Impacts of cover crops on soil physical properties: Field capacity, permanent wilting point, soil-water holding capacity, bulk density, hydraulic conductivity, and infiltration

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IMPACTS OF COVER CROPS ON SOIL PHYSICAL PROPERTIES: FIELD CAPACITY, PERMANENT WILTING POINT, SOIL-WATER HOLDING CAPACITY, BULK DENSITY, HYDRAULIC CONDUCTIVITY, AND INFILTRATION

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ABSTRACT. *Field experiments were carried out to quantify the effects of cover cropping on soil physical properties. Field capacity (FC), permanent wilting point (PWP), soil-water holding capacity (SWHC), bulk density (ρ_b), saturated and unsaturated hydraulic conductivity (K_s and K_{us}, respectively), and infiltration rates were measured and compared for four land cover treatments [cover crop without seed maize (CC), seed maize followed by cover crop (SCCC), bare soil, and seed maize without cover crop (SC)] in three large-scale production fields (~64 ha each) with silt loam soil in the 2012-2013, 2013-2014, 2014-2015, and 2015-2016 cover crop growing seasons. All production fields had been in a maize or soybean and cover crop rotation since 2002 and were farmed with row crops for decades before 2002. Field-measured soil properties in the SCCC treatment were also compared with historical values measured by the USDA-NRCS in 1974. In general, soil physical properties were unaffected by incorporating rotational cover crops into row crop cultivation. No significant differences ($p > 0.05$) in SWHC were observed between the treatments at any of the periods (seasons). When compared to the 1974 NRCS-measured values for the research fields, overall, the FC, PWP, and as a result the SWHC did not exhibit change at the end of the research in 2016 after cultivating cover crops since 2002. K_s values at the topsoil exhibited interannual variation for the same treatments, but there were no significant differences ($p > 0.05$) in K_s between land cover treatments neither in any year nor for the same treatment between years. K_{us} values were not significantly different ($p > 0.05$) between treatments neither for a given year nor between years. On average, the infiltration rate in the SCCC treatment was about 64% lower than in the SC treatment, indicating that incorporating cover crops into a maize-soybean rotation decreased the infiltration rate. While cover crops could be beneficial for grazing due to their nutritional value, and perhaps other benefits, which depend on numerous factors, in this research there was no sufficient evidence that cover crops can significantly alter the soil physical properties that were investigated in these experimental conditions.*

Keywords. *Cover crops, Maize-cover crop rotation, Soil properties.*

Interest in the use and management of cover crops among farmers in the Midwest and other regions of the U.S. has been increasing in recent years. Cover crops have been suggested as rotational crops due to their potential benefits for fertility improvement and management, nutrient cycling, water management, grazing, and other purposes. Cover crops are plants that are seeded in production fields for the purpose of grazing and maintaining or improving soil and ecosystem quality. Historically, cover crops have been grown to provide or supplement nitrogen (N) to the soil for subsequent crops. However, with potentially declining costs of synthetic nitrogen fertilizers, the use of legume cover crops in cropping systems has been declining. In addition to supplying N to a subsequent cash crop, cover crops also have potential to provide additional organic matter to the soil, which might lead to improved soil organic matter, soil physical properties, and soil infiltration characteristics (Macrae and Mehuys, 1985; Patrick et al., 1957; Williams, 1966). Deep-rooted cover crops can be particularly effective in increasing soil-water storage capacity (Reeves, 1994, 1997). They also have potential to improve the soil's capacity to carry machines and improve field accessibility by using (primarily in humid areas with substantial precipitation) and removing excess water and maintaining soil structural components (Kankanen et al., 1998). However, cropping systems including cover crops in rotation do not always increase soil organic matter or change soil

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physical properties, and the literature revealed contrasting findings, as the impacts of cover crops on soil properties depend on numerous factors.

Studies have also shown that the impacts of cover crops on the aforementioned variables differ substantially, depending on numerous factors. For instance, in a 20-year green manure application study, Van der Linden et al. (1987) observed very little change in soil organic matter content (OMC) but observed significant changes in soil physical and biological properties. For a winter wheat and hairy vetch cover crop rotation, Wagger and Denton (1989) reported lesser impacts of cover crops on soil porosity and hydraulic conductivity than in wheel traffic plots. The bulk density was significantly higher in the trafficked than untrafficked plots (1.74 vs. 1.52 g cm^{-3}) after three years and tended to increase with time in the trafficked inter-rows. Associated with higher bulk density values in the trafficked inter-rows, significantly lower values for soil porosity and saturated hydraulic conductivity were observed. When averaged over cover crop type and three years, total porosity in the trafficked areas decreased by 21% below that of the untrafficked areas. After three years, saturated hydraulic conductivity was 6.84 and 0.72 cm h^{-1} in untrafficked and trafficked inter-rows, respectively.

