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Contributions of individual cover crop species to rainfed maize production in semi-arid cropping systems

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Contributions of individual cover crop species to rainfed maize production in semi-arid cropping systems

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ABSTRACT

Cover crop (CC) species selection can contribute to reducing soil penetration resistance (brassica species), improved soil nitrogen (N) cycling (legume species), and suppression of weeds (grass species). However, one of the main concerns about including CCs in water-limited environments is soil water use and the consequences to subsequent crops. To determine the effects of individual CC species under water-limited environments, we evaluated fall and spring CC biomass produced, and soil water and N content, penetration resistance, weed density and biomass during the maize growing season, and maize grain yield. The experiment was conducted under a winter wheat-maize-fallow rotation at two locations (North Platte and Grant, NE) during 2016−2017 and 2017−2018 (four site-years). Treatments consisted of seven popular CC species plus a control (fallow), planted after winter wheat harvest. Spring oats, Siberian kale, and purple top turnip produced greater fall biomass, while cereal rye produced the greatest amount of spring biomass. However, cereal rye reduced soil volumetric water content in North Platte 2016−2017 and increased soil penetration resistance from 20–30 cm soil depth across site-years likely due to soil water use. Spring cover crop growth suppressed weeds early in the maize growing season. Due to its aboveground biomass production, cereal rye decreased weed density and biomass by 80 and 88 %, respectively, compared to the fallow treatment. On the other hand, except for brassicas, CCs decreased N levels in the soil during maize growing season, and all CC species reduced maize grain yield up to 30 % compared to fallow (except spring oats). Spring oats can be an alternative to cereal rye as CC species for semi-arid regions. However, since CCs did not promote any maize yield gain, our findings suggest that producers should use caution when incorporating CCs in their cropping systems in water-limited environments. This research provides valuable information on the potential impact of CCs on rainfed maize production, as well as help producers and agronomists develop better CC management programs for cropping systems in semi-arid regions.

1. Introduction

Cover crops are becoming popular among US row crop producers that pursue more sustainable production practices. 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 primary goal(s) for planting the CCs. Winter-sensitive CC species are frost-killed during winter, which limits their growth to the fall. On the other hand, winter-hardy CC species can survive winter temperatures and accumulate biomass in the fall and spring. Cereal rye (*Secale cereale* L.) is one of the most popular CCs grown in maize (*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,

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Abbreviations: CC(s), cover crop(s); N, nitrogen; FC, field capacity; PWP, permanent wilting point.

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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 potential alternatives 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 is an attribute of grass CCs.

Leguminous species such as hairy vetch (*Vicia villosa*) (winter-hardy) and balansa clover (*Trifolium michelianum* Savi) (winter-sensitive) can fix atmospheric N (N_2) in the soil, potentially supplying N to the subsequent crop (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 loosen the surrounding soil by creating channels with vertical and horizontal growth throughout the soil. These channels may allow for enhanced water infiltration, thus reducing soil erosion.

In semi-arid climates (250–700 mm annual precipitation) of the Central Great Plains (Gallart et al., 2002), no-till winter wheat (*Triticum aestivum* L.)-maize-fallow is the main crop rotation strategy (two grain crops in a three year period). This rotation has two fallow periods: one between winter wheat harvest and maize planting, and another between maize 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 maize planting, which would allow the other fallow period (between maize harvest and winter-wheat planting) to be cultivated with 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 depend upon CC species selection. Winter-sensitive CC (e.g., oats, spring triticale, clover, kale, and turnips) growth is limited to the fall, thus, reducing the risk of excessive spring 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. The increased biomass accumulation in the spring may result in increased soil water use (Holman et al., 2018), and increased risk of yield reduction of the subsequent crops. However, in a winter wheat-maize-fallow rotation, the effect of different CC species (winter-sensitive vs. winter-hardy) on soil water use and subsequent maize grain yield is not well understood.

In winter wheat-maize-fallow rotations, CCs can grow from August (after winter wheat harvest) to May (maize 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 and, reduce light exposure, thus limiting weed establishment and evapotranspiration (Klein, 2012). Effects of CCs on weed suppression are variable in the literature. Previous research reported no weed suppression by CCs in sweet maize 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 by 98 % compared to a control (Hayden et al., 2012). However, the impact of CCs on summer annual weed suppression during the maize growing season in semi-arid environments remains unknown.

Besides soil water use, the inclusion of CCs after winter wheat harvest can induce N immobilization in the soil, which can lead to yield and economic penalties to the subsequent maize crop. Excessive growth of CCs, especially grasses, may increase soil water consumption and extend N 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 potential N credits provided by legume's atmospheric N fixation. Likewise, an irrigated study conducted in eastern Kansas showed that in its third year of implementation, cereal rye reduced maize yields by 9.3 % (Kessavalou and Walters, 1997). Conversely, Tollenaar et al. (1993) found that N fertilization in cereal rye CC minimized the adverse effects on subsequent maize 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 maize grain yield (Reese et al., 2014). Thus, the objectives of this experiment were to evaluate the impact of CC species selection on soil water content and penetration resistance, weed demographics, soil N levels, and subsequent maize grain yield. The experiment hypotheses were that (1) CC species differ in soil water use; (2) CCs decrease soil penetration resistance; (3) CC species differ in their impact on soil N levels; (4) CCs can suppress weeds; and (5) CC species differ in their effects on maize grain yield.

2. Materials and methods

2.1. Field sites and experimental design

Field experiments were conducted at two sites in western Nebraska during the 2016–2017 and 2017–2018 growing seasons (total of four site-years). The experiments 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 fields used in this experiment did not have a history of cover crop (CC) use and had been on a winter wheat-maize-fallow rotation where winter wheat was the crop harvested prior to the experiment establishment. Winter wheat was harvested in early/mid-August in 2016–2017 and late-July in 2017–2018 growing season.

