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Abstract
One perceived cost of integrating winter cover cropping in maize (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] rotation systems is the potential negative impact on soil water storage available for primary crop production. The objective of this 3-yr study was to evaluate the effects of winter cover crops on soil water storage and cover crop biomass production following no-till maize and soybean rotations. Locations were near Brule (west-central), Clay Center (south-central), Concord (northeast), and Mead (east-central), NE. Treatments included crop residue only (no cover crop) and a multi-species cover crop mix, both broadcast-seeded before primary crop harvest and drilled following harvest. Pre-harvest broadcast-seeded cereal rye (*Secale cereale* L.) was also included in the last year of the study because rye was observed to be the dominant component of the mix in spring biomass samples. Soil water content was monitored using neutron probe or gravimetric techniques. Mean

aboveground cover crop biomass ranged from practically 0 to ~3,200 kg ha^{-1} across locations and cover crop treatments. Differences in the change in soil water storage between autumn and spring among treatments occurred in 4 of 20 location–rotation phase–years for the top 0.3 m of soil and 3 of 20 location–rotation phase–years for the 1.2-m soil profile. However, these differences were small (<11 mm for the top 0.3 m and <26 mm for the 1.2-m profile). In conclusion, winter cover crops did not have an effect on soil water content that would impact maize and soybean crop production.

Abbreviations

CC, cover crops
EC, Eastern Nebraska Research and Extension Center near Mead in east-central Nebraska
ET, evapotranspiration
MIX-PRE, cover crop mix planted pre-harvest of primary crops by broadcasting
MIX-POST, cover crop mix planted postharvest of primary crops by drilling
NCC, no cover crop
NE, Haskell Agricultural Laboratory near Concord in northeast Nebraska
PC, primary crops
RYE-PRE, rye cover crop planted pre-harvest of primary crops by broadcasting
SC, South Central Agricultural Laboratory near Clay Center in south-central Nebraska
WC, West Central Water Resources Field Laboratory near Brule in west-central Nebraska

Winter cover crops following maize (*Zea mays* L.) or soybean [*Glycine max* (L.) Merr.] can be important components in current Midwest US cropping systems (Unger and Vigil, 1998; Blanco-Canqui et al., 2015). A recent survey found that a majority of farmers indicated that cover crops “improve soil health”, with fewer reporting other benefits including yield stability and “reduce[d] … inputs” (CTIC, 2017). The same survey found that some of farmers’ primary concerns with cover crops included “time/labor”, “lack of economic return”, “potential yield reduction”, and “cover crop becomes a weed” (CTIC, 2017). In addition to the previous survey data, robust discussions on the positive and negative implications of cover cropping are provided by (Blanco-Canqui et al., 2015, Snapp et al., 2005, Unger and Vigil, 1998, Gabriel et al., 2014). A potentially negative impact of cover crops is possible reduction in soil water available for primary crop production, a particular concern in areas of low rainfall (Unger and Vigil, 1998, Blanco-Canqui et al., 2015). In their review, Unger and Vigil (1998) suggest that in areas with sufficient precipitation, cover crops will have negligible effect on water available for primary crop production. They concluded that cover crops are most appropriate in more humid areas. However, Blanco- Canqui et al. (2015) suggest that there are other soil benefits from cover crops even if they negatively impact soil water. Some reports suggest that cover crops appear to not reduce soil water storage, even in dry years, for humid locations (Basche et al., 2016). For example, cereal rye (*Secale cereale* L.) cover crops in a study in Indiana and Iowa did not result in less soil water storage as compared to no cover crops during the dry year of 2012 at two of their three sites (Daigh et al., 2014, Blanco-Canqui et al., 2015). In contrast, another study in Iowa on cereal rye cover crop revealed a negative impact on maize yield in dry years of 2012 and 2013, but not in other study years (Martinez-Feria et al., 2016).

Authors of recent studies have reported no significant effect of winter crops on soil water content (Basche et al., 2016, Sharma et al., 2017). In a 7-yr study in Iowa, Basche et al. (2016) found no significant differences in maize or soybean yield between cereal rye cover crop and no cover crop treatments (815 mm long-term average annual precipitation). They reported increased available water capacity and greater soil water storage over the growing season for the rye treatment compared with no cover crop; however, they only monitored the top 0.3 m of the soil profile. Furthermore, Basche et al. (2016) suspected that cover crop transpiration was significant, but that rainfall was sufficient to ameliorate the impact. They reported the long-term average precipitation for April and May to be ~190 mm. If the precipitation did offset the cover crop impact, then the cover crops may have decreased deep percolation. However, the authors reported no significant differences in annual total drainage between treatments (Basche et al., 2016; Kaspar et al., 2007, 2012). In another Iowa study, Martinez-Feria et al. (2016) computed cover crop transpiration based on soil water balance differences between plots with and without cover crops and found that rye cover crops had about 21 mm of transpiration per 1000 kg ha^{-1} of biomass production. A 3-yr study in eastern Nebraska included measurements of evapotranspiration (ET) from cover crops in an irrigated maize seed production system (Sharma et al., 2017). They found no differences in ET or average soil water storage during the cover crop growing season between treatments with cover crops in seed maize residue and with seed maize residue only (Sharma et al., 2017). Qi and Helmers (2010), however did observe greater ET for cereal rye cover crops as compared with bare soil in Iowa using draining lysimeters. They also observed reduced lysimeter drainage using the cover crop (Qi and Helmers 2010, Basche et al., 2016).

Potential benefits of cover cropping have been discussed for humid climates (Blanco-Canqui et al., 2015). However, they reported potential negative impacts on soil water storage for primary crop production in dry climates. These benefits could depend on available rainfall or irrigation water availability (Unger and Vigil, 1998; Snapp et al., 2005). For example, in California, Islam et al. (2006) concluded that a three-species cover crop of triticale (*Triticosecale* Wittmack.), common vetch (*Vicia sativia* L.), and cereal rye did not greatly impact soil water content in tomato (*Solanum lycopersicum*

L.) and cotton (*Gossypium hirsutum* L.) under irrigated production (winter precipitation and irrigation ranged from 114 to 349 mm).

Some authors have reported negative impacts on soil water content from cover crops (Gabriel et al., 2014; Nielsen et al., 2015). In Spain, Gabriel et al. (2014) studied the effect of hairy vetch (*Vicia villosa* Roth) and barley (*Hordeum vulgare* L.) cover crops on soil water content in maize plots (average reported annual precipitation 350 mm). They found that soil water content differences were most notable when the primary crop was not growing. They also found that cover crops usually decreased water content. They also estimated cover crop ET using a model calibrated to soil water content observations and reported a general increase in ET for barley and vetch cover crops over fallow in maize. This supports the idea that cover crops may adversely affect soil water content for primary crop production, at least in semiarid areas (Unger and Vigil, 1998). These observations are supported by recent research on the use of cover crops in rainfed proso millet (*Panicum miliaceum* L.) cropping systems in the High Plains (Nielsen et al., 2015) and by the review of Unger and Vigil (1998).

Considering the cited literature, the impact from cover crops on soil water content for primary maize and soybean crop production may be highly dependent on environment (Unger and Vigil, 1998). With increased interest in cover crops in Nebraska, it is important to quantify the effects of cover cropping on soil water available for primary crop production in maize–soybean rotation systems in the dry and transition areas of the Western U.S. Corn Belt and the High Plains. Questions remain on whether the results from other regions are applicable to maize– soybean systems throughout these drier maize and soybean production areas. In Nebraska, precipitation ranges from <400 mm annually (1981–2010 normal) in the west to >900 mm annually in the east (USDA-NRCS 2012; PRISM 2012) (**Figure 1**). This precipitation pattern results in maize and soybean grown in rainfed systems in the eastern portion of the state, and the same crops grown with irrigation in western Nebraska. Thus, potential net depletion of soil water by cover crops may be more impactful in western Nebraska than in Midwest states. Furthermore, it is not entirely known if cover crops are a viable option in semiarid regions like western Nebraska. This is particularly the case in cropping systems that restrict when and how cover crops can be planted and harvested, and if the cover crops can be irrigated. In this region soils quite often freeze before cover crops can be planted and at this point irrigation would not be beneficial or practical. Our objective in this study was to determine the short-term effects of winter cover crop biomass production on soil water storage in maize–soybean rotations across Nebraska.