Including cover crops in an agronomic row crop rotation (i.e., a maize-soybean cropping system) may have positive, neutral, or negative impacts on soil-water storage and soil physical properties depending on the environmental and climatic conditions, management practices, duration of the cover cropping system, soil characteristics, and numerous other factors. Cover crops have potential to enhance recharging of soil-water through their potential influence on soil infiltration rates. Wilson et al. (1982) used double-ring infiltrometer and observed improved infiltration, soil structure, and porosity under cover crops as compared to fallow. They also observed decreased bulk density in the top 0-10 cm soil depth of an eroded Alfisol. Increased infiltration was also observed by Touchton et al. (1984), which was measured using a 0.60 m ring infiltrometer, in cover-cropped plots as compared to fallow for no-till cotton. Increased infiltration could be attributed to the mulch effect of cover crops in the topsoil.

In some studies, cover crops were observed to increase soil infiltration (McVay et al., 1989), increase soil-water retention (Colla et al., 2000), reduce soil evaporation, and increase solar energy harvest (radiation use efficiency) and carbon flux into the soil. Colla et al. (2000) observed increased soil-water holding capacity and soil permeability in cover-cropped plots as compared to a conventional cropping system in a four-year rotation in California's Sacramento Valley. They showed an infiltration rate of 0.028 m^3 m^{-1} during 3 h of irrigation for the conventional treatment and a greater infiltration rate of 0.062 m^3 m^{-1} during 3 h for the cover-cropped system. Odhiambo and Bomke (2007) compared the soil-water content in winter cover crops with bare soil plots in the early spring in British Columbia, Canada. They found that the soil-water content in the cover crop treatment was significantly higher in the top soil (0 to 20 cm), possibly due to the cover crop reducing soil evaporation and increasing the infiltration rate. In a three-year study in Iowa, Qi et al. (2011) showed that winter rye planted in a maize and soybean rotation maintained higher soil-water storage when compared to plots with only maize and soybean with no cover crop. On the other hand, in long-term (1999-2014) field experiments in California's San Joaquin Valley, Mitchell et al. (2015) found that net soil-water storage increased from January to March (the primary growing period for cover crops in California) by 48 and 43 mm in 2013 and 2014, respectively, for the fallow system, whereas in the cover crop mixture plots, there was no additional soil-water storage. Islam et al. (2006) investigated the effect of cover cropping systems on water balance variables (recharge and actual evapotranspiration, ET_a) in California's Central Valley and found a generally higher rye cover crop ET_a (140 mm from November to March) as compared to fallow (110 mm during same period). Ewing et al. (1991) reported that a crimson clover cover crop depleted the soil-water in the topsoil (0.15 m) by 28% more in 1985 and by 55% more in 1986 than the fallow treatment.

The aforementioned studies indicate that the effects of cover cropping on soil physical and chemical properties and soil-water balance components can vary significantly. Thus, investigating the magnitude of potential impacts of cover crops on soil properties for local or regional conditions can result in more effective, relevant, and practical information that can aid users in making management decisions. In the Midwestern U.S., especially in Nebraska, such information has been extremely limited. Moreover, the sub-humid continental climate in the eastern half of the state and the semi-arid climate in the western half make Nebraska more susceptible to both excess rainfall and shortages of rainfall, thus makes it challenging for farmers to incorporate cover crops into their cropping systems for improving soil physical properties without strong research support. The specific objectives of this research were to investigate and quantify the impacts of cover crops in seed maize or soybean rotations on soil physical properties, including field capacity (FC), permanent wilting point (PWP), soil-water holding capacity (SWHC), bulk density (ρ_b), saturated and unsaturated hydraulic conductivity, and infiltration rate.

Materials and Methods

Site Description, Experimental Setup, and Soil and Crop Management

Field research was conducted during the 2012-2013, 2013-2014, 2014-2015, and 2015-2016 cover crop growing seasons on three large-scale (64 ha each) production fields [Bowen Ratio Energy Balance System (BREBS; Irmak, 2010) flux tower field (F1), west field (F2), and east field (F3)] in Seward County near Beaver Crossing, Nebraska. All three research fields are within 1 to 2 km of each other (fig. 1a). All three fields had a center-pivot irrigated seed maize-cover crop rotation with no-till practice. In all three years, there was uniform and vigorous cover crop vegetation grown in all three fields (figs. 1b, 1c, and 1d). The dominant soil in field F1 is Hasting silt loam, which is a well-drained loamy upland soil with a soil-water holding capacity (SWHC) of 126 mm in the top 0.90 m of the soil profile (av-

