the late fall, at 15 cm soil depth both CC winter-sensitive and winter-hardy mixtures reduced the soil water by 24 and 29%, respectively, compared to fallow. The CC winter-sensitive and winter-hardy mixtures also decreased soil water content related to fallow by approximately 19% at 45 cm soil depth. In the early spring readings, soil water content was reduced by CC winter-hardy mixture by 5% related to fallow only at 45 cm soil depth. Similarly, in the late spring, only the CC winter-hardy mixture reduced soil water content, with 12% reduction compared to fallow at both 15 and 45 cm soil depths. In the deeper soil layers (75, 105, 135, and 165 cm) the soil water values were not different throughout the CC and corn growing season.

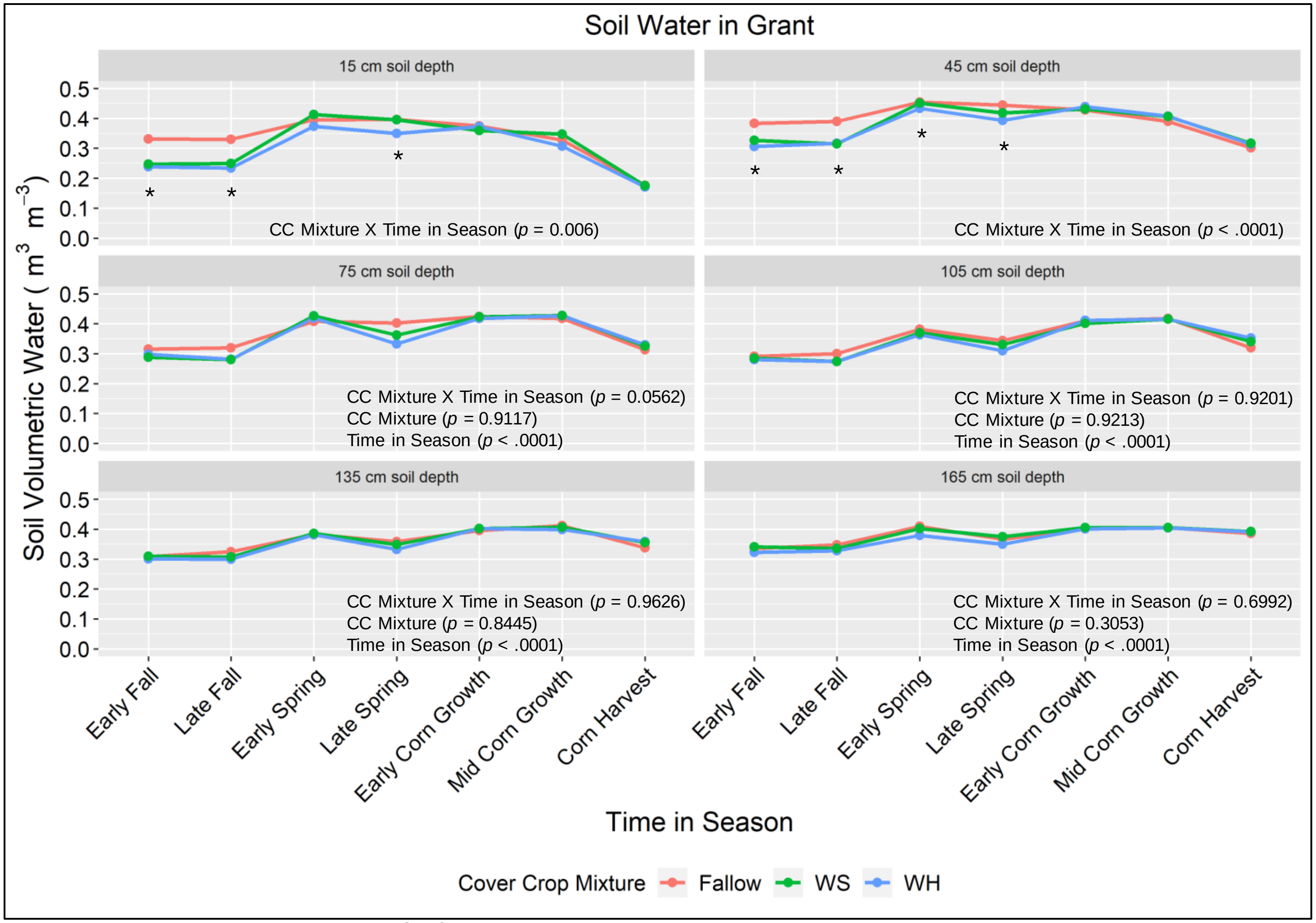

Figure 4-4. Soil volumetric water content (m^3 m^{-3}) at different soil depths (15, 45, 75, 105, 135, and 165 cm) in Grant across years according to the interaction of cover crop (CC) mixtures and time during CC and corn growth season. Abbreviations: WS, cover crop winter-sensitive mixture; WH, cover crop winter-hardy mixture. * represent statistically significant differences ($p \leq 0.05$) between CCs in that specific time in season.

Sidney

In the early fall, the CC winter-sensitive and winter-hardy mixture reduced the soil water at 15 cm soil depth by 41 and 38%, respectively, compared to fallow (Figure 4-5). In addition, at 45 cm soil depth, the soil water content under the CC winter-sensitive and winter-hardy mixtures was 23% lower related to fallow. In the late fall, the soil water differences among CC treatments appeared at all soil depths, except 105 cm soil depth (Figure 4-5). At 15 cm soil depth, the CC winter-sensitive and winter-hardy mixtures reduced soil water content by 32 and 22% as related to fallow. Moreover, at 45 cm soil depth, both the CC winter-sensitive and winter-hardy mixtures decreased soil water content by 25% when compared to fallow. Differently, at 75 cm soil depth, only the CC winter-hardy mixture reduced soil water content (-27%) compared to fallow.