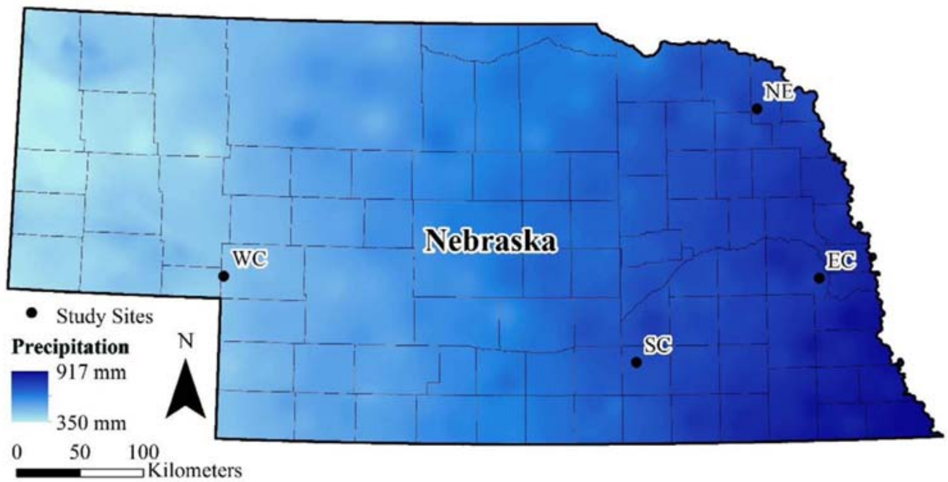

Figure 1. Map of study locations with 1981–2010 normal annual precipitation background. Nebraska state and county border sources: USDA-NRCS (2009b, 2009a). Precipitation data source: USDA-NRCS (2012); source data from PRISM (2012). Study location coordinates were obtained from Google Earth, accessed 13 Nov. 2017. Produced in ArcGIS 10.4 (Esri, Redlands, CA).

Materials and Methods

Study Locations

This study was conducted in field experiments over 3 yr at four University of Nebraska–Lincoln research facilities (**Figure 1**; **Table 1**), representing the major maize–soybean cropping and precipitation agroecoregions of Nebraska. Locations included the Eastern Nebraska Research and Extension Center near Mead in east-central Nebraska (EC); the Haskell Agricultural Laboratory near Concord in northeast Nebraska (NE); the South Central Agricultural Laboratory near Clay Center in south-central Nebraska (SC); and the West Central Water Resources Field Laboratory near Brule in west-central Nebraska (WC). The data presented here were collected from a subset of plots in a larger cover crop study that included different primary crop rotations, cover crop species, and cover crop planting times and methods.

Data were collected between cover crop planting in late 2014 until near cover crop termination in spring of 2017 for a total of three cover crop seasons. Data were collected from two experiments at each location, one in each phase of a maize–soybean rotation each year. Tillage history varied among locations prior to cover crop planting in 2014; however, following cover crop planting in 2014, all plots were managed as no-till. Primary crop row spacing was 0.76 m at all locations with rows oriented approximately north-south, with the exception of WC (described below).

East Central Location

The EC plots were rainfed and located in a sub-humid climate (NDMC, 2017) (Table 1). Normal (1981–2010) annual precipitation near the location was ~750 mm (NCEI, 2017). The October–May precipitation ranged from 239 mm to 379 mm (Table 1) during the study. The soils were Tomek silt loam soil series (fine, smectitic, mesic Pachic Argiudolls) and Filbert (fine, smectitic, mesic Vertic Argialbolls) silt loam soil series (Soil Survey Staff, 2017; USDA-NRCS, 2017), which had been graded in the past for surface irrigation research. The rainfed EC plots were 9 m × 6 rows (4.6 m). The study area had previously been diked for surface irrigation research. In 2016, many plots were inundated with water for less than 1 wk with some plots inundated possibly longer than 1 wk (T. Galusha, personal communication, 2017); this likely masked any potential effects of the cover crops on soil water storage. Some flooded access tubes, or at least partially filled tubes, were observed at other times (e.g., 5 June 2015), though water in tubes may have come from rainfall catchment in some cases. We subsequently eliminated all soil water content data from the spring of 2015 through the spring readings of 2016 from this location.

Northeast Location

The NE location was rainfed and was in a sub-humid climate (NDMC, 2017) (Table 1). The normal (1981–2010) annual precipitation near the location was ~750 mm (NCEI, 2017). The October–May precipitation ranged from 164 mm to 391 mm (Table 1) during the study. The soils were primarily Coleridge silty clay loam (fine-silty, mixed, superactive, mesic Cumulic Haplustolls) mixed with some Baltic silty clay (fine, smectitic, calcareous, mesic Cumulic Vertic Endoaquolls) and Kennebec silt loam (fine-silty, mixed, superactive, mesic Cumulic Hapludolls) soil series (Soil Survey Staff, 2017; USDA-NRCS, 2017). The NE plots were 12 m × 8 rows (6.1 m). The study area had previously been graded for surface irrigation research. Some flooded access tubes, or at least partially filled tubes, were observed at times at NE, though water in tubes likely came from rainfall catchment in all or many cases.

South Central Location

The SC plots were irrigated and located in the transition zone between sub-humid and semiarid climates (NDMC, 2017) (Table 1). The area is impacted by two major air masses: the cold, dry continental air masses in the winter which flow from Canada and the warm, moist air that flows from Gulf of Mexico in summer (Irmak, 2010). The normal (1981–2010) annual precipitation in the area was ~730 mm (NCEI, 2017). Precipitation may vary in quantity and also "timing" during the year and growing season (Irmak, 2015). The October–May precipitation ranged from 147 mm to 319 mm (Table 1) during the study. The soil classification at the location is a Hastings silt loam (fine, smectitic, mesic Udic Argiustolls) series (Soil Survey Staff, 2017; USDA-NRCS, 2017). The plot dimensions were 9 m × 8 rows (6.1 m). Primary crops were irrigated using a lateral move system. No irrigation was applied specifically for cover crop production.

West Central Location

The WC plots were located in a semiarid climate (NDMC, 2017) (**Table 1**) on irrigated fields in a corn–soybean rotation. The normal (1981–2010) annual precipitation in the area is ~430 mm (NCEI, 2017). The October–May precipitation ranged from 122 mm to 282 mm (Table 1) during the study. The plots were located within two adjacent center pivot irrigated fields. The WC fields were planted in concentric circles to account for this geometry, and plots were eight rows (6.1 m) wide radially × 12 m long. Crop rows were generally northerly to southerly orientation in the plots. The soils at WC are primarily Kuma loam series (fine-silty, mixed, superactive, mesic Pachic Argiustolls) (Soil Survey Staff, 2017; USDA-NRCS, 2017). No irrigation was used directly for the cover crop production in this study. The WC plots were not included in the final year of the study (cover crop planting in 2016) because late maize harvest and cold weather did not allow for planting of cover crops. This site represented the most challenging location for this study as it is in a semi-arid region and the corn–soybean cropping system results in timing that can be very challenging in terms of planting and harvesting of cover crops. This site can often have harvest times in late November to early December and soils can be frozen when it is time to plant cover crops.

Experimental Design

Data were collected from an experiment with a factorial treatment design (type of cover crop species and time of cover crop planting). For the soil water storage study, only three of six cover crop treatments were selected: a seven-species mix [cereal rye at 22 kg ha^{-1}, black oats (*Avena strigosa* Schreb.) at 17 kg ha^{-1}, winter pea (*Pisum sativum* L.) at 9 kg ha^{-1}, hairy vetch at 4 kg ha^{-1}, balansa clover (*Trifolium michelianum* Savi) at 3 kg ha^{-1}, radish (*Raphanus sativus* L.) at 2 kg ha^{-1}, and forage collards (*Brassica oleracea* L.) at 1 kg ha^{-1}]; no cover crop (NCC); and in 2016 only, a cereal rye cover crop planted at 67 kg ha^{-1}. The cover crop mix was planted either pre-harvest of primary crops by broadcasting (MIX-PRE) or post-harvest by drilling (MIXPOST) and the rye cover crop was only planted pre-harvest (RYE-PRE) (**Table 2**). The NCC treatment was duplicated (i.e., two identical treatments) at each location and was

Table 1. Research location descriptions, soil, irrigation, and climate information and average weather conditions.