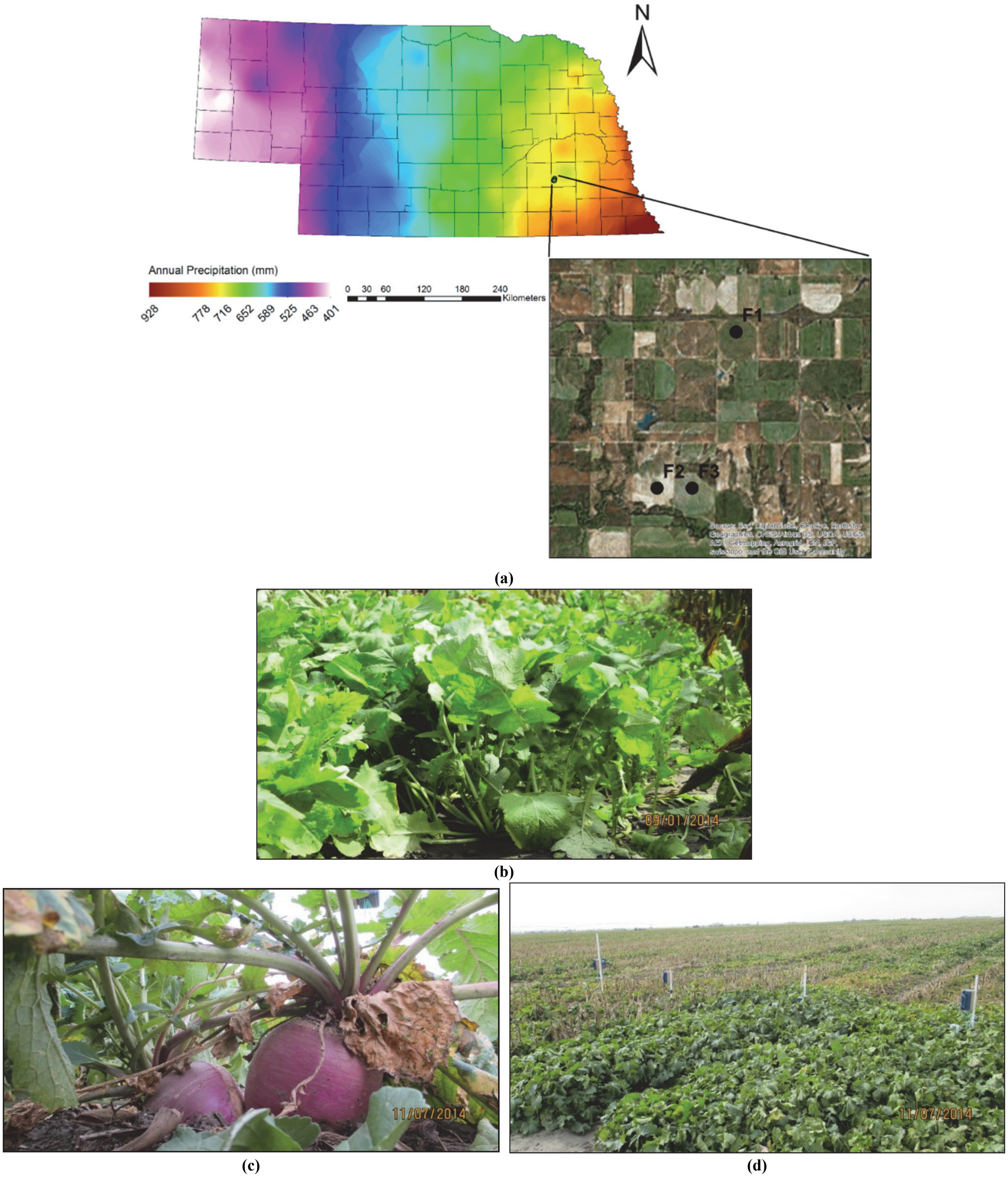

Figure 1. (a) Locations of the three large-scale cover crop research fields (F1, F2, and F3) with annual precipitation variation in Nebraska and (b, c, d) field views of vigorous cover crop vegetation.

erage FC of 32 cm^3 cm^{-3} and PWP of 20 cm^3 cm^{-3}). The other two fields have the same or similar silt loam soils (Butler and Muir silt loam) with SWHC of 142 mm in the top 0.90 m. The long-term (1996-2015) average annual rainfall at the research site is 599 mm. Annual rainfall during this field research was 304, 518, 855, 679, and 612 mm in 2012, 2013, 2014, 2015, and 2016, respectively.

The experimental treatments imposed in each field comprised four land covers: (1) cover crop mixtures planted without seed maize residue from the previous crop (CC), (2) cover crop mixtures planted in seed maize residue (SCCC), (3) seed maize residue only with no cover crop (SC), and (4) bare soil with no residue from agronomic row crops or cover crops. The cover crop treatment (CC) in this research represented the conditions in which there were only cover crops in the plot with no seed maize residue from the previous crop (i.e., no row crop was planted in these plots during the seed maize growing season). The SCCC treatment represented the conditions in which cover crops were planted in the seed maize residue after harvest or broadcasted within the maize plants around physiological maturity before harvesting maize. The SCCC treatment represented the actual production system that growers typically practice in the region. The SC treatment represented the conditions in which no cover crop was planted after harvesting the seed maize, and only seed maize residue existed in the plots. The bare soil treatment represented field conditions with no seed maize, cover crop, or any other crop. Four plots (one for each treatment) of 6.5 m × 4.5 m were established in each field and were maintained throughout the research period. For the cover crop plots (CC and SCCC), cover crop mixtures (more than one cover crop) were grown in all fields except field F2 in the 2012-2013 cover crop season and field F1 in 2013-2014, when only a single cover crop was grown. Information about the cover crop mixtures, cover crop planting dates, seed maize planting and harvesting dates, cover crop termination dates, and other agronomic management practices and dates for the three fields and three growing seasons is presented in table 1. We made sure that the CC and bare soil plots did not receive any seed during the seed maize and soybean planting. In addition, the bare soil and SC plots were covered with tarps when the cover crop seeds were broadcasted and when fertilizers were applied so that these plots did not receive any cover crop seeds. Weeds and other unwanted plants were manually uprooted on a regular basis from all plots each year.