Likewise, in the early spring, the soil water differences among CC treatments were detected at 15, 45 and 75 cm soil depths (Figure 4-5). The CC winter-sensitive mixture decreased soil water content by 14% at 15 cm, and 18% at 45 cm soil depth as related to fallow. However, at 75 cm soil depth, only the CC winter-hardy mixture reduced soil water content (-18%) compared to fallow. On the other hand, in the late spring, the CC winter-hardy mixture decreased the soil water content by 22 and 16% at 75 cm soil depth only when compared to fallow and CC winter-sensitive mixture, respectively (Figure 4-5). Lastly, at corn harvest, the soil water content was increased by 18% by CC winter-hardy mixture as compared to fallow (Figure 4-5).

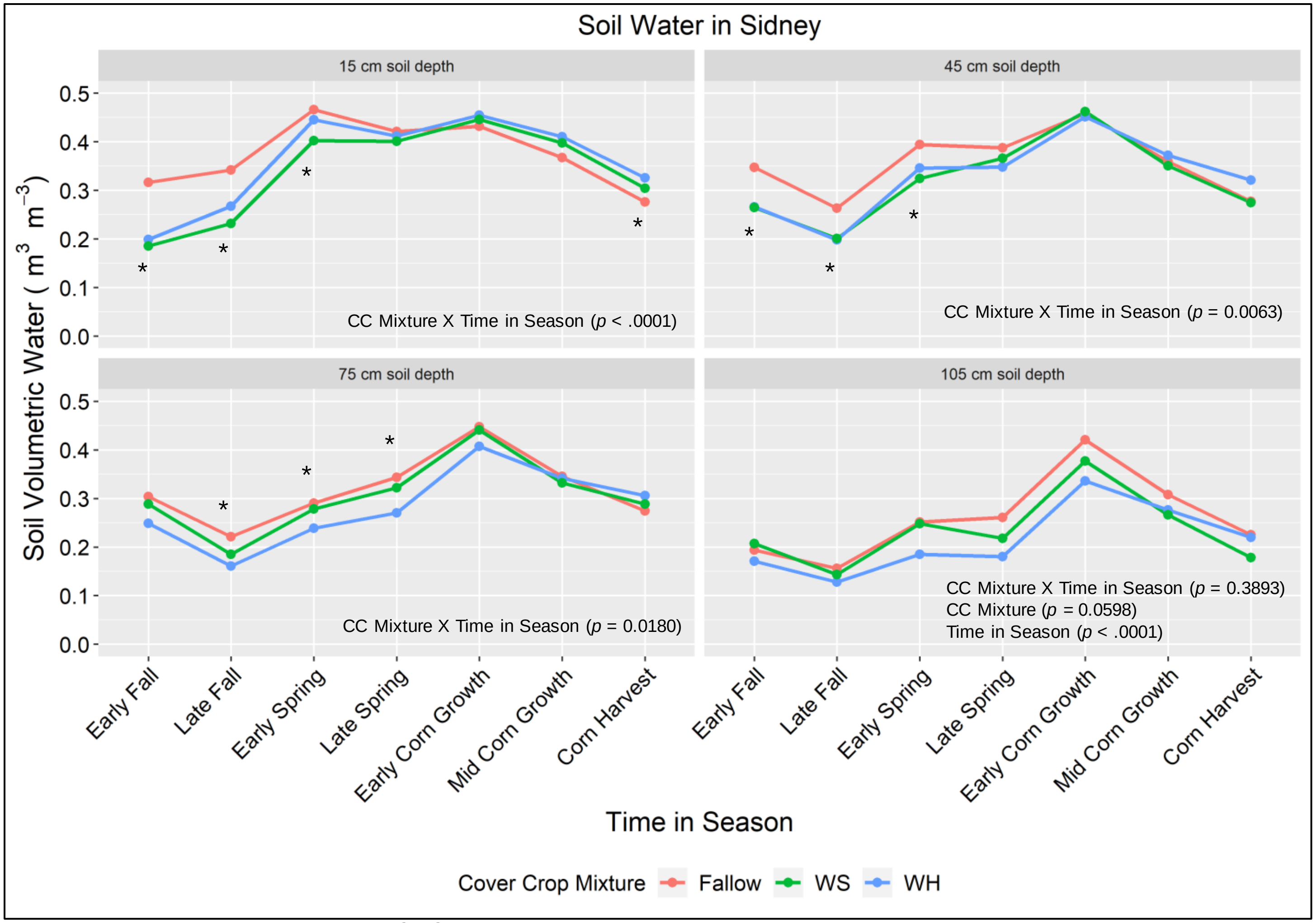

Figure 4-5. Soil volumetric water content (m^3 m^{-3}) at different soil depths (15, 45, 75, and 105 cm) in Sidney across years according to the interaction of cover crop (CC) mixtures and time during CC and corn growth season. Abbreviations: WS, cover crop winter-sensitive mixture; WH, cover crop winter-hardy mixture. * represent statistically significant differences ($p \leq 0.05$) between CCs in that specific time in season.

Soil Fertility and Chlorophyll Readings

Soil fertility data were analyzed by soil depth to access possible soil nutrient differences caused by CCs and/or WSH at each specific soil depth. The mean and standard errors for CC mixtures, WSH, sites and interaction effects on soil nitrate, soil P, soil K at 0-10 cm soil depth and chlorophyll readings are in Table 4-4, whereas the values for 10-20 cm soil depth are presented in Table 4-5.