The experimental design was a randomized complete block with four replications. The treatments included seven cover crop species and one control (fallow with no cover crop). The CC species treatments representing diverse 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 experiment were as follows: spring oats at 67 kg ha^{-1}; spring triticale at 67 kg ha^{-1}; cereal rye at 67 kg ha^{-1}; balansa clover at 22 kg ha^{-1}; hairy vetch at 45 kg ha^{-1}; purple top turnip at 22 kg ha^{-1}; and Siberian kale 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, whereas cereal rye and hairy vetch are winter-hardy species. Cover crops were drilled at 19 cm row spacing and 2.5 cm seed depth. The individual plot size was 4.6 m wide and 15.2 m long. Cover crops were planted in September (2016–2017), and August (2017–2018) within 7–30 days after winter wheat harvest. Cover crops were terminated at maize planting in 2017 and two weeks before maize 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. Maize was planted at 76 cm row spacing and a seed depth of 3.8 cm. Information regarding CC planting and termination dates, maize planting and harvest dates, hybrid selection, and seeding and fertilization rates in each site-year are described in Table 1.

Table 1
Cover crop (CC) planting and termination time, maize planting and harvest time, maize 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). Maize was planted 0-2 weeks after CC termination. Maize hybrids, seeding, and fertilizer rates followed standard management practices at each site-year. Pre and post-emergence herbicides were applied to control weeds when maize reached the V6-V7 development stage (Abendroth et al., 2011).

Site-years	CC planting date	First hard freeze date*	CC termination date	Maize planting date	Weed control date	Maize hybrid	Maize seeding rate (seeds ha^{-1})	Fertilizer (time, source, rate)	Maize harvest date
Grant 2016–2017	08 Sep 2016	09 Dec 2016	24 May 2017	24 May 2017	24 May 2017	DKC52–61 (102 days maturity)	38300	Maize pre-planting: N-K-S at 118N-59K-5.6S kg ha-1; Maize planting: ammonium polyphosphate (10N-34P-0 K) at 65 kg ha-1.	13 Oct 2017
Grant 2017–2018	22 Aug 2017	02 Nov 2017	06 May 2018	24 May 2018	23 Jun 2018	DGVT2PRIB (101 days maturity)	37065	Maize planting: ammonium polyphosphate (10N-34P-0 K) at 65 kg ha-1; Maize V3 development stage: UAN (32N-0P-0 K) at 310 kg ha-1.	23 Oct 2018
North Platte 2016–2017	07 Sep 2016	09 Dec 2016	02 May 2017	05 May 2017	20 Jun 2017	Hoegemeyer 7643RR (106 days maturity)	41018	Maize pre-planting : UAN (32N-0P-0 K) at 89 kg ha-1; Maize planting: ammonium polyphosphate (10N-34P-0 K) at 110 kg ha-1.	27 Oct 2017
North Platte 2017–2018	01 Aug 2017	01 Nov 2017	04 May 2018	23 May 2018	27 Jun 2018	Hoegemeyer 7643RR (106 days maturity)	41018	Maize pre-planting: UAN (32N-0P-0 K) at 112 kg ha-1; Maize planting: ammonium polyphosphate (10N-34P-0 K) at 110 kg ha-1.	17 Oct 2018

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

2.2. Data collection

2.2.1. Weather data

Precipitation and air temperature from each site-year were compared to the historical average data for Grant and North Platte from 1985 through 2015 (Fig. 1). It is essential to note that Grant is historically a drier location than North Platte, and a similar trend was observed during this experiment (Fig. 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 experiment 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.

2.2.2. Cover crop aboveground biomass

Aboveground biomass samples of all CC species were collected in the fall after the first hard freeze event (temperature below 0 °C for more than two consecutive days), 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 replaced with volunteer wheat as a treatment. Volunteer wheat was not collected in any other CC treatment, although present in hairy vetch plots in the spring. Spring triticale was also sampled in the spring because of unexpected winter survival. Fallow plots were kept volunteer wheat and weed-free during the CC growing season by spraying glyphosate. 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 until constant dry biomass was achieved, and weighed.

2.2.3. Soil water content

Soil volumetric water content (Θ_v, $m^3\ m^{-3}$) was measured 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 layer. Six readings were recorded from 0–20 cm depth on each plot every other week starting at maize planting and ending when maize reached the R2 (blister) development stage (Abendroth et al., 2011). The maize development stage upon which the readings were performed varied across site-years. 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 0–20 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 until a constant weight was reached. The gravimetric soil water content (Θg, grams of water per grams of soil) was quantified as (Hillel, 1998):

$$\Theta g = (\text{soil wet weight} - \text{soil dry weight}) \,/\, \text{soil dry weight} \qquad (1)$$

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):

$$\Theta_v = (\Theta g \times \rho\text{soil}) \,/\, \rho\text{water} \qquad (2)$$

Where ρsoil is the soil bulk density (grams of dry soil per cubic centimeters, the ratio of soil dry mass to sample volume), and ρwater 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 from each site were used to adjust the sensor readings (data not shown). A similar calibration methodology has been used in other studies (Tarara and Ham, 1997; Song et al., 1998; Werle et al., 2014a).

2.2.4. Soil penetration resistance

Soil penetration resistance (MPa) was measured 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 0–30 cm soil depth in each plot at maize planting time. The penetrometer was pushed down into the soil profile at a constant speed of 1 cm s^{-1}, and the depth of each measurement was at an interval of 2.54 cm.