EXPERIMENTAL PROCEDURES AND DATA COLLECTION

In this research, not all soil properties were measured every year, as some of the soil properties do not change in a short period of time. However, sufficient data were gathered every year to make valid conclusions on the impacts of cover crops on soil physical properties. The following analyses were made in this research:

1. Long-term impacts of cover crops on FC, PWP, and SWHC in production fields with seed maize and cover crop rotations:
   - Comparison of FC, PWP, and SWHC values that were measured by the USDA-NRCS in 1974, when no cover crops were planted in the fields, with the values measured in this research in 2015 for the SCCC treatment, which had been under a cash crop (field maize, seed maize, and soybean) and cover crop rotation since 2002.

2. Impact of cover crops in seed maize rotation on soil bulk density:
   - Short-term (2013 to 2016) impacts of cover crops and no cover crops on soil bulk density by comparing bulk density values for the SCCC and bare soil plots measured in this research in 2013 with values measured in 2016.
   - Long-term impacts of cover crops on soil bulk density by comparing values measured by the USDA-NRCS in 1974 with values measured in this research in 2016.

3. Comparison of unsaturated and saturated hydraulic conductivities of soil among four land cover treatments:
   - All treatments (CC, SCCC, SC, and bare soil) were measured in this research in 2013, 2014, and 2015.

Table 1. Management for three large-scale cover crop research fields for the 2012-2013, 2013-2014, 2014-2015, and 2015-2016 cover crop (CC) growing seasons. F1 = field with Bowen Ratio Energy Balance System (BREBS) flux tower station, F2 = west field, and F3 = east field.

Season	Management	Field F1	Field F2	Field F3
2012-2013	Seed maize planting date	22 Apr. 2012	29 Apr. 2012	30 Apr. 2012
	Seed maize harvesting date	21 Aug. 2012	28 Aug. 2012	28 Aug. 2012
	CC planting date	8 Sept. 2012	30 Aug. 2012	28 Aug. 2012
	CC planting method	Drill	Drill	Broadcast
	CC type	Winter pea, common vetch, hairy vetch, cereal rye, oats, nitro radish, and rapeseed	Forage sorghum	Turnip, radish, and Ethiopian cabbage
	CC termination	30 Apr. 2013	Winter kill	Winter kill
2013-2014	Seed maize planting date	11 May 2013	1 Jun. 2013	24 May 2013
	Seed maize harvesting date	2 Oct. 2013	10 Oct. 2013	9 Oct. 2013
	CC planting date	13 Oct. 2013	14 Aug. 2013	11 Aug. 2013
	CC planting method	Drill	Broadcast	Broadcast
	CC type	Cereal rye	Turnip, radish	Turnip, radish, millet, and winter pea
	CC termination	6 May 2014	Winter kill	Winter kill
2014-2015	Seed maize planting date	17 May 14	8 May 2014	7 May 2014
	Seed maize harvesting date	26 Sept. 14	25 Sept. 2014	25 Sept. 2014
	CC planting date	7 Aug. 2014	10 Aug. 2014	9 Aug. 2014
	CC planting method	Broadcast	Broadcast	Broadcast
	CC type	Turnip, radish, and Ethiopian cabbage	Turnip, radish, and Ethiopian cabbage	Turnip, radish, and Ethiopian cabbage
	CC termination	Winter kill	Winter kill	Winter kill
2015-2016	Soybean planting date	13 May 15	3 May 2015	2 May 2015
	Soybean harvesting date	7 Oct. 15	3 Oct. 2015	10 Oct. 2015
	CC planting date	No cover crop	5 Oct. 2015	No cover crop
	CC planting method	Drill	Broadcast	Drill
	CC type	Cereal rye	Cereal rye	Cereal rye
	CC termination	End of research	End of research	End of research

Analyses of soil physical properties were made in the laboratory (Ward Laboratory, Kearney, Neb.) from soil cores taken from each plot twice each year: in the fall before cover crops were planted, and in the spring after cover crops were terminated and before the row crop was planted. FC and PWP were measured at four soil depths (0-5, 5-20, 20-40, and 40-60 cm) in each plot in each field in spring 2014, fall 2014, spring 2015, and fall 2015. FC and PWP determinations were based on three samples per plot. Three undisturbed soil core samples per plot were collected and sent to the laboratory for FC and PWP analyses. SWHC was calculated as the amount of water held between FC and PWP for each soil layer and summed for the 0 to 0.6 m soil profile. Bulk density (ρ_b) and infiltration rate measurements were conducted in field F1. Bulk density was measured in 2013 at 0-15 cm depth and again in 2016 at two depths (0-15 cm and 15-30 cm) in two treatments (SCCC and bare soil). The volume of the sampler used to collect the soil core samples for bulk density was 154 cm^3 (5.7 cm diameter and 6 cm height). The undisturbed soil samples for bulk density measurement were placed in plastic-lined bags and transported to the laboratory. Five samples from each depth and each plot were taken at each sampling time (spring and fall). Bulk density was determined on an oven-dry (105°C) basis.