At 0-10 cm soil depth, the soil nitrate levels changed according to the main effects of sites ($p < .0001$) (Table 4-4). Grant soil nitrate levels were 50, 115 and 145% higher than Gothenburg, Sidney and North Platte, respectively. Those differences were likely due to the nitrogen fertilization plan at each site (Table 4-2). However, there was no CC mixture or WSH effects on soil nitrate. Soil P was approximately 115% greater in Gothenburg and Grant, when compared to North Platte and Sidney (Table 4-4). On the other hand, soil P levels were influenced by the CC mixtures ($p = 0.0103$) (Table 4-4). Both the CC winter-sensitive and winter-hardy mixtures decreased soil P by 10% compared to fallow. Soil K differed according to sites ($p < .0001$) (Table 4-4). In Sidney, soil K levels were 26, 63 and 53% higher than Gothenburg, North Platte and Grant, respectively. Those differences were likely due soil mineralogy/fertility of each site. Similarly to soil nitrate, soil K levels were not affected by CC mixtures or WSH treatments at 0-10 cm soil depth.

At 10-20 cm soil depth, the CC winter-hardy mixture reduced soil nitrate by 18% compared to CC winter-sensitive and fallow (Table 4-5). Regarding differences among sites ($p < .0001$), the higher levels of nitrate in the soil were found in Grant (11 mg kg^{-1} NO_3-N), Gothenburg (8.4 mg kg^{-1} NO_3-N) and North Platte (8.3 mg kg^{-1} NO_3-N), and the lower levels in Sidney (5.3 mg kg^{-1} NO_3-N) (Table 4-5). Soil P and K were also affected by the sites ($p < .0001$) (Table 5). Soil P in Gothenburg was 46, 48 and 110% higher than Sidney, Grant and North Platte, respectively. In Sidney, soil K levels were 38, 61 and 70% higher than North Platte, Gothenburg and Grant, respectively.

There was a significant interaction effect of CC mixtures and sites regarding the chlorophyll readings ($p < .0001$). Within sites, the CC mixtures (both CC winter-sensitive and winter-hardy) reduced the chlorophyll reading values by 10 and 5% on average in Grant and North Platte, respectively, compared to fallow (Table 4-4). Likewise, in Sidney, the CC mixtures reduced the chlorophyll readings with the most detrimental impact by the CC winter-hardy followed by the CC winter-sensitive mixture. However, there was no differences in the chlorophyll readings in Gothenburg (Table 4-4). In addition, the WSH was neither significant in any interaction nor as a main effect in the soil fertility and chlorophyll readings at any site (Tables 4-4 and 4-5). The chlorophyll readings revealed that CCs likely induced nitrogen immobilization during corn reproductive stages across and within sites.

Table 4-4. Soil nitrate, total phosphorus and total potassium at 0-10 cm soil depth collected at corn V6 development stage, and corn leaf chlorophyll readings measured at corn R2 development stage according to cover crop (CC) mixtures, wheat stubble height (WSH)†, sites and the interaction of sites and CCs. Sites in western Nebraska include Gothenburg, North Platte, Grant and Sidney. Years are included as random effects in the ANOVA model. Numbers followed by different uppercase letters represent statistical differences among main effects of CC and WSH, whereas lowercase letters represent statistical differences among main effects of sites with Tukey adjustment at the $p \leq 0.05$.

	Soil Nitrate (mg kg^{-1} NO_3-N)			Soil Total Phosphorus (mg kg^{-1} P)			Soil Total Potassium (mg kg^{-1} K)			Chlorophyll Readings		
Cover Crops (CC)	Mean	SE +-		Mean	SE +-		Mean	SE +-		Mean	SE +-	
NCC	17.8	1.7		32.0	1.6	A	236.0	7.0		55.4	0.4	A
WS	18.5	1.7		28.7	1.5	B	238.0	7.1		52.8	0.5	B
WH	16.0	1.8		28.9	1.4	B	245.0	6.7		51.9	0.5	C
Winter Wheat Stubble Height (WSH)												
Short	17.4	1.4		29.8	1.2		239	5.3		53.4	0.4	
Tall	17.5	1.4		29.9	1.3		241	6.0		53.3	0.4	
Sites (S) x CC												
Gothenburg	*18.3*	*1.6*	*b*	*40.0*	*1.6*	*a*	*249*	*4.3*	*b*	*56.5*	*0.2*	*a*
NCC	16.9	1.9		43.7	2.9		241	6.6		57	0.2	NS
WS	18.6	2.6		38.6	2.9		248	9.4		56.8	0.3	
WH	19.3	3.6		37.8	2.3		257	6.0		55.6	0.4	
North Platte	*11.2*	*0.6*	*c*	*22.8*	*0.6*	*b*	*192*	*2.6*	*c*	*57*	*0.3*	*a*
NCC	13.5	1.2		24.2	0.9		187	3.6		58.6	0.3	A
WS	9.78	0.7		21.9	1.3		193	5.9		56.6	0.5	B
WH	10.3	0.8		22.1	0.9		197	3.7		55.8	0.4	B
Grant	*27.5*	*2.9*	*a*	*38.8*	*1.0*	*a*	*205*	*3.8*	*c*	*51.3*	*0.5*	*b*
NCC	29	5.0		41.3	1.8		203	5.9		54.6	0.4	A
WS	29.7	2.6		35.9	1.9		203	7.2		49.2	0.9	B
WH	23.7	3.6		39.1	1.3		209	6.8		50	1	B
Sidney	*12.8*	*1.1*	*c*	*18.0*	*0.7*	*c*	*313*	*5.2*	*a*	*48*	*0.5*	*c*
NCC	11.8	2.1		18.7	1.1		315	8.7		50.6	1	A

WS	16	2.1	18.5	1.3	310	10.5	47.9	0.6	B
WH	10.5	1.0	16.8	1.1	315	8.4	45.3	0.6	C
					p-values				
S	**<.0001**		**<.0001**		**<.0001**		**<.0001**		
CC	0.0824		**0.0103**		0.1424		**<.0001**		
S x CC	0.1332		0.6949		0.9581		**<.0001**		
WSH	0.985		0.9939		0.8789		0.7621		
S x WSH	0.4227		0.3781		0.4384		0.2569		
CC x WSH	0.4384		0.5465		0.6432		0.4036		
S x CC x WSH	0.7531		0.8562		0.8857		0.4267		

Abbreviations: WS, cover crop winter-sensitive mixture; WH, cover crop winter-hardy mixture; SE, standard error of the mean. †winter wheat short (26 cm) and tall (58 cm) stubble height.