Location	*Location information*		*Month–year‡*	*T_{air} (°C)*	*WS (m s^{-1})*	*RH (%)*	*ET_r§ (mm)*	*Rs (MJ m^{-2} d^{-1})*	*P (mm)*	*CGDD¶ (°C d^{-1})*
			Average weather conditions and historic precipitation†							
East-central, near Mead, NE	Latitude#	41°9′ N	Oct. 2014–Apr. 2015	2.6	3.8	69	571	9.8	239	1135
	Longitude#	96°25′ W	May–Sept. 2015	21	3.1	78	715	17.3	646	3158
	Elevation (m)#	350	Oct. 2015–Apr. 2016	4.9	4.1	73	584	9.9	373	1354
	Field capacity (m^3 m^{-3})††	0.33, 0.31	May–Sept. 2016	22	2.9	73	840	19.7	608	3314
	Wilting point (m^3 m^{-3})††	0.20, 0.21	Oct. 2016–Apr. 2017	4.8	3.8	74	506	8.8	276	1352
	Irrigation method	Not Irrigated	May–Sept. 30 yr§§						487	
	Climate‡‡	Sub-humid	Oct.–Apr. 30 yr§§						260	
Northeast, near Concord, NE	Latitude#	42°22′ N	Oct. 2014–Apr. 2015	1.4	4.8	70	611	11	164	1011
	Longitude#	96°57′ W	May–Sept. 2015	19	3.7	77	763	18.4	621	2943
	Elevation (m)#	430	Oct. 2015–Apr. 2016	2.6	5.2	77	516	9.7	391	1059
	Field capacity (m^3 m^{-3})††	0.36, 0.32, 0.31	May–Sept 2016 2	0	3.6	72	892	20.4	375	3086
	Wilting point (m^3 m^{-3})††	0.27, 0.18, 0.17	Oct. 2016–Apr 2017	2.7	4.8	76	483	8.9	305	1086
	Irrigation method	Not Irrigated	May–Sept. 30 yr§§						464	
	Climate‡‡	Sub-humid	Oct.–Apr. 30 yr§§						291	
South-central, near Clay Center, NE	Latitude#	40°35′ N	Oct. 2014–Apr. 2015	3.1	4.2	666	86	11.6	147	1167
	Longitude#	98°9′ W	May–Sept. 2015	21	3.2	76	791	18.5	496	3151
	Elevation (m)#	560	Oct. 2015–Apr. 2016	5	4.1	71	633	10.5	319	1328
	Field capacity (m^3 m^{-3})††	0.34	May–Sept. 2016	21	3.3	73	895	20.3	371	3217
	Wilting point (m^3 m^{-3})††	0.14	Oct. 2016–Apr 2017	4.6	4.1	72	596	10.2	201	1305
	Irrigation method	Linear move sprinkler	May–Sept. 30 yr§§						484	
	Climate‡‡	Sub-humid/semi-arid	Oct.–Apr. 30 yr§§						247	
West-central, near Brule, NE	Latitude#	41°10′ N	Oct. 2014–Apr. 2015	3.6	4.4	60	827	11.8	122	1220
	Longitude#	102°2′ W	May–Sept. 2015	20	3.8	64	1048	21	391	3038
	Elevation (m)#	1110	Oct. 2015–Apr. 2016	3.9	4.1	66	689	11.3	282	1127
	Field capacity (m^3 m^{-3})††	0.27	May–Sept. 2016	20	3.6	60	1070	20.8	218	3024
	Wilting point (m^3 m^{-3})††	0.12	Oct. 2016–Apr 2017	4.1	4.4	59	819	11.9	156	1253
	Irrigation method	Center pivot	May–Sept. 30 yr§§						278	
	Climate‡‡	Semi-arid	Oct.–Apr. 30 yr§§						154	

† Weather variables are average daily air temperature (T_{air}), wind speed (WS), average relative humidity (RH), total tall reference evapotranspiration (ETr), average solar radiation (Rs), total precipitation (P), and cumulative grow-degree-days (CGDD).

‡ Growing seasons approximated using full month periods reported here. Primary cropping period approximately May–September, cover cropping period approximately October–April.

§ ETr provided by the HPRCC, computed using a Penman equation (HPRCC, 2017).

¶ Computed using a 0°C base and no temperature ceiling as Sharma and Irmak (2017) and Allen and Robinson (2007).

Google Earth Pro (Google LLC, Mountain View, CA), accessed 18 Dec. 2017. Elevations are above sea level.

†† For east-central, northeast, west-central: Soil Survey Staff (2017), for south-central: Irmak (2015).

‡‡ NDMC (2017)

§§ Average total precipitation for the 1981 to 2010 normal period (NCEI 2017).

randomized as being “PRE” or “POST”; however such was by name only accommodating the factorial design, with the two replicates treated the same. The treatment design for the analyses herein was considered to be unstructured for EC, NE, and SC, and the duplicated NCC plots were included as additional replicates of a single NCC treatment (six replications total). In the 2016–2017 cover crop season, when the RYE-PRE was included, the plots for one of the NCC treatments were randomly dropped.

Table 2. Planting and harvest dates for primary crops (PC) maize and soybean; planting and termination dates for cover crops (CC) at four Nebraska locations in 3 yr.

Cropping operation†	*Location‡ and cropping system§* *EC* *M-CC-Sy-CC-M-CC*	*EC* *Sy-CC-M-CC-Sy-CC*	*NE* *M-CC-Sy-CC-M-CC*	*NE* *Sy-CC-M-CC-Sy-CC*	*SC* *M-CC-Sy-CC-M-CC*	*SC* *Sy-CC-M-CC-Sy-CC*	*WC* *M-CC-Sy-CC-M-CC*	*WC* *Sy-CC-M-CC-Sy-CC*
CC broadcast	8–11 Sept. 2014	8–11 Sept. 2014	18 Sept. 2014	10 Sept. 2014	18–19 Sept. 2014	9–16 Sept. 2014	21 Oct. 2014	21 Oct. 2014
PC harvest	–	–	–	–	–	–	–	–
CC drill	23 Oct. 2014	23 Oct. 2014	28 Oct. 2014	28 Oct. 2014	21 Oct. 2014	21 Oct. 2014	8 Nov. 2014	8 Nov. 2014
CC biomass	28 Apr. 2015	15 Apr. 2015	29 Apr. 2015	13 Apr. 2015	30 Apr. 2015	15 Apr. 2015	14 Apr. 2015	14 Apr. 2015
CC termination	29 Apr. 2015	16 Apr. 2015	2 May 2015	17 Apr. & 2 May 2015	28 Apr. 2015	15 Apr. 2015	4 June 2015	4 June 2015
PC plant	18 May 2015	29 Apr. 2015	18 May 2015	27 Apr. 2015	27 May 2015	1 May 2015	–	–
CC broadcast	9 Sept. 2015	3 Sept. 2015	10 Sept. 2015	10 Sept. 2015	4 Sept. 2015	3 Sept. 2015	29 Sept. 2015	29 Sept. 2015
PC harvest	9 Oct. 2015	26 Oct. 2015	13 Oct. 2015	13 Oct. 2015	7 Oct. 2015	27 Oct. 2015	13 Oct. 2015	10 Nov. 2015
CC drill	14 Oct. 2015	28 Oct. 2015	16 Oct. 2015	16 Oct. 2015	12 Oct. 2015	27 Oct. 2015	11 Dec. 2015	11 Dec. 2015
CC biomass	15 Apr. 2016	25, 26 Apr. 2016	22 Apr. 2015	5 May 2016	13, 15 Apr. 2016	4 May 2016	14 Apr. 2016	15 Apr. 2016
CC termination	22 Apr. 2016	26 Apr. 2016	23 Apr. 2016	5 May 2016	22 Apr. 2016	5 May 2016	28 Apr. 2016	28 Apr. 2016
PC plant	6 May 2016	ca. 9 May, 2016	6 May 2016	18 May 2016	12 May 2016	13 May 2016	15 May 2016	16 May 2016
CC broadcast	8 Sept. 2016	6 Sept. 2016	8 Sept. 2016	8 Sept. 2016	–	–	14 Sept. 2016	14 Sept. 2016
PC harvest	9 Nov. 2016	23 Oct. 2016	1 Nov. 2016	14 Oct. 2016	18 Oct. 2016	10 Oct. 2016	14 Nov. 2016	28 Sept. 2016
CC drill	11 Nov. 2016	25 Oct. 2016	2 Nov. 2016	2 Nov. 2016	21 Oct. 2016	14 Oct. 2016	–	14 Oct. 2016
CC biomass	–	–	–	–	–	–	–	–
CC termination	5 May 2017	25 Apr. 2017	~9 May 2017	~9 May 2017	–	–	–	–
PC planting	–	12 May 2017	–	–	12 May 2017	8 May 2017	–	–

† PC, primary crop; CC, cover crop.

‡ Locations are east-central (EC), northeast (NE), south-central (SC), and west-central (WC), Nebraska.

§ Cropping systems are for 2014, 2015, and 2016, with M = maize, Sy = soybean, and CC = cover crop.