The bulk density, FC, PWP, and SWHC measured in the SCCC treatment in this research were compared to historical soil property data measured by the USDA-NRCS. The soil properties reported in the NRCS soil survey for Beaver Crossing were measured in 1974 (Mr. Neil Dominy, USDA-NRCS, personal communication, February 2017). The three research fields had been cultivated with an agronomic row crop (maize or soybean) and cover crop rotation since 2002 and were cultivated with a maize-soybean rotation for decades before 2002. Thus, this research presented a unique opportunity to assess the long-term impacts of cover crops on soil physical properties when comparing the data measured in 2015 (FC, PWP and SWHC) and in 2013 and 2016 (bulk density) with the NRCS-reported soil properties that were measured long before cover crops were incorporated into the crop rotations in the three research fields. Thus, comparative analyses of the data before and after cover crops were implemented provided invaluable information and quantitative assessments of the long-term impacts of cover crop cultivation on several soil physical properties.

Unsaturated Hydraulic Conductivity Using Mini Disk Infiltrometer

Infiltration rate measurements to determine soil unsaturated hydraulic conductivity were carried out using a Mini Disk infiltrometer (Decagon Devices, Inc., Pullman, Wash.). Two measurements were taken from each plot in all three years. The Mini Disk infiltrometer measures the unsaturated hydraulic conductivity of soil at tensions in the range of 0.5 to -7 cm (0.05 to 0.69 kPa, 0.00049 to 0.00681 atm, or 0.00725 to 0.10008 psi) (fig. 2). It consists of two chambers: the upper chamber controls the suction, and the lower chamber (21.2 cm in height) holds water for infiltration through the bottom of the unit via a porous, sintered, stainless steel disk (4.5 cm in diameter, 0.3 cm thick). The volume of water in the lower chamber infiltrates into the soil at a rate determined by the suction selected in the upper chamber. The rate of infiltration from the lower chamber into the soil is a function of the soil's hydraulic and physical properties. The small diameter of the disk at the bottom of the infiltrometer allows undisturbed measurements on relatively level soil surfaces (Decagon Devices, 2005). The Mini Disk infiltrometer requires only 135 mL of water to operate. Measurements were recorded at 30 s intervals, as recommended for silt loam soil, for up to 1 h of measurement duration using 1 cm of suction each time. The unsaturated hydraulic conductivity (K_{us}) was determined using the method proposed by Zhang (1997). Cumulative infiltration versus time was measured, and the following function was fitted to the data:

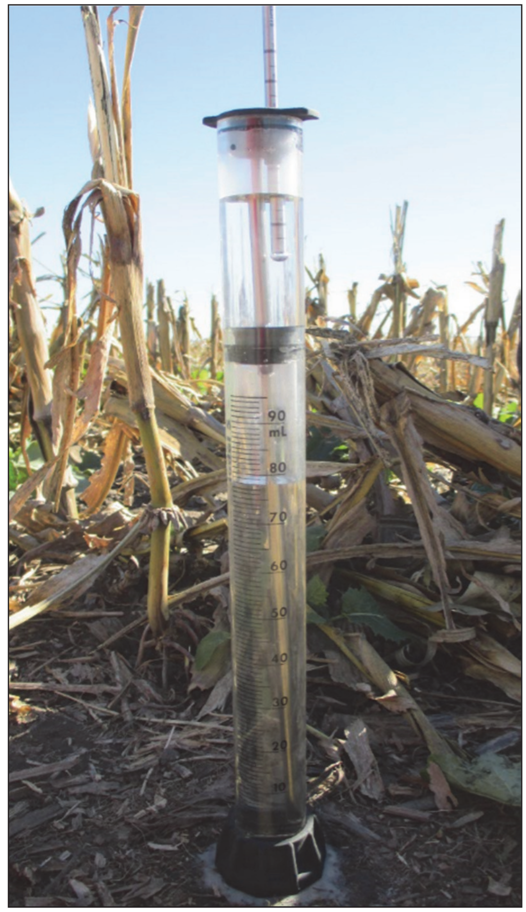

Figure 2. Mini Disk infiltrometer used for measuring unsaturated hydraulic conductivity (*K_{us}*) of different treatments in this research. This picture was taken when measuring *K_{us}* in the SC plot.