Table 4-5. Soil nitrate, total phosphorus and total potassium at 10-20 cm soil depth collected at corn V6 development stage, and corn leaf chlorophyll readings measured at corn R2 development stage according to cover crop (CC) mixtures, wheat stubble height (WSH)†, sites and the interaction of sites and CCs. Sites in western Nebraska include Gothenburg, North Platte, Grant and Sidney. Years are included as random effects in the ANOVA model. Numbers followed by different letters represent statistical differences among main effects with Tukey adjustment at the $p \leq 0.05$.

	Soil Nitrate ($mg\ kg^{-1}\ NO_3$-N)			Soil Total Phosphorus ($mg\ kg^{-1}$ P)			Soil Total Potassium ($mg\ kg^{-1}$ K)		
Cover Crops (CC)	Mean	SE +-		Mean	SE +-		Mean	SE +-	
NCC	8.7	0.8	A	17.3	1.3		188	5.8	
WS	8.8	0.6	A	16.2	1.1		184	5.5	
WH	7.2	0.7	B	16.1	1.0		186	5.5	
Winter Wheat Stubble Height (WSH)									
Short	8.0	0.5		16.2	0.9		185	4.6	
Tall	8.5	0.6		16.8	0.9		187	4.6	
Sites (S)									
Gothenburg	8.4	0.5	A	23.3	1.8	A	157	2.87	C
North Platte	8.3	0.6	A	11.1	0.4	C	184	2.71	B
Grant	11.0	1.3	A	15.7	0.8	B	149	2.17	D
Sidney	5.3	0.3	B	16.0	1.1	B	253	2.39	A
				p-values					
S	**<.0001**			**<.0001**			**<.0001**		
CC	**0.0387**			0.6336			0.6814		
S x CC	0.7842			0.9887			0.8288		
WSH	0.474			0.5607			0.5787		
S x WSH	0.2026			0.8018			0.9955		
CC x WSH	0.4179			0.7897			0.5717		
S x CC x WSH	0.8716			0.9838			0.6771		

Abbreviations: WS, cover crop winter-sensitive mixture; WH, cover crop winter-hardy mixture; SE, standard error of the mean. †winter wheat short (26 cm) and tall (58 cm) stubble height.

There were positive correlations between soil nitrate and corn grain yield at both 0-10 (R = 0.16, p = 0.031) and 10-20 cm (R = 0.28, p <.0001) soil depths (Figure 4-6). In addition, soil P at 0-10 (R = 0.51, p <.0001) and 10-20 cm (R = 0.27, p = 0.0002) soil depth were positively correlated with corn grain yield. The chlorophyll readings were also positively correlated (R = 0.70, p <.0001) with corn grain yield. Although the correlations of soil nitrate and soil P with corn grain yield were significant at both depths, their correlation coefficients at 10-20 cm and 0-10 cm soil depth were higher. These results corroborate with the ANOVA in Tables 4-4 and 4-5. Therefore, based on the ANOVA and Pearson correlation coefficients, soil nitrate at 10-20 cm, soil P at 0-10 cm soil depth, and chlorophyll readings were affected by CC mixtures and correlated to corn grain yield.