The experimental design at WC was split-plots with cover crop planting time as a whole plot factor and cover crop type as the split-plot. The treatment design was a factorial for most analyses. Thus NCC treatments were thus kept separate for that location (NCC-PRE and NCC-POST, respectively). The experimental design for the other three locations, EC, SC, and NE, was a generalized randomized complete block design with three replications at EC and four replications at SC and NE. At WC, the whole plots were arranged in a completely randomized design. Treatments were applied to the same plots during the entire duration of the study at all locations. Data were collected from only three replications of each treatment (three of each no-cover treatment in the first 2 yr). For SC, NE, and WC, the monitored replicates were selected randomly without regard to blocking, thus resulting in incomplete blocks (NE and SC) or whole plots (WC), which were treated as missing data.

Weather and Climate Data

Weather and climate data were obtained from three sources. The primary source was the Nebraska Mesonet weather data network (Mesonet; https://mesonet.unl.edu). Mesonet data were obtained from the High Plains Regional Climate Center (https://hprcc.unl.edu). There were Mesonet stations near (≤~3.1 km; HPRCC, 2018; Google Earth Pro (Google LLC, Mountain View, CA) each of the experimental locations (**Table 3**), as determined using Google Earth Pro. Winter precipitation data and long-term average precipitation data for the 1981–2010 normal period were also obtained from the US NOAA's Global Historic Climatology Network (GHCN) weather stations in the vicinity (Table 3). The winter precipitation data were retrieved from the High Plains Regional Climate Center and the normal period average climate data were obtained from NCEI (2017). Mesonet data were validated using tipping bucket rain gauges, which were installed near the plots

Table 3. Weather stations used for each study location.

Location†	*Mesonet*‡	*GHCN*§
EC	Memphis 5	N Mead 6 S
NE	Concord 2 E	Haskell Ag Lab
SC	Harvard 4 SW	Clay Center 6 ESE and Hastings 4 N
WC	Big Springs 8 NE	Big Springs and Ogallala

† Locations are east-central (EC), northeast (NE), south-central (SC), and west-central (WC), Nebraska.

‡ Nebraska Mesonet (https://mesonet.unl.edu), with data provided by the High Plains Regional Climate Center (HPRCC; https://hprcc.unl.edu).

§ The U.S. National Oceanic and Atmospheric Administration's Global Historic Climatology Network, with data provided by the HPRCC, used for winter precipitation and when Mesonet data were missing.

during portions of the non-winter months. These rain gauges were RAINEW 111 Tipping Bucket Wired Rain Gauges (RainWise, Inc., Trenton, ME) coupled with Model UA-003–64 HOBO Pendent Event Data Loggers (Onset Computer Corporation, Bourne, MA).

Measurements

Cover crop aboveground biomass samples were harvested about 2 wk prior to primary crop planting each spring (Table 2), with the exception of WC for the 2014 cover crop season, where it was sampled earlier and biomass data from that location-year were subsequently eliminated from this study. Samples were collected from two random 0.46 m^2 sub-areas in each cover crop plot and subsamples were combined into one measurement for each plot. Harvested biomass samples only included cover crop species.

Soil water measurements were taken using neutron probes CPN 503 ELITE Hydroprobe and 503 DR Hydroprobe (CPN, Inc., Concord, CA) and Troxler Model 4300 Soil Moisture Gauge (Troxler Electronic Laboratories, Inc., Research Triangle Park, NC). During readings the probes were centered at 0.15, 0.46, 0.76, and 1.07 m below soil surface ± ~0.05 m. Differences in access tube heights, neutron probe stop settings, and in some cases neutron count times, occurred and were considered random error. Total neutron access tube depth also varied between locations and sometimes between plots at a given location. The only exception to the neutron probe method occurred on 6 Apr. 2015 at SC, when soil water contents were determined gravimetrically for logistical reasons. For the gravimetric method, bulk density was assumed uniform for each measurement depth and bulk densities were provided by S. Irmak (unpublished data, 2010).

Neutron probe calibrations were determined locally based on gravimetric measurements or cross-calibration with a calibrated neutron probe. However, the probe used at NE between 23 Mar. 2015 and 21 Sept. 2015, had a less certain calibration and data from that site for this period were eliminated from the final analysis.

Volumetric water content measurements were converted to soil water storage in mm. Soil water storage was analyzed for the 0.15-m water content measurements (representing the top ~0.3 m of soil) and for an average of the top four measurement depths (0.15, 0.46, 0.76, and 1.07 m), approximately representing the managed root zone for the primary crops (surface to ~1.2 m depth).

Soil water storage was monitored near time of cover crop planting, time of termination, and throughout the primary crop growing season to determine the effect of the cover crops on early season soil water storage available for primary crop growth and development (Tables 2 and 4). It should be noted that on some dates, not all plots or depths were measured because

Table 4. Soil water storage measurement dates.

Location			
EC	*NE*	*SC*	*WC*
5 Nov. 2014	12 Dec. 2014	–	**3 Dec. 2014**†
26 Mar. 2015	23 Mar. 2015	6 Apr. 2015	**6 Apr. 2015**
–	15 Apr. 2015	–	–
5 June 2015	27 May 2015	–	–
–	23 June 2015	–	10 July 2015
24 July2015	23 July 2015	29 July 2015	22 July 2015
–	21 Aug. 2015	–	5 Aug. 2015
25 Sept. 2015	21 Sept. 2015	1 Oct. 2015	**1 Oct. 2015**
10 Nov. 2015	**20 Oct. 2015**	**30 Oct. 2015**	–
–	–	–	9 Mar. 2016
22 Mar. 2016	5 May 2016	11 Apr. 2016	11 Apr. 2016
26 May 2016	**2 June 2016**	**17 June 2016**	**10 June 2016**
27 July 2016	20 July 2016	29 July 2016	20 July 2016
23 Sept. 2016	28 Sept. 2016	–	27 Sept. 2016
1 Dec. 2016	**10 Nov. 2016**	**5 Dec. 2016**	–
24 Apr. 2017	**8 May 2017**	**3 Apr. 2017**	–

† Bolded values were included in computing change in soil water storage during the principal cover crop growing period.

of water in the access tubes or damaged access tubes. Some neutron probe measurement sets were accomplished on consecutive days because of time constraints or access tube conditions. In such cases, only the first measurement date is shown in **Table 4**.

Statistical Analysis

Statistical analyses were computed using PROC GLIMMIX in SAS 9.4 (SAS Institute, Inc., Cary, NC). The residuals were assumed Gaussian in all cases. Blocking was treated as a random effect, and blocking variance was allowed to be zero if computed to be so. Tukey-Kramer adjustments were used to account for multiple treatment comparisons. Treatment differences were considered significant using a cutoff probability value of 5% > |t| and 5% > F. Estimated least-squares means were used for treatment comparisons. Each location, rotation phase, and year were analyzed separately (location and rotation for repeated measures analyses). Therefore, conclusions should not be drawn among the analyses.

For the biomass analyses, we tested the assumption that treatment variances were equal. In cases where the variances were found to be significantly different (at the 5% level) we analyzed the data using treatment specific variances. Residuals were assumed to be normally distributed. For the biomass, we did not include blocking, this facilitated testing for equal treatment variances. If blocking were included, in some cases blocking effects would have been zero and in the case of WC, since the NCC treatment was excluded from biomass analyses, the experimental design at WC reduced to a completely randomized design anyway. In biomass analyses, if two or more replicates of a treatment had zero biomass, then SAS PROC MEANS was used to compute treatment means and confidence intervals.

The difference between spring and autumn soil water storage was used as an indication of the net impact of the cover crops on soil water storage for the primary crop. We note that the timing of autumn and spring measurements varied notably among locations and years (Table 4). We acknowledge that some of the difference in soil water storage may result from differences in neutron probes used and/or calibrations. In the case of SC, the gravimetric measurements also introduced a difference in methodologies and uncertainty regarding bulk density. However, we assumed that these differences would affect all treatments.

Repeated measures analyses were also performed on soil water storage for all dates by location and crop rotation as a means of presenting the time series of collected data. Several covariance structures were tested, to determine which was the most appropriate for each analysis. For each analysis, we selected the structure that resulted in the lowest corrected Akaike's information criterion (SAS, 2018) and for which PROC GLIMMIX computed variance for all covariance parameters (except the blocking and blocking by treatment terms). The primary crop rotation phase factor was not accounted for in repeated measures analysis. In the repeated measures analyses, the NCC plots were separated into "PRE" and "POST," following designation in the experimental design, even though both were identical in treatment. The reason for this was that it enabled PROC GLIMMIX to properly compute the degrees of freedom.