2.2.5. Weed demographics

Weeds were identified, enumerated, and collected for total aboveground biomass determination when maize reached the V6 (six leaves

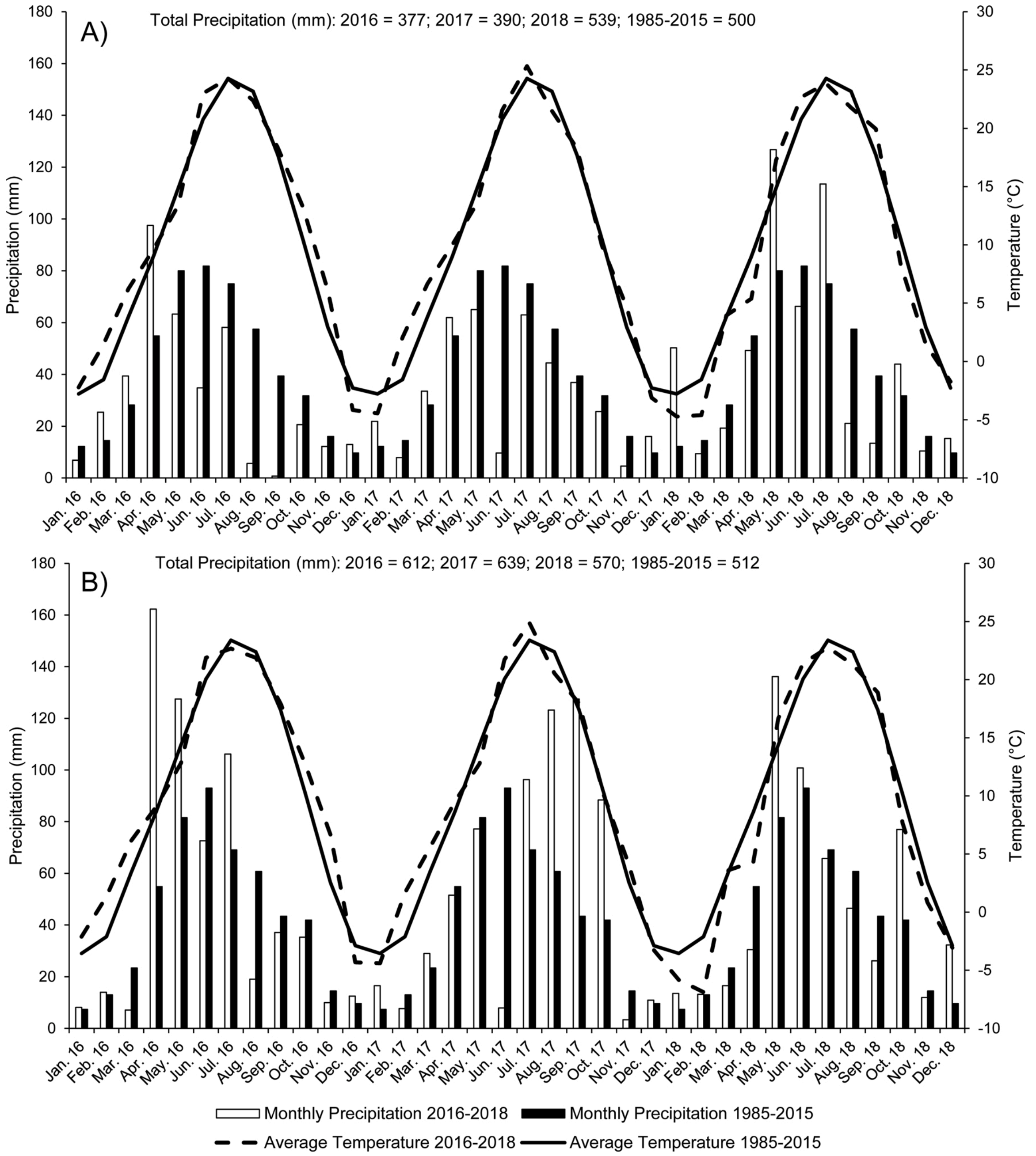

Fig. 1. Average temperature and monthly precipitation for Grant (A) and North Platte, NE (B) during the years of 2016, 2017, 2018, and the period of 1985-2015. Source: High Plains Regional Climate Center, https://hprcc.unl.edu (accessed on 02 Oct. 2020.

with collar visible) development stage to evaluate the effects of CCs on summer annual weed suppression on early-season maize development. After sampling, weeds were controlled using herbicides (Table 1) to avoid any possible impact on maize productivity. Aboveground weed biomass samples were randomly collected from each plot using two quadrats of 0.093 m^{-2}. The 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 maize planting. The other site-years did not receive a pre-emergence herbicide application.

2.2.6. Soil nitrogen levels

A composite soil sample of eight cores using a straight tube probe (2.5 cm diameter) was collected from 0 to 10 and 10–20 cm soil depth at each plot when maize reached the V6 development stage. This stage was selected to allow for CC decomposition, and potential N cycling (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 N (sum of organic and inorganic N). Soil organic matter was determined by the loss on ignition method (Hoskins, 2002). Inorganic N is a combination of nitrate (NO3-N) and ammonium (NH4-N). Nitrate and ammonium were analyzed with the weak acid H3A extract on a Lachat 8000 flow injection analyzer (Hach Company, Loveland, Colorado). Total N was also analyzed by the H3A extract (Apollo 9000, Teledyne-Tekmar; Mason, Ohio). The organic N was calculated by subtracting the total N from the inorganic N.

2.2.7. *Maize grain yield and yield components*

The maize plant population was measured by counting the number of plants in three rows of maize in each plot for the whole plot length when maize reached the R2 development stage. The two center maize rows of each plot were hand-harvested (2.65 m long per maize row) covering an area of 4.065 m^{-2} (Lauer, 2002). Six maize ears were randomly selected from the hand-harvested area to estimate yield components. Maize grain yield components were estimated by counting the 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 maize ears were threshed using a stationary maize ear sheller (ALMACO, Nevada, IA). After threshing, kernel weight was recorded. Kernel moisture was measured using a meter (Model Dickey John GAC 2100 Agri Bench Grain Moisture Tester, Dickey-John Corporation, Auburn, IL), and grain yield was adjusted to 15.5 % moisture content.

2.3. *Statistical analysis*

All response variables in this experiment (CC biomass in the fall and spring, soil penetration resistance, weed density and biomass, residue, organic matter, total N, organic N, ammonium, nitrate, inorganic N, maize 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. The soil water content data measured through the maize growing season was analyzed by site-year (fixed effect) as a repeated measure so that maize development stage was considered as time in the model. The variables weed density and biomass, total N, organic N, ammonium, nitrate, inorganic N, maize plant population, number of kernels per row, kernels per ear, and 100-kernel weight were log-transformed prior to the ANOVA to satisfy the Gaussian assumptions of normality (back-transformed means are presented for ease of interpretation). For all variables in the experiment, the separation of means for interactions and main effects were 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 to support ANOVA results.