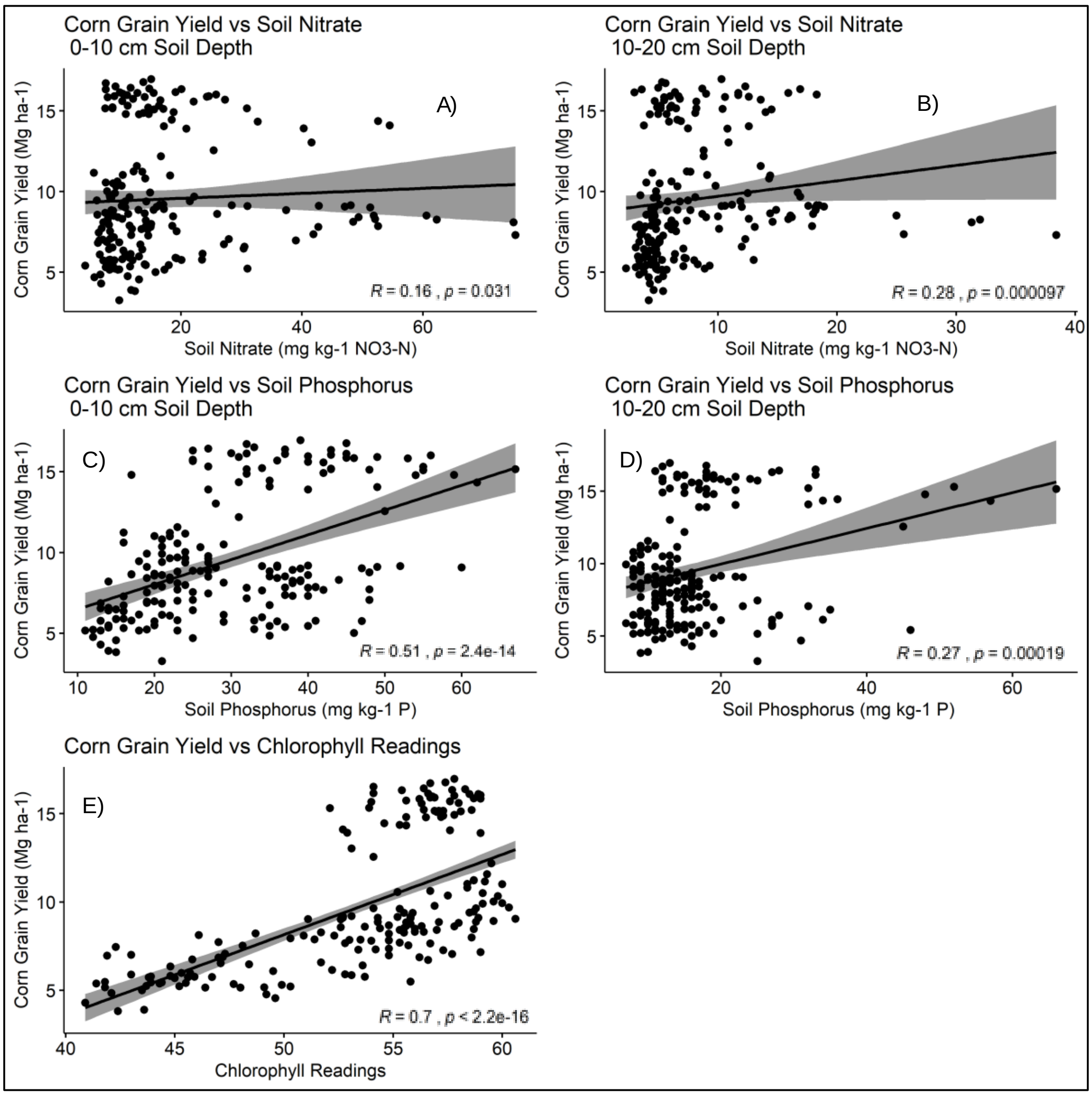

Figure 4-6. Pearson correlations of soil nitrate (A and B) and phosphorus (C and D) collected at corn V6 development stage at 0-10 and 10-20 cm soil depth, and chlorophyll readings (E) at corn R2 development stage with corn grain yield for all data points across sites (Gothenburg, North Platte, Grant and Sidney) and years (2017-2018 and 2018-2019). Shaded area represents the confidence interval of 95% of the regression line.

Corn Grain Yield and Yield Components

Corn grain yield results were influenced by the interaction of CCs and sites (p = 0.0094). Cover crops decreased subsequent corn grain yield in western Nebraska, except in Gothenburg (Table 4-6) where the CC mixture treatments (winter-sensitive and winter-hardy) reached similar yields as the fallow treatment. However, at the other sites the CC winter-hardy mixture decreased corn grain yield compared to fallow. In Grant, both CC mixtures decreased corn grain yield by 13% compared to fallow. In North Platte, the CC winter-sensitive and winter-hardy mixtures reduced corn grain yield by 12 and 16%, respectively, compared to fallow. In Sidney, however, the CC winter-sensitive mixture did not reduce corn grain yield but the CC winter-hardy mixture severely decreased corn grain yield (-23%) when compared to fallow. Comparing the sites, corn grain yield followed a geographic pattern going from east to west in Nebraska, which is associated with higher to lower precipitation amounts in each site (Tables 4-1 and 4-6). Therefore, the highest corn grain yield was observed in Gothenburg, followed by North Platte, Grant and Sidney. In addition, the corn grain yield was likely influenced by soil fertility (nitrate, P and K levels) of each site (Tables 4-4 and 4-5). Thus, with increased precipitation and overall higher soil fertility compared to the other sites, Gothenburg reached greater corn grain yields compared to North Platte, Grant and Sidney.

Table 4-6. Corn grain yield and yield components (corn plant population, number of kernels per ear, and 100 count kernel weight) according to cover crop (CC) mixtures, winter wheat stubble height (WSH)[†], and interaction of sites with CCs. Sites in western Nebraska include Gothenburg, North Platte, Grant and Sidney. Years are included as random effects in the ANOVA model. Numbers followed by different uppercase letters represent statistical differences among main effects of CC and WSH, whereas lowercase letters represent statistical differences among main effects of sites with Tukey adjustment at the $p \leq 0.05$.

	Corn Grain Yield (Mg ha^{-1})			Corn Plant Population (plants ha^{-1})			Kernels per Ear			100-Kernel Weight (g)		
Cover Crops (CC)	Mean	SE +-		Mean	SE +-		Mean	SE +-		Mean	SE +-	
Fallow	10.2	0.4	A	40949	1503		674	10	A	33	0.6	A
WS	9.4	0.5	B	40970	1478		654	10	AB	32	0.7	B
WH	8.9	0.5	C	40269	1542		638	11	B	31	0.6	C
Stubble Height (SH)												
Short	9.5	0.4		40230	1230		651	8		31.8	0.5	
Tall	9.6	0.4		41232	1225		660	9		32.1	0.5	
Sites (S) x Cover Crop (CC)												
Gothenburg	*15.4*	*0.1*	*a*	*59848*	*555*	*a*	*680*	*10.4*	*b*	*37.8*	*0.5*	*a*
Fallow	15.7	0.2	NS	59767	1017	NS	689	20.3	NS	38	0.9	NS
WS	15.5	0.2		59962	1019		682	17.6		38.1	1	
WH	14.9	0.3		59815	905		670	16.4		37.4	0.8	
North Platte	*9.4*	*0.2*	*b*	*33431*	*655*	*c*	*647*	*5.1*	*c*	*33.5*	*0.4*	*b*
Fallow	10.4	0.2	A	32623	1192	NS	662	6.8	NS	35.7	0.6	A
WS	9.2	0.3	B	33555	1162		650	9.1		33.4	0.5	B
WH	8.7	0.2	B	34064	1095		627	8.6		31.3	0.6	C
Grant	*7.5*	*0.2*	*c*	*33687*	*902*	*c*	*728*	*10.9*	*a*	*28.3*	*0.6*	*c*
Fallow	8.2	0.2	A	34670	1588	NS	753	12.4	NS	28.7	0.7	NS
WS	7.1	0.4	B	34600	1249		720	19.7		27.9	1.2	
WH	7.2	0.4	B	31791	1792		711	22.6		28.4	1.1	
Sidney	*5.9*	*0.1*	*d*	*35795*	*369*	*b*	*567*	*6.33*	*d*	*28.3*	*0.3*	*c*
Fallow	6.6	0.2	A	36215	639	NS	593	10.4	NS	29.5	0.4	A