All interactions were tested at a 10% probability for $> F$. When interactions involving measurement date were not significant, we only investigated the main effects of treatments (treatment factors for WC) where these were significant. Main effects of measurement date were considered less interesting. In all interaction cases, simple effects were examined if the treatment (treatment factor WC) effect F-tests were significant when sliced by measurement date (or another factor in the case of WC) at a 5% probability for $> F$. Main effects and treatment or factor simple effects were tested at a 5% probability for $> F$ and $> |t|$.

Results and Discussion

Study Conditions

Mesonet precipitation ranged from 97% to 102% of the plot rain gauge when the plot rain gauge data were considered reliable. We therefore used Mesonet precipitation in all further analyses and discussions. Total October 2014 through April 2015 precipitation was less than the reported 1981–2010 Normal for nearby stations for all study locations, ranging from 21 mm less than normal to 127 mm less for EC and NE, respectively (Table 1, **Figure 2**). Conversely, the May through September 2015 precipitation was greater than or similar to the normal values, ranging 12 mm more to 159 mm greater for SC and EC, respectively. The October 2015 through April 2016 precipitation

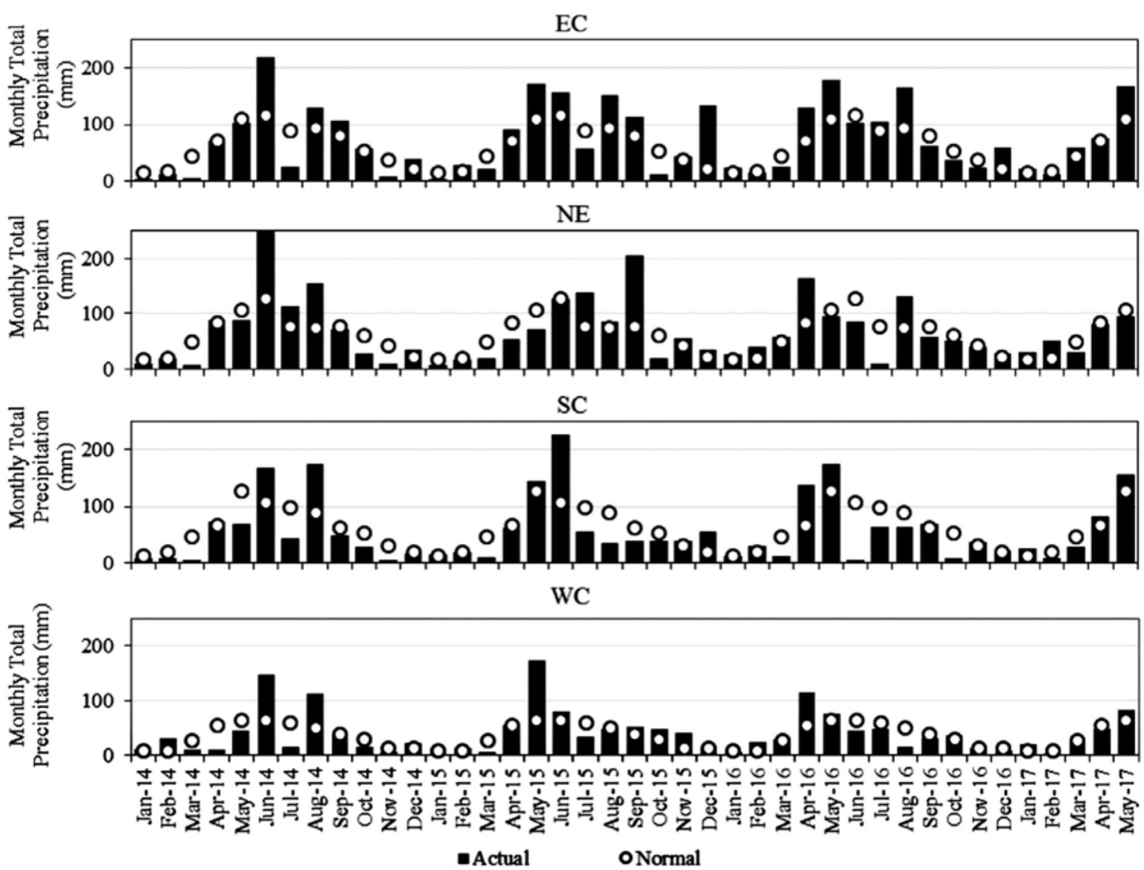

Figure 2. Monthly measured and 1981–2010 normal period average monthly precipitation. Climate normals are from NCEI (2017). The climate normal GHCN stations for each location are as follows: EC = Mead 6S NE US, NE = NE Nebraska Experimental Station NE US, SC = Clay Center NE US, and WC = Big Springs NE US. The truncated bar for NE is 527 mm (precipitation from the GHCN station was 324 mm for that same month).

was also greater than normal at all locations. The May through September 2016 precipitation ranged from 113 mm less at SC to 121 mm greater at EC. The precipitation during this period was less than normal at all locations except EC. The October 2016 through April 2017 precipitation ranged from 46 mm less at SC to 16 mm greater at EC.

Cover Crop Biomass

Where differences occurred between the MIX-PRE and MIX-POST, the latter had less biomass except for SC following maize in 2016 (**Figure 3**). The biomass results at EC, NE, and SC were of often similar magnitude to cereal rye cover crop biomass reported by Basche et al. (2016), who seeded before

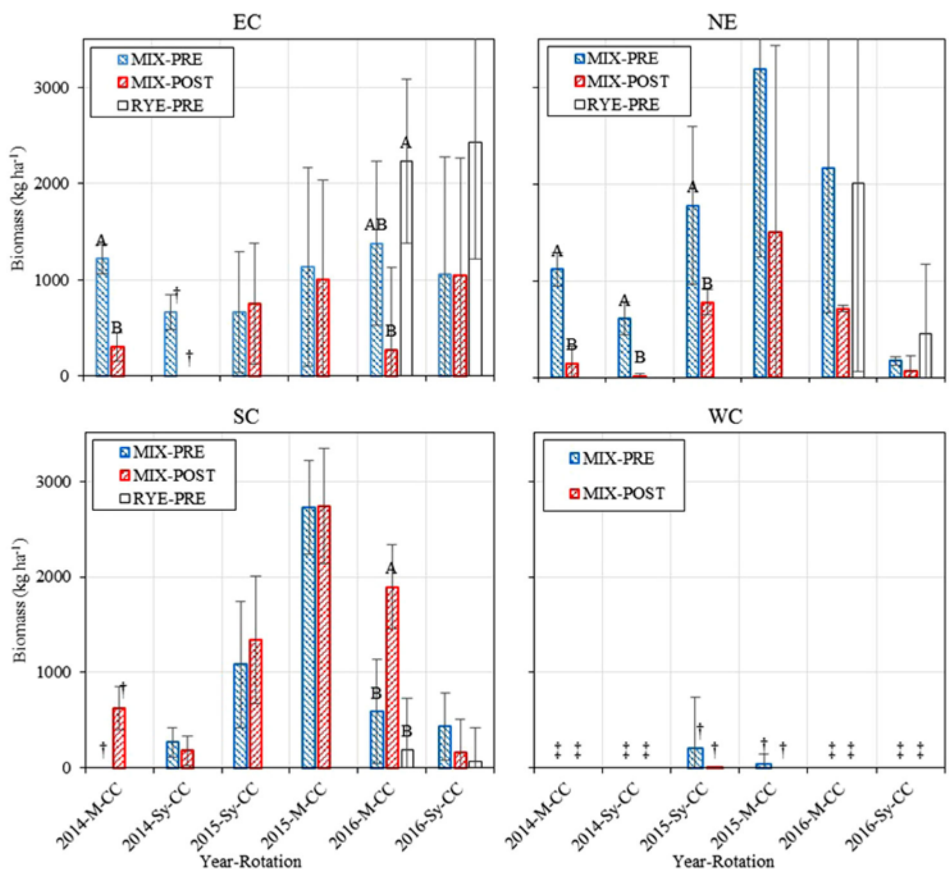

Figure 3. Mean cover crop biomass. Rotation phases are M = maize, Sy = soybean, and CC = cover crop; the year corresponds to the primary crop season and cover crop planting. The error bars are 95% confidence intervals of the means. The truncated error bars would be symmetrical of the lower limits. Each cluster of bars is an individual analysis. Identical letters in a cluster represent no statistical significance. Where no letters are presented, differences were not significant. † = Means were computed using PROC MEANS; ‡ = No data.

harvest or within a day after harvest. In 2016, RYE-PRE had greater biomass than MIX-POST following maize at EC, but had less than MIX-POST at SC. This is possibly because of timing of precipitation at EC vs. SC that year, both having similar September precipitation (62 mm at EC, 67 mm at SC), but SC received ~42 mm of that prior to broadcast and EC received most afterward. The generally large biomass production at SC may be attributed to the favorable weather conditions (Table 1) and crop irrigation, among other factors. For example, the average temperature for the October 2015– April 2016 growing season at SC was 5.0°C, which was higher than NE and WC, but relatively similar to EC.