$$I = C_1 t + C_2 \sqrt{t} \quad (1)$$

where C_1 (cm s^{-1}) and C_2 (cm $s^{-1/2}$) are parameters related to hydraulic conductivity and soil sorptivity, respectively; I is the cumulative infiltration; and t is time. C_1 and C_2 in this equation are not constant values and change with treatment. The K_{us} was determined using the following equation:

$$K(h) = \frac{C_1}{A} \quad (2)$$

where C_1 is the slope of the curve of the cumulative infiltration versus the square root of time, and A is a value relating the Van Genuchten parameters (Van Genuchten, 1980) for 12 soil texture classes to the radius of the disk and applied tension. A is computed from the following equations:

$$A = \frac{11.65\left(n^{0.1}-1\right)\exp\left[2.92\left(n-1.9\right)\alpha h_o\right]}{\left(\alpha r_o\right)^{0.91}} \quad \text{for } n \geq 1.9 \tag{3}$$

$$A = \frac{11.65\left(n^{0.1}-1\right)\exp\left[7.5\left(n-1.9\right)\alpha h_o\right]}{\left(\alpha r_o\right)^{0.91}} \quad \text{for } n < 1.9 \tag{4}$$

where n and α are the Van Genuchten parameters for the silt loam soil (n = 1.41 and α = 0.02), r_o is the disk radius (2.25 cm), and h_o is the suction at the disk surface (-2 cm).

Saturated Hydraulic Conductivity Using Double- and Single-Ring Infiltrometers

Five saturated hydraulic conductivity (K_s) measurements per plot were taken using a single-ring infiltrometer in 2013 and 2014 for each treatment. In 2015, a double-ring infiltrometer (fig. 3) was used to measure K_s. The procedure reported by Nimmo et al. (2009) was followed for K_s determinations from infiltration capacity data, which were obtained from single-ring infiltrometer measurements. According to Nimmo et al. (2009), K_s was calculated as:

$$K_s = \frac{L_G}{t}\ln\left[\frac{L_G+\lambda+D_o}{L_G+\lambda+D}\right] \tag{5}$$

where t is the time during which the ponded water depth falls from its initial value of D_o to D, and L_G is the ring-installation scaling length, which was calculated as:

$$L_G = C_1 d + C_2 b \tag{6}$$

where C_1 and C_2 are empirically determined constants with values of 0.993 and 0.578, respectively (Reynolds and Elrick, 1990), b is the ring radius, and d is the ring insertion depth. In equation 5, λ is an index that represents how strongly water is driven by capillary forces in a particular soil. The value of λ was taken as 0.25 m, as suggested by Nimmo et al. (2009). K_s values from the double-ring infiltrometer were calculated using a modified version of Philip's equation (Philip, 1957) as:

$$i\left(t\right) = St^{\frac{1}{2}} + At \tag{7}$$

where $i(t)$ is cumulative infiltration, S represents soil sorptivity, and coefficient A characterizes long-term infiltration, which approximates K_s.

Figure 3. Double-ring infiltrometer used to measure saturated hydraulic conductivity (K_s) of different treatments in this research. This picture was taken when measuring K_s in a bare soil plot.

Data Analysis

Statistical analyses of the data were conducted using analysis of variance in SAS (ver. 9.3. SAS Institute Inc., Cary, N.C.), and comparisons among means were made using least significant difference (LSD) at $p < 0.05$ and $p < 0.1$. For FC and PWP, the experiment followed a randomized complete block design with the three fields (F1, F2, and F3) as three replications or blocks in time. Each block had four land cover treatments (CC, SCCC, SC, and bare soil) throughout the research period. Differences in the same land cover treatment over time as well as differences between treatments within a given season were investigated. Because bulk density and hydraulic conductivity were measured only in field F1, a t-test was used to determine potential differences between treatments over time.

Results and Discussion

Field capacity, Permanent Wilting Point, and Soil Water Holding Capacity

The FC and PWP values of the four land cover treatments at 0-5, 5-20, 20-40, and 40-60 cm soil depths from spring 2014 to fall 2015 are presented in figures 4a through 4h and table 2. No significant differences ($p > 0.05$) in FC or PWP were observed among the four treatments in spring and fall 2014. However, in spring and fall 2015, significant differences were observed among the treatments. The PWP in spring 2015 at 0-5 cm depth was significantly greater ($p < 0.05$) for SCCC (19.1 $cm^3\ cm^{-3}$) than for the bare soil treatment (16.1 $cm^3\ cm^{-3}$). In fall 2015, the PWP at 5-20 and 20-40 cm depths was significantly greater for the bare soil treatment than for SCCC and SC. In the same season, the FC was also significantly greater ($p < 0.05$) for the bare soil treatment than for SC at 20-40 cm depth (table 2). The maximum FC and PWP values for all treatments, except for bare soil, in fall 2015 were observed at 40-60 cm depth. The maximum FC and PWP values among all treatments were 39.8 $cm^3\ cm^{-3}$ and 25.5 $cm^3\ cm^{-3}$, respectively, at 40-60 cm depth for SC in fall 2015. When comparing the same treatment in different seasons, no significant increases or decreases were observed, except for a few instances that could be due to differences in soil properties and/or experimental or measurement error.