WS	6.0	0.2	AB	35762	736	565	8.8	28.4	0.4	AB
WH	5.0	0.2	B	35408	557	544	10.4	27	0.4	B
					p-values					
S	**<.0001**			**<.0001**		**<.0001**		**<.0001**		
CC	**<.0001**			0.557		**0.0029**		**<.0001**		
S x CC	**0.0094**			0.3531		0.948		**0.0025**		
WSH	0.3687			0.2018		0.3004		0.3829		
S x WSH	0.9506			0.9683		0.8752		0.9826		
CC x WSH	0.8572			0.568		0.8907		0.9883		
S x CC x WSH	0.7539			0.6121		0.9652		0.6983		
					Pearson Correlation Coefficients					
Corn Grain Yield (Mg ha^{-1})	1			**R = 0.63 (*p* <.0001)**		**R = 0.45 (*p* <.0001)**		**R = 0.82 (*p* <.0001)**		

Abbreviations: WS, cover crop winter-sensitive mixture; WH, cover crop winter-hardy mixture; SE, standard error of the mean; NS, not significant. †winter wheat short (26 cm) and tall (58 cm) stubble height.

Corn plant population was only affected by the main effect of sites (*p* <.0001). Gothenburg had higher corn plant population, followed by Sidney, Grant and North Platte (Table 4-6). This result was expected based on the corn seeding rates used at each site (Table 4-2). The number of kernels per ear was affected by the main effects of CCs and sites (Table 4-6). The CC winter-sensitive treatment reached similar number of kernels per ear as the fallow. However, the CC winter-hardy mixture reduced the number of kernels per ear by 5% compared to fallow. Regarding sites, the number of kernels per ear were higher in Grant, followed by Gothenburg, North Platte and Sidney. Differently, the 100-kernel weight was affected by the interaction of CCs and sites (Table 4-6). In North Platte, the CC winter-hardy mixture decreased the 100-kernel weight by 6 and 12% compared to CC winter-sensitive and fallow, respectively. Similarly, the CC winter-sensitive mixture reduced the 100-kernel weight by 6% compared to fallow. In Sidney, the 100-kernel weight decreased by 8% under the CC winter-hardy mixture when compared to fallow. Yet, there were no differences in the 100-kernel weight among CC mixtures in Gothenburg and Grant. Thus, in general, the CC winter-hardy mixture had the most detrimental impact in corn grain yield and yield components. The WSH was neither significant in any interaction nor as a main effect in the corn grain yield and yield components.

Discussion

In semi-arid regions such as western Nebraska, precipitation amounts affect most aspects of crop production. During the two growing seasons of this study, the average precipitation was above the 30-year historic which certainly affected the response variables measured. It is important to note that the precipitation distribution during the year can dictate CC management practices in semi-arid Nebraska. If CCs are planted after winter wheat harvest, producers must consider that precipitation in the fall is historically limited, and that the bulk of the precipitation happens late in the spring and early summer (Table 4-1). Therefore, excessive CC growth in the fall (CC winter-sensitive and winter-hardy mixtures) can reduce soil water content during that period, but precipitation in the spring may recharge soil water in the surface layers for subsequent crops (Figures 4-2, 4-3, 4-4, and 4-5). However, CC winter-hardy mixtures accumulate biomass in the spring at an expensive cost of using soil water both in the fall and spring, especially from deep soil layers (15-45 cm soil depth and deeper in the soil profile). Thus, even with above normal precipitation patterns, this study showed lower corn grain yield with CC treatments. Our results showed that CCs depleted soil water from deep soil layers during early and late fall, and early and late spring (Figures 4-2, 4-3, 4-4 and 4-5). Therefore, the effects of soil water depletion on corn were likely early in the season (from corn emergence to V10 development stage) affecting the formation of the number of kernels per ear (Table 4-6). Ear formation in corn is known to happen around V6-V7 development stage (Stevens et al., 1986). In a previous study, Claassen and Shaw (1970) observed a 12 to 15% yield reduction in corn after water stress occurred during the V6 corn development stage. In addition, the above normal precipitation observed in all sites also helps to explain the lack of difference among the WSH management. However, in a study conducted in North Dakota, Bauer and Tanaka (1986) observed an increment in soil water storage of 33 mm by increasing wheat stubble cut height from 10 to 36 cm. Hence, the WSH had no impact in soil water, but results could have been different in drier years.