The soil penetration resistance was regressed against soil water content by fitting an exponential regression model. The exponential regression model was fitted across data from all treatments and site-years, and the *p*-value indicates the significance of the slope at $\alpha = 0.05$. The exponential regression model was chosen because of its best fit in comparison to other models, where the adjusted coefficient of determination (R^2) served as an indication of goodness of fit. The exponential regression analysis was performed using the *nlme* (Lindstrom et al., 2020) package in R (R Development Core Team, 2020).

3. Results

3.1. *Cover crop fall biomass*

Cover crop biomass in the fall differed according to species ($p < 0.001$). Overall, spring oats (2674 kg ha^{-1}), purple top turnips (2157 kg ha^{-1}), and Siberian kale (2151 kg ha^{-1}) produced the greatest amount of fall aboveground biomass. In contrast, volunteer wheat (105 kg ha^{-1}) and hairy vetch (675 kg ha^{-1}) consistently produced the lowest amount of biomass among CCs evaluated (Table 2). Among grasses, spring oats had 50 and 62 % more biomass in the fall than cereal rye (1784 kg ha^{-1}) and spring triticale (1649 kg ha^{-1}), respectively.

3.2. *Cover crop spring biomass*

Spring triticale (1837 kg ha^{-1}), cereal rye (4223 kg ha^{-1}), volunteer wheat (2038 kg ha^{-1}), and hairy vetch (806 kg ha^{-1}) overwintered and produced biomass in the spring. Cereal rye produced the greatest amount of spring biomass compared to spring triticale (+129 %), volunteer wheat (+107 %), and hairy vetch (+424 %) (Table 2). Spring triticale winter survival was unexpected in this experiment. If a producer plants spring triticale as a CC winter-sensitive and it survives the winter, proper spring termination practices become necessary.

3.3. *Weed demographics*

Weed species distribution varied by site. 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 ($p = 0.0027$) and biomass ($p = 0.0012$) were impacted by CC species selection (Table 2). The fallow treatment showed the greatest weed density and biomass among all treatments. Cereal rye (-80 %) and volunteer wheat (-69 %) reduced weed density. Similarly, spring oats (-90 %), spring triticale (-71 %), cereal rye (-88 %), volunteer wheat (-67 %), and purple top turnip (-60 %) reduced weed biomass compared to fallow treatment.

3.4. *Soil water content*

Soil volumetric water content (Θ_v, m^3 m^{-3}) measured from 0–20 cm soil depth decreased as maize developed from VE to R2 development stage (Fig. 2). Still, all Θ_v readings were above the permanent wilting point (PWP) and close to the field capacity (FC) level at all site-years. Cereal rye reduced Θ_v at maize emergence (VE development stage)

Table 2

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

	CC Fall Biomass (kg ha^{-1})			CC Spring Biomass (kg ha^{-1})			Weed Density (weeds m^{-2})			Weed Biomass (kg ha^{-1})		
Species	Mean	SE+-		Mean	SE+-		Mean	SE+-		Mean	SE+-	
Fallow	–	–		–	–		123	35	A	230	86	A
SO	2674	333	A	–	–		58	13	AB	24	3	D
ST	1649	177	B	1837	143	B	53	12	AB	65	19	CD
CR	1784	183	B	4223	333	A	25	4	B	27	12	D
VW	105	27	C	2038	192	B	38	7	B	76	31	CD
HV	675	103	C	806	181	C	73	16	AB	100	26	ABC
PTT	2157	345	AB	–	–		91	14	AB	92	30	BC
KS	2151	340	AB	–	–		81	15	AB	204	61	AB
	p-values											
Species	<.0001			<.0001			0.0027			0.0012		

Abbreviations: 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.