For WC, none of the cover crop biomass means were different than zero (Figure 3). The relatively small biomass accumulation at that location may be a result of late planting dates related to weather and lack of autumn rainfall. Although there was indication of greater biomass in the 2014 season, data were not included because the sampling date was not well synchronized with neutron probe readings. However, cover crop establishment was generally difficult for the data presented, at WC. Precipitation at WC from October–April was 122 mm, 282 mm, and 156 mm for 2014–2015, 2015–2016, and 2016–2017, respectively (Table 1). Cover crop drilling was typically late autumn at WC (Table 2). The total precipitation for the 30 d following the cover crop drilling date was about 7 mm at WC for the 2014 and 2015 seasons compared with >19 mm at the other sites. Also, 7-d average air temperature centered on the drilling date was about 4°C at WC and >10°C at the other locations. Similarly, 7-d average soil temperature centered on the drilling date was about 4°C at WC and >12°C at the other locations. These factors probably reduced cover crop establishment and growth because cumulative growing degree days and precipitation during the cover crop growing seasons were similar at WC and other sites. The cover crops were not irrigated at any site. The WC location was also dry in terms of evaporative demand, having the lowest average October–April relative humidity and the largest reference ET among locations. When coupled with the low total precipitation this may have contributed to the minimal biomass production.

We expected that any cover crop impact on soil water storage would be associated with several variables, including cover crop biomass accumulation. This impact would be both in terms of cover crop ET (Martinez-Feria et al., 2016; Sharma et al., 2017) and soil evaporation during primary crop growth (Blanco-Canqui et al., 2015). However, cover crop biomass would also be related to other cover crop benefits as discussed by Blanco-Canqui et al. (2015) and Unger and Vigil (1998).

Assuming that the 21 mm per 1000 kg ha^{-1} from Martinez-Feria et al. (2016) for rye is reasonable for our locations and cover crop species, we computed possible cover crop transpiration for each site. Note that our observations were that rye accounted for the majority of spring biomass samples in the seven-specie mix. In 2016 and 2017, biomass was quantified by specie and rye was >87% of the total observed biomass for all included plots with data and non-zero total biomass, except in 3 low biomass yielding plots (<11 kg ha^{-1}) where rye was not observed in 2017 and one plot with >600 kg ha^{-1} with no observed rye at EC in 2016. For EC the transpiration was estimated to be between ~0 and 51 mm, at NE ~0 to 67 mm, at SC ~0 to 57 mm, and negligible at WC (since cover crop biomass was statistically not different than zero for that site). As mentioned earlier, Sharma et al. (2017) found that cover crop season ET for cover crops with production seed maize residue was not different than seed maize residue alone in Nebraska.

Differences in Spring and Autumn Soil Water Storage

The spring soil water storage in the top 0.3 m was either greater than that in the autumn or the difference was not different from zero in all cases (**Figure 4**). Where treatment differences occurred, they were small, <11 mm, and are not expected to have notable impact on the following primary crop considering that October–April precipitation was >120 mm for all cases.

In all cases, the 1.2-m soil profile was wetter in the spring than in the autumn or the difference was not different from zero (**Figure 5**). Most of the observed treatment differences for the 1.2-m profiles were <15 mm (<0.013 m^3 m^{-3}) and were likely too small to be agronomically important considering maize has been reported to have ~450–630 mm of seasonal ET (Djaman and Irmak, 2013; Suyker and Verma, 2009) and soybean ~420–600 mm (Irmak et al., 2014; Suyker and Verma, 2009) in Nebraska. At SC for maize–cover crop between 30 Oct. 2015 and 17 June 2016, MIX-PRE had a difference that was 26 mm greater than the NCC. This could represent increased available water for the primary crop with cover crops. This location–rotation–year also had large observed biomass yield (Figure 3). Possible mulching effects on evaporation may be a contributing factor (Blanco-Canqui et al., 2015), which we suspect may have greater impact than cover crop transpiration prior to the autumn readings. Blanco-Canqui et al. (2011) also observed greater springtime soil water content in cover crop plots as compared to NCC plots about a year after the end of a long-term study and suggested decreased evaporation as a cause. However, no differences were observed for SC maize–cover crop between 30 Oct. 2015 and 17 June 2016 in the top 0.3 m (Figure 4) as might be expected (Blanco-Canqui et al., 2011).

The above results suggest that cover crops had small influence on soil water storage. These results agree with average soil water storage findings of Sharma et al. (2017). The results suggest that either ET is similar between the treatments or that differences in ET are compensated by differences in drainage (Qi and Helmers, 2010; Basche et al., 2016). Thus, it is possible that

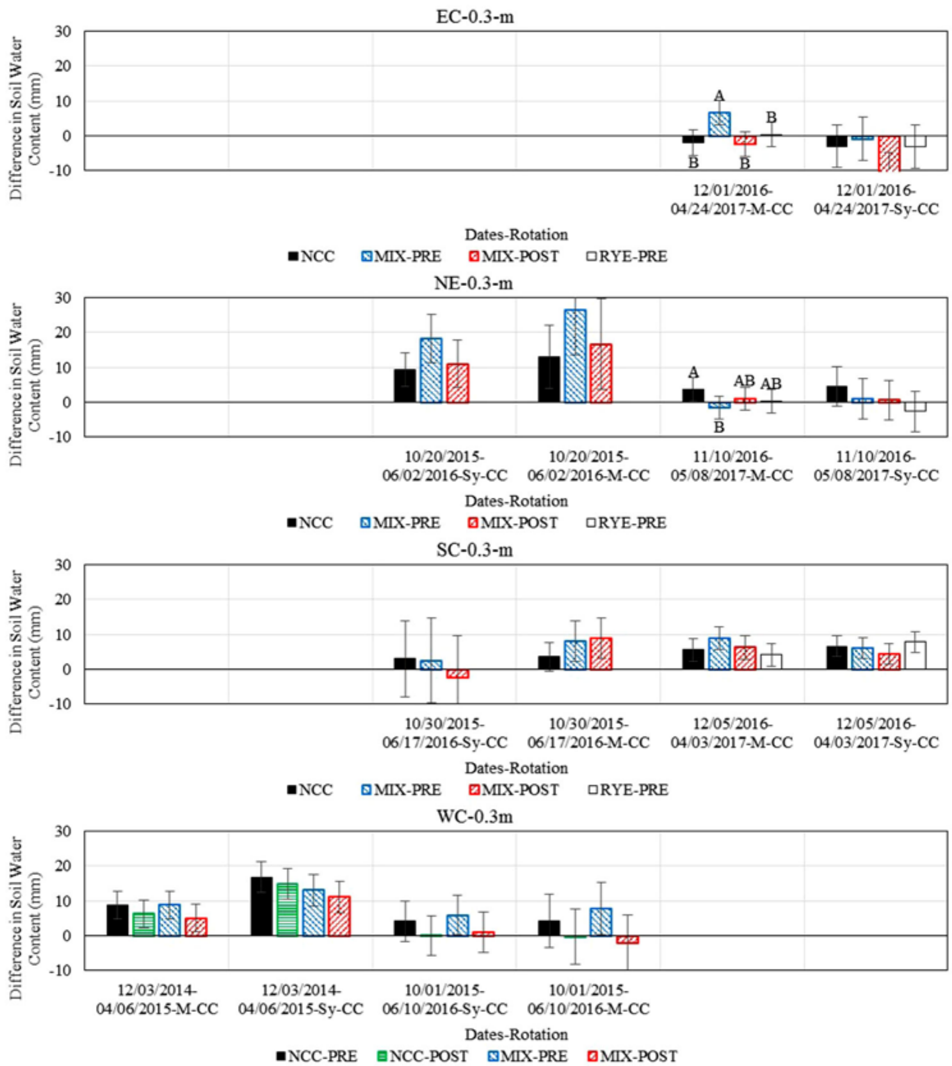

Figure 4. Mean spring minus preceding autumn soil water storage in the top 0.3 m of the soil profile. Crop rotation phases are M = maize, Sy = soybean, and CC = cover crop. Treatments are NCC = no cover crop, MIX = cover crop mix, and RYE = cereal rye, with PRE = pre-harvest broadcasted, and POST = post-harvest drilled. The error bars are 95% confidence intervals of the means. The truncated error bars would be symmetrical of the displayed limits. Each cluster of bars is an individual analysis. Identical letters in a cluster represent no statistical significance. Where no letters are presented, differences were not significant. All data included here had at least two replicates.

cover crops resulted in reduced deep percolation. However, Nielsen et al. (2015) observed some differences in their study in western Nebraska and Colorado. They did, however, observe a smaller effect on water content for a site and year that had comparatively lower cover crop plant population.