Cover crop winter-sensitive and winter-hardy mixtures increased soil residue coverage compared to fallow treatment (Table 4-3). The higher soil residue promoted by CCs and above average precipitation probably contributed to the lack of differences in soil water during corn growing season between CCs and fallow coverage in Gothenburg and Grant, and the decreased soil water under fallow plots in North Platte and Sidney. High soil residue coverage has been documented to reduce evaporation, reducing soil water loss (Nielsen et al., 2005), especially under high temperatures during summer. Moreover, CCs can contribute to increased soil water infiltration (Blanco-Canqui, 2018), which likely occurred in North Platte during late corn development stages under CC winter-hardy mixtures (Figure 4-3). This can be beneficial for the water balance of subsequent crops (e.g. field peas and winter wheat). However, the improved residue coverage in the soil promoted by CC mixtures also induced N immobilization in corn. Both soil and plant measurements showed reduced N levels under CC treatments when compared to fallow (Tables 4-4 and 4-5). Although the CC mixtures presented legume and brassica species, the majority of the biomass collected was from grasses (Table 4-3). The grass enriched species in the mixtures likely contributed for N immobilization as the C:N ratio of those species is higher (particularly as they reach reproductive stages) than legumes and brassicas which increase their decomposition time (Blanco-Canqui et al., 2015). Therefore, there might be a lack of synchrony in the N release by CCs and the corn N demands at key grow developmental stages such as corn V4-V5 (potential number of kernels per ear are formed) and VT-R1 (number of kernels per ear are defined) (Abendroth et al., 2011). Previous studies also documented N immobilization in corn following CCs to occur during corn V6 to VT development stage (Nevins et al., 2020). Reduced N and P levels likely contributed to the reduced 100-kernel weight in North Platte and Sidney (Table 4-6). Any corn plant stress at grain filling period may reduce kernel weight due to reduced starch accumulation (Abendroth et al., 2011).

The geographic pattern going from east to west in Nebraska is not only associated with higher to lower precipitation amounts in each site, but also with corn grain yields. Gothenburg has a greater average annual precipitation and, consequently, higher corn grain yield potential that the other studied sites. This also allows an increased seed rate/corn population which increases the corn grain yield potential. Sidney, for example, due to its historical lower precipitation, has lower corn yield potential as compared to the other sites studied. Despite showing similar yields of CC winter-sensitive and fallow, Sidney showed the biggest detrimental impacts by CC winter-hardy mixture use (-23% corn yield).

From a grain yield perspective, the results of this study do not support the adoption of CCs in western Nebraska. However, the lack of differences among CCs and fallow plots in Gothenburg reinforces the argument that CCs may fit in certain climates with more precipitation accumulation. Hence, Gothenburg is more suitable to CC adoption than the other studied sites. A review study showed neutral impact of winter CCs in environments where water was not a limiting factor (Marcillo and Miguez, 2017). As the precipitation gradient decreases from east to west in the Great Plains, considerations about CC use in semi-arid regions should follow similar criteria to minimize risk of decreasing rainfed corn yields.

Conclusions

The findings from this study emphasize the soil water dynamics by CCs in semi-arid regions of the Great Plains. Cover crop winter-sensitive and winter-hardy mixtures induced soil water depletion compared to fallow during CC growing season, especially at deeper soil layers. On the other hand, the WSH management did not affect soil water at any time in the season. A poor stand (and consequently low biomass production) of legume and predominance of grass CC species in the CC mixes was observed in this study, which probably lead to reduced N levels in the soil and corn plants. Perhaps a legume rich CC mixture could improve nitrogen fixation and cycling alleviating N immobilization in corn. In addition, CC mixtures reduced soil P content in the 0-10 cm soil depth. Consequently, CC mixtures reduced corn grain yield and yield components at all sites, except Gothenburg. The high corn yield potential and increased precipitation pattern at Gothenburg reduced the risk of detrimental impacts of CCs in subsequent corn. Therefore, CC use in semi-arid environments without risks to subsequent corn grain yield is limited. Our findings suggest that the reduced water availability during early corn development stages combined with N and P reductions in the soil were the main detrimental effects of CCs that affected corn grain yield.

Cover crops can help with weed management programs (short-term benefit), and increase nutrient cycling (long-term benefit) over the years. However, in the short term during initial stages of adoption, CCs may be detrimental for dryland crop production in western Nebraska. Understanding the objective for growing CCs in such environments is of extreme importance. Producers must evaluate what type of benefits and risks CCs can bring to the crop rotation. Winter-sensitive CC species are an alternative for growers that might want to control winter annual weeds and have an extra income through grazing. On the other hand, CC winter-hardy species may help on summer annual weed suppression and soil erosion reduction. However, both CC mixtures use soil water in superficial and deep soil layers decreasing subsequent rainfed corn grain yield during the initial years of adoption (Rosa et al., 2019).

Although there was no evidence of positive or negative effects of WSH in this study, we understand that this practice helps winter wheat producers to harvest faster with a stripper header, and may also help to manage water (increase snow capture and reduce water evaporation) in drier years as compared to the ones in this study. However, likely due to above normal precipitation amounts, this study neither found any evidence of the impact of WSH in any of the variables evaluated, nor that WSH could minimize the effects of soil water use by CCs. Producers should prioritize as much as possible soil residue cover, increase snow retention, and consequently preserve soil moisture for following crops.

Future research should be conducted to evaluate WSH and CCs in dry/normal precipitation years to elucidate those questions. Moreover, future studies should evaluate the long-term effect of CCs in semi-arid cropping systems, looking to mitigate N immobilization issues, and minimize the risks of soil water use. Also, it is necessary to gain a better understanding of the synchrony of N cycling back to the soil and quantify the extra residue coverage brought by CCs in reducing water evaporation prior and during the corn growing season. Hence, this study aid to develop recommendations for WSH and CC management that optimize soil water use and overall productivity of rainfed cropping systems of semi-arid environments of the Great Plains during initial stages of CC adoption.