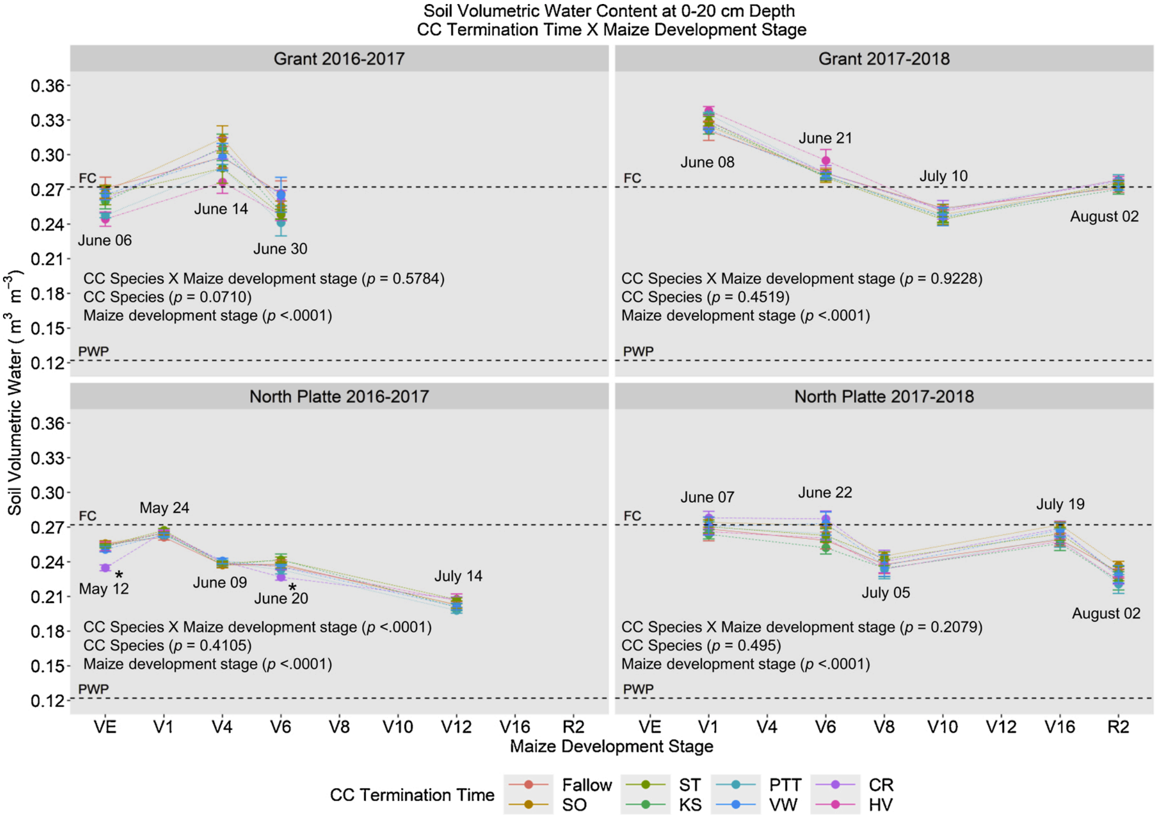

Fig. 2. Soil volumetric water content at 0 to 20 cm soil depth at each site-year in western Nebraska according to the interaction of cover crop (CC) species and maize development stage. Abbreviations: FC, field capacity; PWP, permanent wilting point; SO, spring oats; ST, spring triticale; CR, cereal rye; VW, volunteer wheat; HV, hairy vetch; PTT, purple top turnip; KS, Siberian kale; VE, V1, V4, V6, V8, V10, V16, R2 maize development stage. * represent statistically significant differences at $p \leq 0.05$. FC and PWP data were obtained from the Web Soil Survey, https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm (accessed on 02 Oct. 2020) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

and V6 development stage in North Platte 2016–2017 only. In other site-years, there were no differences among CC species regarding Θ_v at the 0–20 cm soil depth.

3.5. Soil penetration resistance

Measured penetration resistance values (Mpa) were plotted against the adjusted measured volumetric water content (Θ_v, $m^3\ m^{-3}$) from 0–20 cm soil depth at maize planting time to determine the correlation of penetration resistance with the Θ_v values using a methodology similar to Busscher et al. (1997); Busscher and Bauer (2003), and Blanco-Canqui et al. (2006). An exponential equation 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 (Fig. 3). Fig. 3 shows that variations in Θ_v explained 65 % of the variation in the soil penetration resistance measured indicating high dependency on Θ_v. Thus, the penetration resistance values were adjusted by taking the ratio of the equation shown in Fig. 3 to reduce the confounding effect of the measured Θ_v on the penetration resistance values:

$$y_a = y_m \exp(-9.54(0.137-x)) \tag{3}$$

Where y_a was the adjusted penetration resistance, y_m was the measured penetration resistance, x the adjusted measured Θ_v, and 0.137 an arbitrary chosen Θ_v to which values were adjusted. Eq. 3 was used for all site-year's penetration resistance readings to ensure a uniform correction.

The soil penetration resistance results showed an interaction between CC species treatment and depth (Fig. 4). Thus, the results are presented in megapascal (MPa) at each depth according to the CC species. Soil penetration resistance in the fallow treatment ranged from 0.25 to 1.29 MPa; for spring oats from 0.25 to 1.21 MPa; for spring triticale from 0.23 to 1.37 MPa; for cereal rye from 0.25 to 1.72 MPa; for volunteer wheat from 0.24 to 1.41 MPa; for hairy vetch from 0.23 to 1.38 MPa; for purple top turnip from 0.25 to 1.26 MPa; and, for Siberian

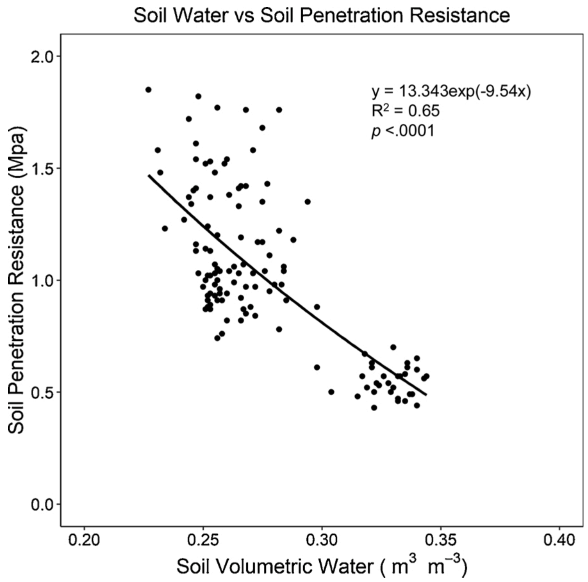

Fig. 3. Regression of unadjusted soil penetration resistance as a function of adjusted soil volumetric water content measured at maize planting time for all data points across site-years in western Nebraska.

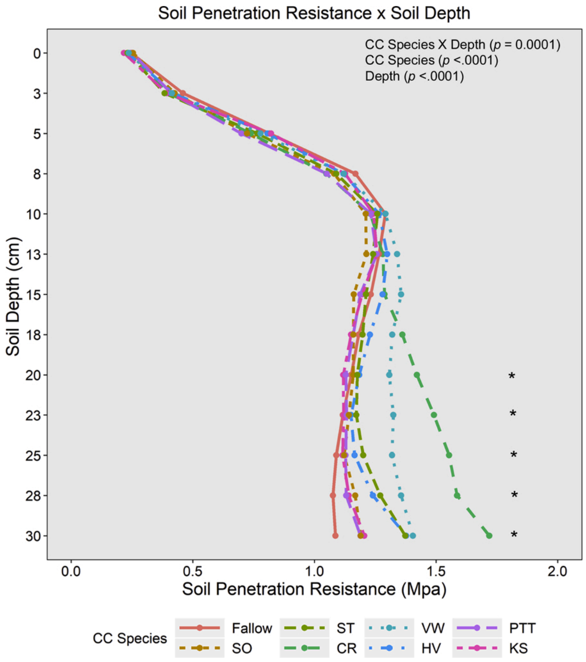

Fig. 4. Adjusted soil penetration resistance at 0 to 30 cm depth at maize planting time according to the interaction of soil depth and cover crop (CC) species across site-years† in western Nebraska. Adjustment of soil penetration resistance (Eq. 3) was applied to all site-years to ensure a uniform correction. Abbreviations: SO, spring oats; ST, spring triticale; CR, cereal rye; VW, volunteer wheat; HV, hairy vetch; PTT, purple top turnip; KS, Siberian kale. Site-years were included as random effects in the ANOVA model. *represent statistically significant differences at $p \leq 0.05$. †Grant 2016-2017, Grant 2017-2018, North Platte 2016-2017, and North Platte 2017-2018 (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