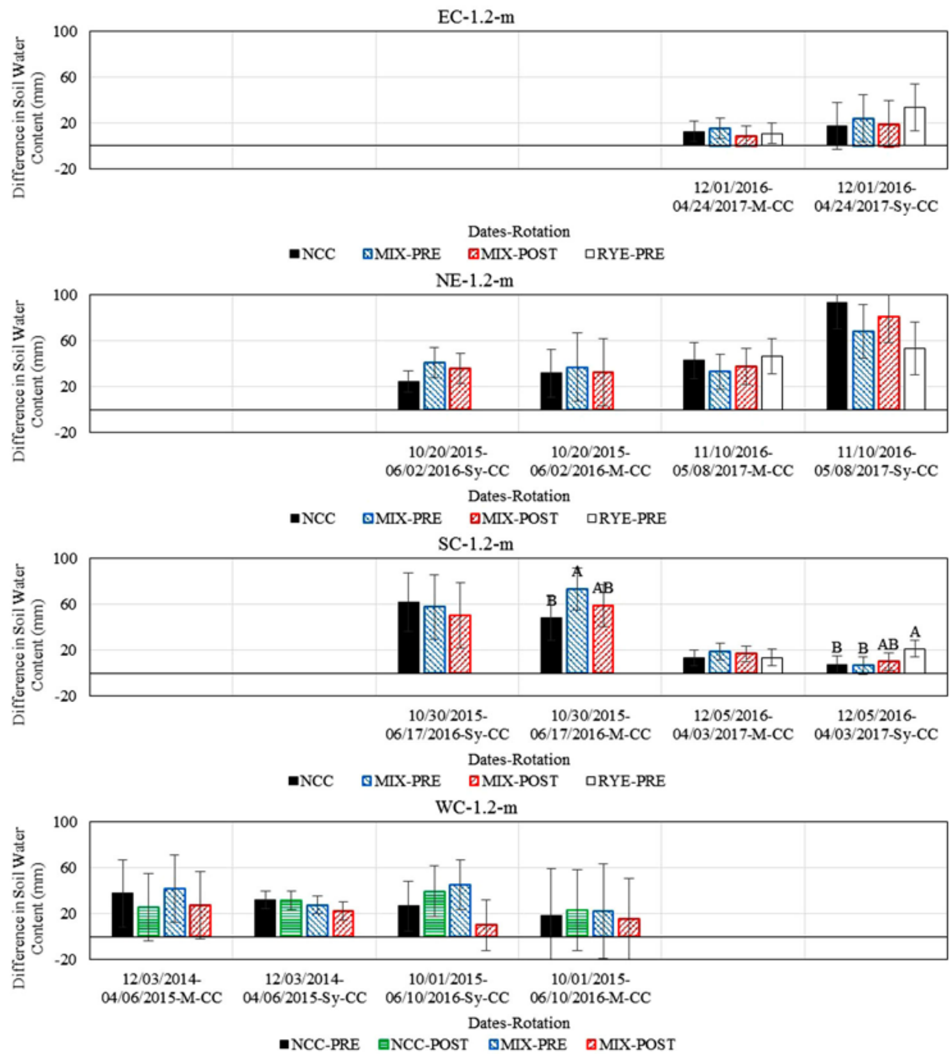

Figure 5. Mean spring minus preceding autumn 1.2-m soil profile water storage. Crop rotation phases are M = maize, Sy = soybean, and CC = cover crop. Treatments are NCC = no cover crop, MIX = cover crop mix, and RYE = cereal rye, with PRE = pre-harvest broadcasted, and POST = post-harvest drilled. The error bars are 95% confidence intervals of the means. The truncated error bars would be symmetrical of the displayed limits. Each cluster of bars is an individual analysis. Identical letters in a cluster represent no statistical significance. Where no letters are presented, differences were not significant. All data included here had at least two replicates.

This supports our findings for WC, with low biomass in 2015. If more biomass were produced, perhaps differences would have been observed for WC. However, in the 2014 cover crop season, when there was presumably more cover crop biomass at WC, we still did not observe differences (Figure 4 and 5).

One reason for the lack of difference among treatments could be that sufficient rainfall had been accumulated in all plots by the spring reading dates. Basche et al. (2016) suggest that such may be the case. Also, our driest location, WC, had essentially zero cover crop biomass production (except apparently in 2014–2015). Annual cover crop transpiration in our study may have been about 0 to 70 mm based on our biomass results and the relationship of 21 mm per 1000 kg ha^{-1} of Martinez-Feria et al. (2016), which was developed for rye. Recall that we typically observed the majority of the mix treatment spring biomass samples to be rye. It is probable that in many years this amount of soil water depletion would be replenished during spring and summer rainfall at most of the locations. If we assume that the primary crop growing season ends at the end of October with 60% of available water depleted from the top 1.2 m of the soil profile (Yonts et al., 2008), then depletion would be about 120 mm, 160 mm, 140 mm, and 140 mm for EC, NE, SC, and WC, respectively, using the maximum available water capacity for each location reported by Soil Survey Staff (2017). The 1981–2018 normal October–April precipitation was about 260 mm, 290 mm, 250 mm, and 150 mm, respectively, for the same sites (Table 1) (NCEI 2017). Therefore, neglecting runoff and presuming timing of precipitation is favorable to replenish the cover crop water extraction, 70 mm of cover crop transpiration would likely have no significant impact at EC, NE, and SC, and may not be entirely replenished by rainfall at WC. If we represent the cover crop growing period by the October–April precipitation for the study years and otherwise use similar estimates for depletion with 70 mm of cover crop transpiration, then precipitation would be sufficient for all years at EC. Similarly, precipitation would be sufficient for 2 of 3 yr at NE, and 1 yr at SC and WC, with 1 yr being a marginal ~10 mm deficit at SC.

Our observations may also be the result of other sources of soil water storage variability. For instance, the tillage history at each of the sites followed by no-till management during this study may have affected the bulk density and water content. However, we anticipate that these effects should impact all plots. Other sources of variability were mentioned in the materials and methods section. Another possibility is that most of the cover crop effect may be in the upper soil profile (<0.3 m, see Figure 4), as may be expected if the cover crop rooting depths were shallow. It is also possible that soil evaporation is of similar magnitude to cover crop ET (P. Jasa, personal communication, 2017). For instance Sharma et al. (2017) did not find differences in ET between a cover crop and a seed corn residue treatment. Finally, our analysis may omit effects (e.g., depletion) caused by the pre-harvest-planted cover crops prior to the autumn readings (Tables 1 and 2). Thus, our spring to autumn differences may have not fully captured the cover crop effect. Further investigation into other water balance components as Qi and Helmers (2010) may provide useful insight into the climatic limitations regarding cover crop impacts on soil water storage.

Soil Water Storage over Time

The seasonal patterns of soil water storage for the 0.3-m upper layer are apparent in **Figures 6 and 7**; however, temporal variations between measurement dates were not captured. Simple effect treatment differences (when interactions were significant) and treatment main effects (when interactions were not significant) were small (<15 mm). The variability in the data is visible in the behavior of the two NCC lines. For the 1.2 m profile, there were no