The SWHC values in the 0-60 cm soil profile for the four land cover treatments are presented in figure 5. No significant differences in SWHC were observed between the treatments in any of the periods (seasons) (fig. 5). However, even though not significant, there was a 6% increase in SWHC in the CC treatment from spring 2014 to fall 2015. In addition,

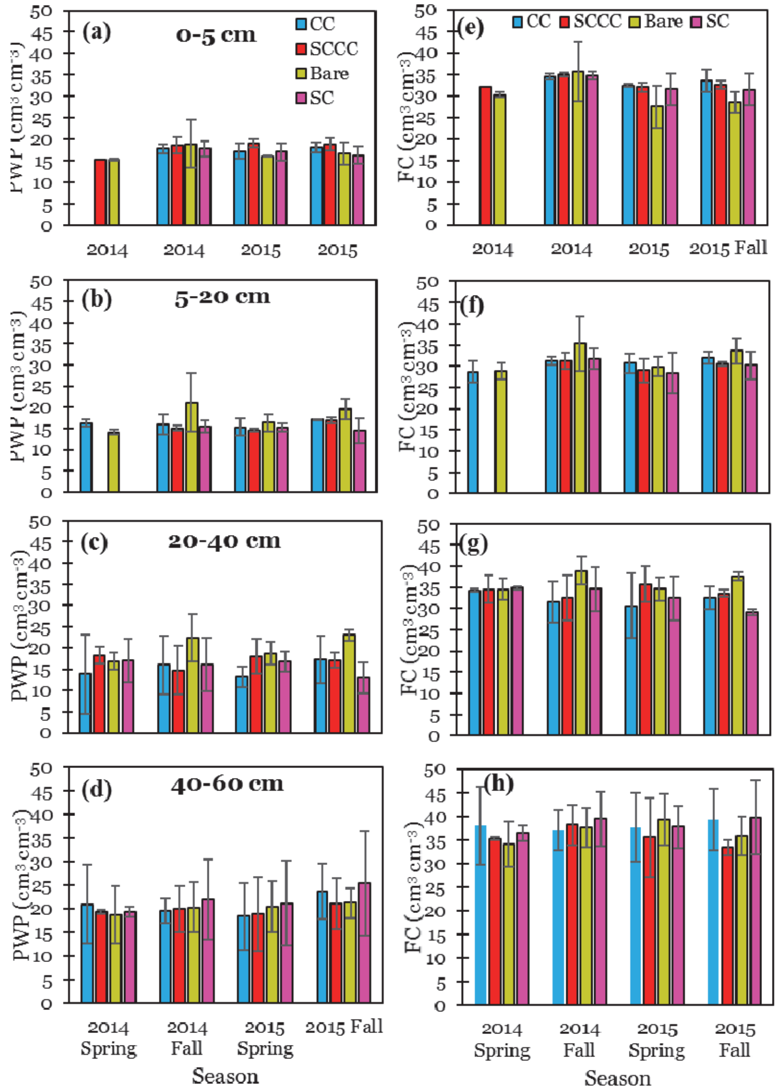

Figure 4. (a through d) Permanent wilting point and (e through h) field capacity of four land cover treatments at the 0-5, 5-20, 20-40, and 40-60 cm soil depths from spring 2014 to fall 2015. Land cover treatments: CC = cover crop without seed maize, SCCC = seed maize followed by cover crop, bare soil = bare soil with no residue cover, and SC = seed maize without cover crop.

Table 2. Measured permanent wilting point (PWP) and field capacity (FC) of four land cover treatments in the 0-5, 5-20, 20-40, and 40-60 cm soil depths from spring 2014 to fall 2015. Land cover treatments: CC = cover crop without seed maize, SCCC = seed maize followed by cover crop, bare soil = bare soil with no residue cover, and SC = seed maize without cover crop.[a]