kale from 0.22 to 1.26 MPa (Fig. 4). Cereal rye increased the soil penetration resistance from 20 to 28 cm soil depth among the CC species, except compared to volunteer wheat. At 30 cm soil depth, soil penetration resistance under cereal rye was 0.31 MPa greater than volunteer wheat, the second greater value. Likewise, volunteer wheat increased soil penetration resistance from 28 to 30 cm soil depth compared to fallow. Hairy vetch and spring triticale also increased soil penetration resistance by 27 and 26 %, respectively, over fallow at 30 cm soil depth.

3.6. *Soil nitrogen levels*

Soil nitrate ($p = 0.0301$) and inorganic N ($p = 0.0231$) at 0–10 cm soil depth were affected by CC species treatments (Table 3). Surprisingly, hairy vetch reduced both soil nitrate and inorganic N by approximately 40 % compared to fallow treatment. Similarly, spring oats reduced inorganic N by 41 % over fallow. Soil organic matter, total N, organic N, and ammonium were not impacted by CC species selection at 0–10 cm soil depth. In addition, both nitrate ($R = 0.61, p < .0001$) and inorganic N ($R = 0.65, p < .0001$) were strongly positively correlated with maize grain yield (Table 3).

Total N ($p = 0.0268$), nitrate ($p = 0.0029$), and inorganic N ($p = 0.0085$) at 10–20 cm soil depth were affected by CC species selection (Table 4). Cereal rye reduced total N by 26 % compared to fallow. Likewise, soil nitrate was reduced by spring oats (-40 %), spring triticale (-34 %), cereal rye (-41 %), volunteer wheat (-41 %), and hairy vetch (-34 %) when compared to fallow treatment. In addition, inorganic N was reduced compared to fallow by spring oats (-35 %), spring triticale (-30 %), cereal rye (-35 %), volunteer wheat (-35 %), hairy vetch (-27 %), and Siberian kale (-18 %). Soil organic matter, organic N, and ammonium at 10–20 cm soil depth were not impacted by CC species selection. Also, there were positive correlations between maize grain yield and total N ($R = 0.41, p < .0001$), and strong positive correlations of maize grain yield with nitrate ($R = 0.68, p < .0001$), and inorganic N ($R = 0.69, p < .0001$).

3.7. *Maize grain yield and yield components*

Maize grain yield was affected by CC species selection ($p < 0.0001$, Table 5). In general, CC species decreased maize grain yield compared to fallow (8.7 Mg ha^{-1}), except for spring oats (7.5 Mg ha^{-1}). Cereal rye (6.1 Mg ha^{-1}) had the most detrimental effect on maize grain yield among all CC species in this experiment, decreasing maize grain yield up to 30 % compared to fallow.

Pearson's linear correlation showed that most of the yield components affected maize grain yield, especially the number of kernels per row ($R = 0.54, p < .0001$), kernels per ear ($R = 0.54, p < .0001$), and 100-kernel weight ($R = 0.61, p < .0001$) (Table 5). No effects of CC species on maize plant populations were detected in this experiment ($p = 0.2241$). On the other hand, the number of kernel rows per ear ($p = 0.0055$), number of kernels per row ($p = 0.0326$), kernels per ear ($p =$

Table 3
Soil organic matter and N forms (total, organic and inorganic N, nitrate, and ammonium) at 0 to 10 cm soil depth collected at maize V6 development stage according to cover crops species across site-years† in western Nebraska. Site-years were included as random effects in the ANOVA model. Numbers followed by different letters within columns represent statistically significant differences with Tukey adjustment at $p \leq 0.05$. Pearson correlation coefficients represent the relationship of soil organic matter and N forms with maize grain yield.

	Organic Matter (g kg^{-1})			Total N (mg kg^{-1} N)			Organic N (mg kg^{-1} N)			Ammonium (mg kg^{-1} NH_4-N)			Nitrate (mg kg^{-1} NO_3-N)			Inorganic N (mg kg^{-1} N)		
Species	Mean	SE+-		Mean	SE+-		Mean	SE+-		Mean	SE+-		Mean	SE+-		Mean	SE+-	
Fallow	2.4	0.1	NS	36.6	5.2	NS	13.9	0.8	NS	5.8	1.4	NS	17.4	4.4	A	23.2	5.5	A
SO	2.4	0.2		27.4	2.7		13.4	0.8		3.3	0.5		10.5	2.3	AB	13.8	2.6	B
ST	2.5	0.1		33.7	5.8		13.3	0.7		5.1	1.3		16.1	5.4	AB	21.2	6.4	AB
CR	2.5	0.1		30.3	4.9		13.3	0.4		4.3	1.1		13.0	4.2	AB	17.3	5.2	AB
VW	2.5	0.2		29.7	3.7		13.2	0.7		4.4	0.8		12.4	3.2	AB	16.9	3.7	AB
HV	2.5	0.2		26.8	3.1		13.3	0.6		3.7	0.6		10.3	2.9	B	14.0	3.4	B
PTT	2.5	0.2		33.5	5.4		13.2	0.8		5.0	1.2		15.8	5.1	AB	20.8	6.2	AB
KS	2.3	0.1		31.9	4.9		12.0	0.7		4.9	1.2		15.9	4.6	AB	20.8	5.6	AB
	p-values																	
Species	0.8285			0.0705			0.4196			0.2875			0.0301			0.0231		
	Pearson Correlation Coefficients																	
Maize Grain Yield (Mg ha^{-1})	$R = 0.45$ ($p < .0001$)			$R = 0.47$ ($p < .0001$)			$R = -0.13$ ($p = 0.1585$)			$R = 0.58$ ($p < .0001$)			$R = 0.61$ ($p < .0001$)			$R = 0.65$ ($p < .0001$)		

Abbreviations: N, nitrogen; 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; NS, not significant. †Grant 2016–2017, Grant 2017–2018, North Platte 2016–2017, and North Platte 2017-**2018**.