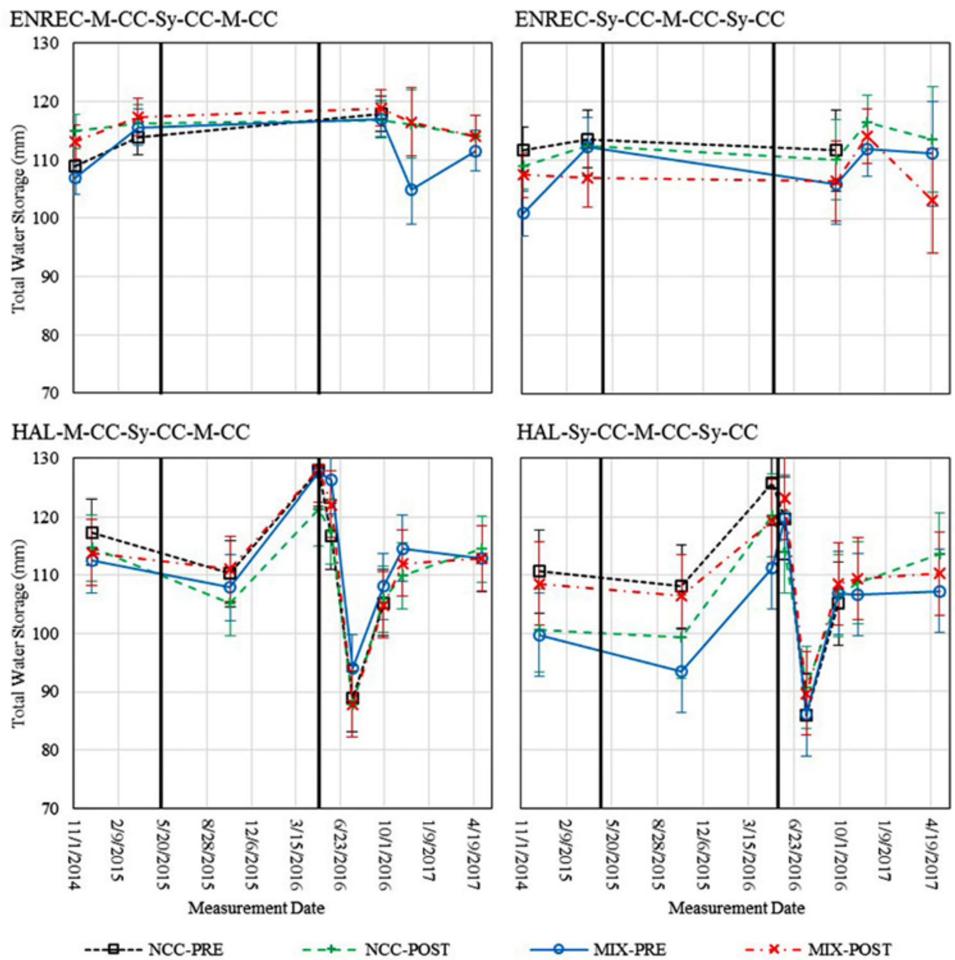

Figure 6. Mean soil water storage for the top 0.3 m of the soil profile computed using repeated measures analyses for EC (top) and NE (bottom). Crop rotation phases are M = maize, Sy = soybean, and CC = cover crop. Treatments are NCC = no cover crop, MIX = cover crop mix, and RYE = cereal rye, with PRE = pre-harvest broadcasted, and POST = post-harvest drilled. For NE Sy-CC-M-CC-Sy-CC, on 5 May 2016, there were no data for MIX-POST; all other cases presented had at least two replicates per treatment for each date. Vertical black lines are approximate primary crop planting dates. Error bars are 95% confidence intervals of the estimated means. The truncated error bars would be symmetrical of the displayed limits.

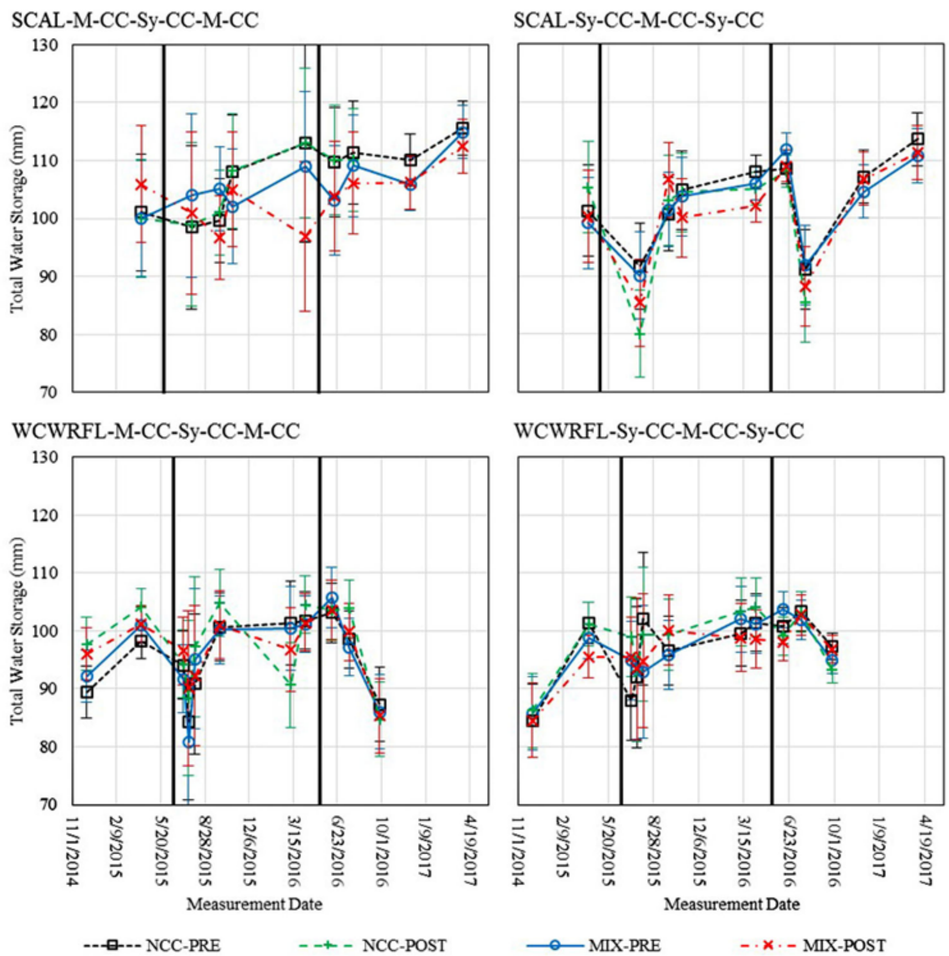

Figure 7. Mean soil water storage for the top 0.3 m of the soil profile computed using repeated measures analyses for SC (top) and WC (bottom). Crop rotation phases are M = maize, Sy = soybean, and CC = cover crop. Treatments are NCC = no cover crop, MIX = cover crop mix, and RYE = cereal rye, with PRE = pre-harvest broadcasted, and POST = post-harvest drilled. For WC Sy-CC-M-CC-Sy-CC on June 10, 2016, there was only one replicate for MIX-PRE; all other cases presented had at least two replicates per treatment for each date. Vertical black lines are approximate primary crop planting dates. Error bars are 95% confidence intervals of the estimated means. The truncated error bars would be symmetrical of the displayed limits.

significant treatment main effects and the only significant treatment simple effects was ~24 mm between the two NCC treatments at EC maize–cover crop–soybean–cover crop– maize–cover crop on 23 Sept. 2016, the one case where the measurement time × treatment interaction was significant.

Based on the results of the repeated measures analyses, there was little evidence that the cover crops had a significant impact on soil water storage during the primary crop growing season. However, we did not account for crop phase effects in these analyses. This would suggest that any effects of soil water depletion from cover crop ET or effect of cover crop residue on primary crop ET were either minor or less than the least significant differences herein. Other effects of cover crops on soil water storage may include changes to soil infiltration (Blanco-Canqui et al., 2015) and available water capacity, as observed by Basche et al. (2016). We do not expect that the duration of the current study was long enough to achieve differences in these soil hydraulic properties to significantly affect our soil water storage measurements.

Conclusions

Variations in soil water storage as affected by cover crops in maize–soybean rotations were studied at four locations throughout Nebraska. Cover crop biomass production was quite variable among cover crop treatments. At WC (the driest location), reported cover crop biomass was practically zero due to planting difficulties, weather and primary crop harvest dates, and lack of precipitation. This is a common situation in the semiarid part of Nebraska and brings into question the viability of growing cover crops in a corn–soybean rotation in this region.

Few treatment differences were found in spring minus autumn soil water storage for EC, NE, and SC. For WC, cover crop biomass was often small; therefore, a significant impact on soil water storage was not expected. The treatment differences were typically small. If ET was different between treatments, cover crops may have reduced deep percolation. In most years of the study at EC, NE, and SC, we demonstrated that October–April precipitation was sufficient to refill a depleted soil profile and accommodate ~70 mm of cover crop transpiration. In the 2014 cover crop season, when such was not the case at SC and NE, our cover crop biomass production was also low.

Our results from this study across four sites in Nebraska suggest negligible impact of cover crops on soil water storage for primary crop production. Also, winter cover crops are likely of limited value (on the basis of biomass production) in areas with both late cover crop planting and weather conditions like WC. However, locations similar to SC seem suitable for cover crop adoption on the basis of biomass productivity (both MIX treatments following maize in 2015 were >2700 kg ha^{-1}). We conclude that winter cover crops grown in the conditions of our study would have negligible impact on soil water storage for the primary maize and soybean crops. Based on results from Iowa and our analyses, it is expected that, in a normal year, all but the western most site would receive sufficient rainfall to negate the impact of 1000 kg ha^{-1} of rye-dominated cover crop biomass production.

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