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CHAPTER 5: SUMMARY AND GENERAL CONCLUSIONS

With the increased popularity of cover crops (CC) across the United States it is imperative to study its positive and negative effects within the variety of cropping systems. Producers of winter wheat-corn-fallow rotations in semi-arid regions rely on strategies that enhance soil water retention to sustain agronomically and economically their cropping systems. Lately, the inclusion of CCs after winter wheat raised questions whether CCs could be beneficial suppressing weeds, reducing soil erosion and increasing soil residue cover. However, there is a major concern that CCs may also deplete soil water and reduce nitrogen in the soil for the subsequent crop. Therefore, our findings emphasize the importance of CC management practices when adopting CCs in semi-arid rainfed cropping systems of western Nebraska. In this sense, producers should have clear objectives when incorporating CCs into their cropping system. Three studies were conducted is western Nebraska to study the impact of CC planting and termination time (study 1), CC species selection (study 2), and CC mixes and wheat stubble management (study 3) on the subsequent corn yield.

In the first study, planting CCs early in the fall increased CC biomass production in the fall and early in the spring. Thus, if the goal is fall grazing CCs, early fall planting of CC winter-sensitive species would be the best stratetegy. However, if the objective is to produce more CC biomass late in the spring, then the CC planting time is not of such importance, but CC winter-hardy species should be used as they survive winter conditions. The late termination of CCs promoted greater soil residue cover which helped on summer annual weed suppression. In addition, our results showed trends that soil respiration, organic matter and soil carbon might improve with the long-term adoption of CCs, fostering healthier soils in semi-arid cropping systems. However, late terminated CCs in the spring reduced soil water content at the time of corn planting. Moreover, CCs reduced nitrogen availability in the soil for the subsequent corn crop, especially when CCs were terminated late in the spring. Cover crops reduced corn grain yield regardless of CC planting and termination time. However, planting CC late in the fall and terminating them early in the spring minimized their detrimental impacts on corn yield.

In our second study, cereal rye was the most impactful CC species. Cereal rye ability to produce biomass in the fall and spring was important to promote weed suppression of up to 89% compared to fallow treatments. At the same time, our CC species study did not find any positive or negative effect of CCs in soil water from 0 to 20 cm soil depth and penetration resistance, except for cereal rye. Cereal rye increased soil penetration resistance from 20 to 30 cm soil depth likely because of soil water use beyond 0 to 20 cm soil depth. Consequently, cereal rye had the most negative impacts on corn grain yield and yield components. If producers chose to plant cereal rye, they must be aware of cereal rye's weediness potential in winter wheat and its negative impacts on corn yield. On the other hand, spring oats reached similar yields as the fallow treatment, which probably makes spring oats the best CC species (amongst the ones studies herein) option for producers to grow under water-limited environments.

On the third study, CC winter-sensitive and winter-hardy mixtures induced soil water depletion compared to fallow during CC growing season, especially at deeper soil layers (45 cm and deeper). On the other hand, the winter wheat stubble (WSH) management did not affect soil water at any time in the season. A poor stand (and consequently low biomass production) of legume and predominance of grass species in the CC mixes was observed, which probably lead to reduced N levels in the soil and corn plants. Perhaps a legume rich CC mixture could improve nitrogen fixation and cycling alleviating N immobilization in corn. In addition, CC mixtures reduced soil P content in the 0-10 cm soil depth. Consequently, CC mixtures reduced corn grain yield and yield components at all sites, except at Gothenburg. The high corn yield potential and higher precipitation at Gothenburg reduced the risk of detrimental impacts of CCs in subsequent corn. Therefore, CC use in semi-arid environments without risks to subsequent corn grain yield is limited. Our findings suggest that the reduced water availability during early corn development stages combined with N and P reductions in the soil were the main negative effects of CCs that reduced corn grain yield.

Although the majority of the variables evaluated in these studies showed negative impacts of CCs, there is a potential to include CCs in semi-arid cropping systems and minimize the risks of severe economic loss. Producers must evaluate what type of benefits and risks CCs can bring to the crop rotation. Winter-sensitive CC species are an alternative for growers that might want to control winter annual weeds and have an extra income through grazing. On the other hand, winter-hardy CC species may help with summer annual weed suppression and soil erosion reduction. However, both CC winter-sensitive and winter-hardy species use soil water in superficial and deep soil layers, and will likely decrease subsequent rainfed corn grain yield during the initial years of adoption. Reducing the CC growing window at least in the first years of implementation might be the best strategy to establish a successful CC system in western NE. Also, align the producer goals with the CC management practices is necessary when growing CCs in semi-arid cropping systems. Strategies to mitigate soil water reduction at the beginning of the corn growing season and N immobilization towards V6 to R1 development stage are key to minimize corn grain yield loss due to CC adoption in western Nebraska.

Our findings did not show any evidence of positive or negative effects of winter wheat stubble management (WSH) in this study. However, we understand that keeping tall winter wheat stubble might help producers to harvest winter wheat faster with a stripper header, and also to manage water (increase snow capture and reduce water evaporation) in drier years as compared to the ones in these research projects. However, likely due to above-normal precipitation amounts, the CC and WSH management study neither found any evidence of the impact of WSH in any of the variables evaluated, nor that WSH could minimize the effects of soil water use by CCs. Yet, winter wheat stubble should be cut as high as possible to promote soil residue cover, increase snow retention, and consequently preserve soil moisture for the following crops.

Future studies should evaluate the long-term effect of CCs in semi-arid cropping systems, looking to different ways to mitigate N immobilization issues and minimize the risks of soil water use. Also, it is necessary a better understanding of the synchrony of N cycling back to the soil, as well as quantify the extra residue coverage promoted by CCs in reducing water evaporation prior and during the corn growing season. Evaluating different legume CC species as well as its establishment may help on N contribution through N fixation. In addition, researchers must focus on evaluating WSH and CCs in dry/normal precipitation years to elucidate questions regarding soil water depletion. Hence, these studies will aid to develop initial recommendations for CC and WSH management that optimize soil water use, weed suppression, soil quality, and overall productivity of rainfed cropping systems of semi-arid environments during initial stages of CC adoption.