Table 4
Soil organic matter and N forms (total, organic and inorganic N, nitrate, and ammonium) at 10 to 20 cm soil depth collected at maize V6 development stage according to cover crops species across site-years[†] in western Nebraska. Site-years were included as random effects in the ANOVA model. Numbers followed by different letters within columns represent statistically significant differences with Tukey adjustment at $p \leq 0.05$. Pearson correlation coefficients represent the relationship of soil organic matter and N forms with maize grain yield.

	Organic Matter (g kg^{-1})			Total N (mg kg^{-1} N)			Organic N (mg kg^{-1} N)			Ammonium (mg kg^{-1} NH_4-N)			Nitrate (mg kg^{-1} NO_3-N)			Inorganic N (mg kg^{-1} N)		
Species	Mean	SE+-		Mean	SE+-		Mean	SE+-		Mean	SE+-		Mean	SE+-		Mean	SE+-	
Fallow	2.2	0.1	NS	24.9	2.4	A	12.9	1.0	NS	2.2	0.3	NS	9.9	1.8	A	12.1	2.0	A
SO	2.2	0.1		19.3	1.3	AB	11.4	0.7		1.9	0.2		5.9	1.0	B	7.8	1.1	B
ST	2.2	0.1		19.5	2.2	AB	11.1	0.6		1.9	0.3		6.5	1.7	B	8.4	1.9	B
CR	2.2	0.1		18.5	1.4	B	10.8	0.4		2.1	0.3		5.8	1.3	B	7.9	1.5	B
VW	2.2	0.1		19.1	1.5	AB	11.0	0.7		2.1	0.2		5.8	1.1	B	7.9	1.2	B
HV	2.0	0.2		20.2	1.8	AB	11.6	0.5		2.4	0.3		6.5	1.4	B	8.8	1.6	B
PTT	2.2	0.1		22.4	2.4	AB	11.7	0.7		2.2	0.3		8.5	2.0	AB	10.7	2.3	AB
KS	2.1	0.1		20.9	2.2	AB	10.9	0.7		2.1	0..		7.8	1.9	AB	9.9	2.1	B
	p-values																	
Species	0.9588			0.0268			0.1585			0.8305			0.0029			0.0085		
	Pearson Correlation Coefficients																	
Maize Grain Yield (Mg ha^{-1})	R = 0.53 (p <.0001)			R = 0.41 (p <.0001)			R = -0.14 (p = 0.1235)			R = 0.61 (p <.0001)			R = 0.68 (p <.0001)			R = 0.69 (p <.0001)		

Abbreviations: N, nitrogen; 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; NS, not significant. [†]Grant 2016−2017, Grant 2017−2018, North Platte 2016−2017, and North Platte 2017-**2018**.

Table 5
Maize grain yield and yield components (maize 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 were included as random effects in the ANOVA model. Numbers followed by different letters within columns represent statistically significant differences with Tukey adjustment at $p \leq 0.05$. Pearson correlation coefficients represent the relationship of maize yield components with maize grain yield.

	Maize Grain Yield (Mg ha^{-1})			Maize 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+-	
Fallow	8.7	0.2	A	33920	1082	NS	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																	
Maize 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: 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; NS, not significant. [†]Grant 2016−2017, Grant 2017−2018, North Platte 2016−2017, and North Platte 2017−2018.

0.0025), and 100-kernel weight ($p = 0.0134$) were affected by CC species selection (Table 5). 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 fallow (Table 5). Likewise, spring oats, hairy vetch, and purple top turnip reduced the 100-kernel weight by 9, 9, and 8%, respectively, compared to fallow. Thus, similar to the maize grain yield, cereal rye negatively affected the majority of the maize yield components.

4. Discussion

Cover crop biomass production was dependent on whether CCs were winter-sensitive or winter-hardy. The winter-sensitive species spring oats, purple top turnip, and Siberian kale reached the greatest biomass in the fall. These species might have good potential for grazing, reducing costs related to CC implementation with no need for CC termination. 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 experiment, cereal rye was the most consistent CC species in terms of biomass production, especially in the spring. 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 across the Central Great Plains.

Soil water content decreased during the maize growing season (Fig. 2). This result was expected since precipitation amounts decrease from summer to fall (Fig. 1), and the maize demands for water keeps increasing, reaching its peak at VT (tassel stage) and R1 (silking stage) development stages (Westgate et al., 2004; Abendroth et al., 2011). Any water stress at this development stage could potentially impact pollination, decreasing maize grain yield by affecting the number of kernels per ear. The increased biomass production by cereal rye in the spring probably induced the increased soil water consumption, impacting the Θ_v at North Platte 2016−2017. In a previous study, cereal rye decreased Θ_v from 0–20 cm soil depth among sole CCs at maize planting (Appelgate et al., 2017). Still, Θ_v in cereal rye plots (and all other treatments) were above the PWP, which does not characterize water unavailability from 0–20 cm soil depth. 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 soil water differences among CC species may be due to the above-average precipitation during the spring in those site-years, which kept the Θ_v close to FC (Fig. 1). Our experiment suggests that the 2018 spring precipitation probably minimized the effect of CCs in Θ_v from 0–20 cm soil depth. Although the TDR sensor measurements do not show Θ_v differences among CC species in 0–20 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 by CC species from 0–20 cm soil depth, which is a critical layer for maize establishment and initial root growth (Fig. 4). Approximately 45 % of the maize rooting system is at 0–20 cm soil depth (Yamaguchi et al., 1990; Rosa et al., 2019). Thus, in their first year of implementation, CCs did not affect the soil penetration resistance at this depth. However, from 20–30 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 maize root growth to scavenge water and nutrients in deeper soil layers (Unger and Kaspar, 1994). As shown by Eq. 3, and Fig. 3, the soil penetration resistance values were associated with soil water. Since the TDR sensor could only measure Θ_v from 0–20 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 maize 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; Florence et al., 2019). In semi-arid environments, the previous crop residue (winter wheat) associated with no-till works as a physical barrier to suppress weeds (Klein, 2012). In addition to previous crop residue, CCs fill the gaps that could otherwise be occupied by weeds (Liebman and Staver, 2001). Previous research found that intercropping safflower with beans reduced weed pressure (Sadeghi and Sasanfar, 2013). The ability of a crop canopy to limit soil light exposure, and compete for soil water and nutrients compose an efficient competition against weeds. This experiment showed that spring oats and cereal rye produced the greatest aboveground biomass in the fall and spring, respectively. Thus, cereal rye reduced summer annual weed populations (weed density and biomass), being an effective tool for weed management (Table 2). In addition, other grass species like volunteer wheat, spring oats, and spring triticale also contributed to weed suppression. A recent study published by Pittman et al. (2020) in Virginia revealed that CC species with greater carbon:nitrogen (C:N) ratio, like cereal rye, increased CC biomass and soil coverage, and consequently increased summer annual weed suppression. Cereal rye residue may also release allelochemicals that inhibit weed emergence (Weston, 1996; Koehler-Cole et al., 2020). 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 early-season suppression of weeds. Thus, it is essential to have CCs growing in the spring if the goal is to reduce summer annual weeds.

Cover crops, especially grasses, reduced N levels in the soil and likely induced N immobilization during the maize growing season (Table 3). Grass residue decomposition is known to be slow in comparison to legumes (Blanco-Canqui et al., 2015) because of their greater C:N ratio. As an effect of comparison, cereal rye at flowering stage (when terminated in the spring in this study) has a C:N ratio of 37:1, while hairy vetch is 11:1 (USDA/NRCS, 2011). A previous study conducted in Brazil showed that CCs increase C:N ratio in the soil profile when compared to fallow (Rosolem et al., 2016). Since soil samples were collected at the maize V6 development stage most of the grass CC residue was still visible on the soil surface. Therefore, we speculate that there was not enough time for grass CCs to complete N cycling by that time. Lower N values in grass CC plots could potentially reduce nitrate prone to leaching (White et al., 2017); however, it also means less N available for maize uptake. Therefore, it is difficult to estimate N mineralization and associate with the crop N requirements (Snapp and Fortuna, 2003). Biotic or abiotic stresses at maize 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 maize. Although hairy vetch is a winter-hardy legume CC, it produced low biomass, leaving space for considered amounts of volunteer wheat growth in the spring (data not collected), which probably increased the total C:N ratio of this treatment, inducing N immobilization. On the other hand, purple top turnip did not affect N levels at either 0–10 cm or at 10–20 cm soil depth. Purple top turnip is considered a good N scavenger (Sustainable Agriculture Network, 2007; Tuulos et al., 2014), and its residue decomposed during the spring, which helped to return some of the N to the top layers of the soil. Therefore, this study did not confirm soil N cycling by CCs in semi-arid environments.

Maize grain yield and yield component results validate the concerns of producers about adopting CCs in semi-arid environments. Most of the CC species reduced maize grain yield and yield components, especially cereal rye (Table 5). Although not measured deeper than 20 cm soil depth, we hypothesize that soil water depletion likely happened deeper than 20 cm soil depth under cereal rye, volunteer wheat, spring triticale, and hairy vetch based on the soil penetration resistance results. Ear formation in maize is known to happen around V6-V7 development stage (Stevens et al., 1986), so it is possible that early-season water stress occurred in this study to justify the maize grain yield decrease. In addition, cereal rye remarkably decreased N levels in the soil. Therefore, both soil water and N were limiting factors for maize grain yield. Other studies documented that cereal rye reduces soil water and N availability due to excessive growth (Campbell et al., 1984; Nevins et al., 2020), decreasing maize 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 to persist into the spring will likely induce N immobilization and serve as a potential host of wheat streak mosaic virus (Wegulo et al., 2008). Volunteer wheat needs to be monitored in both fall and spring when growing CCs in a winter wheat-maize-fallow rotation. Volunteer wheat can establish, especially under a poor CC stand in the fall or the spring if planting winter-sensitive CC species.

Since our experiments were conducted in rainfed semi-arid environments, the precipitation during spring and early summer played an important role in the success of the crops cultivated. In this sense, water storage is essential 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 parts of the Central Great Plains, 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 N immobilization (Appelgate et al., 2017). Thus, the reduced precipitation during spring and early summer of 2017 plus the CC termination near maize planting time likely contributed to increased N immobilization, soil water depletion, and consequently, lower maize grain yield under CC treatments (Table 4).

5. Conclusions

Our findings emphasize the importance of species selection when adopting CCs. This experiment shows that under the winter wheat-maize-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. On the other hand, our experiment did not find any positive or negative effect of CC species on soil water and penetration resistance from 0–20 cm soil depth. However, cereal rye increased soil penetration resistance from 20–30 cm soil depth, likely because of soil water use beyond 0–20 cm soil depth. Additionally, most CCs reduced N levels in the soil. Thus, CCs did not contribute to any gain in maize grain yield. Instead, the majority of the CC species reduced maize grain yield, except for spring oats, which did not affect maize grain yield. Maize grain yield reduction by CCs was probably related to soil water use below 20 cm soil depth and reduced N availability during maize growing season. Therefore, future experiments should evaluate not only soil water content deeper in the soil, but N mineralization by different CC species, calibrating N requirements for maize as a subsequent crop following CCs in semi-arid environments.

Additionally, our findings reflect the short-term (1 cycle of crop rotation) impact of CC adoption as part of the winter wheat-maize-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 calibration to determine when N will be available for the subsequent crop uptake. However, if the producer aims to increase maize grain yield, then growing CCs may not work, at least in the short-term in winter wheat-maize-fallow rotations of western Nebraska. Long-term CC adoption investigations are necessary to provide a conclusive answer about CC use in semi-arid regions 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 critical 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 maize yield, spring oats (or spring oats combined with brassicas, in case of grazing) might be the best CC species option for producers to grow under water-limited environments.

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Declaration of Competing Interest

The authors report no declarations of interest.

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