		Soil Depth							
		0-5 cm		5-20 cm		20-40 cm		40-60 cm	
Season	Treatment	PWP ($cm^3\ cm^{-3}$)	FC ($cm^3\ cm^{-3}$)	PWP ($cm^3\ cm^{-3}$)	FC ($cm^3\ cm^{-3}$)	PWP ($cm^3\ cm^{-3}$)	FC ($cm^3\ cm^{-3}$)	PWP ($cm^3\ cm^{-3}$)	FC ($cm^3\ cm^{-3}$)
Spring 2014	CC	-	-	a 16.3 a	a 28.7 a	a 13.9 a	a 34.3 a	ab 20.7 a	a 38.0 a
	SCCC	a 15.2 a	a 32.1 a	-	-	a 18.4 a	a 34.6 a	a 19.4 a	a 35.2 a
	Bare soil	a 15.2 a	b 30.3 b	a 14.1 a	a 28.8 a	a 16.9 a	a 34.5 a	a 18.7 a	a 34.1 a
	SC	-	-	-	-	a 17.0 a	a 34.9 a	ab 19.4 a	a 36.5 a
Fall 2014	CC	a 17.9 a	a 34.4 a	a 15.9 a	ab 31.2 a	a 16.0 a	a 31.5 a	ab 19.6 a	a 37.0 a
	SCCC	ab 18.7 a	a 34.9 a	a 15.1 a	a 31.3 a	a 14.7 a	a 32.6 a	a 19.9 a	a 38.1 a
	Bare soil	a 18.9 a	a 35.6 a	b 21.1 a	b 35.3 a	a 22.3 a	a 38.8 a	a 20.3 a	a 37.6 a
	SC	a 17.8 a	a 34.7 a	a 15.4 a	a 31.7 a	a 16.2 a	ab 34.6 a	ab 22.0 a	a 39.5 a
Spring 2015	CC	a 17.3 ab	a 32.4 a	a 15.3 a	ab 30.7 a	a 13.2 a	a 30.6 a	a 18.5 a	a 37.6 a
	SCCC	b 19.1 a	a 32.0 a	a 14.6 a	a 29.0 a	a 18.1 a	a 35.7 a	a 18.9 a	a 35.5 a
	Bare soil	a 16.1 b	ab 27.4 a	a 16.4 a	ab 29.8 a	a 18.7 a	a 34.6 a	a 20.5 a	a 39.4 a
	SC	a 17.2 ab	a 31.5 a	a 15.3 a	a 28.4 a	a 16.8 a	ab 32.4 a	a 21.2 a	a 37.7 a
Fall 2015	CC	a 18.1 a	a 33.4 a	a 17.1 ab	b 31.9 a	a 17.3 ab	a 32.5 ab	b 23.7 a	a 39.3 a
	SCCC	b 18.9 a	a 32.5 a	a 17.1 b	a 30.5 a	a 17.2 b	a 33.6 ab	a 21.1 a	a 33.3 a
	Bare soil	a 16.8 a	b 28.5 a	b 19.5 a	b 33.7 a	a 23.1 a	a 37.5 a	a 21.3 a	a 35.8 a
	SC	a 16.3 a	a 31.5 a	a 14.6 b	a 30.2 a	a 12.7 b	b 29.1 b	b 25.5 a	a 39.8 a

[a] Means within a season (i.e., comparing different treatments in the same season) followed by the same letter are not significantly different at the 5% significance level. Means between seasons (i.e., comparing the same treatment in different seasons) preceded by the same letter are not significantly different at the 5% significance level. No letters imply no significant differences between seasons.

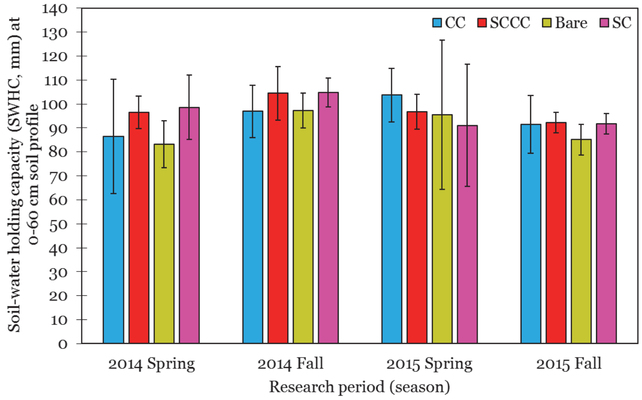

Figure 5. Soil-water holding capacity (SWHC) in the 0.60 m soil profile for four land cover treatments: CC = cover crop without seed maize, SCCC = seed maize followed by cover crop, bare soil = bare soil with no residue cover, and SC = seed maize without cover crop.

comparing SCCC and SC for the first two measurement periods (spring and fall 2014), the SWHC was lower in SCCC than in SC. However, in spring and fall 2015, SWHC was higher in SCCC than in SC. At the end of the experiment in fall 2015, the maximum SWHC in the 0-60 cm soil profile was observed in SCCC, SC, and CC (92.16, 91.76, and 91.54 mm, respectively) (fig. 5), and all three treatments had slightly greater SWHC values than the bare soil treatment (85.1 mm).

When comparing the values at the beginning of the experiment (in spring 2014) with those at the end of the experiment, the SWHC essentially did not change, and all values were similar to their initial values. The slightly different SWHC values between cropping systems versus bare soil treatments (6.4, 7.0, and 6.6 mm difference between CC, SCCC, and SC and the bare soil treatment, respectively) are most likely within the measurement and experimental errors when conducting field research under natural conditions when natural soil variability is considered. Some of the interannual variability in SWHC for the same treatment could also be attributed to the variability in soil properties and/or experimental and measurement errors. However, this comparison may be considered a short-term comparison when investigating the potential impacts of cover crops on soil physical properties. It is expected that a longer duration (e.g., six or seven years) may be necessary for the crop residue to be incorporated into the soil profile to potentially increase OMC and in turn increase SWHC. Thus, in a later section, the SWHC values that were measured in this research are compared to the historical NRCS-measured SWHC values to make more robust assessments of cover crop impacts on SWHC.

Bulk Density

With the incorporation of cover crops into the row cropping system, no increase or decrease in bulk density (ρ_b) was observed from 2013 to 2016 at 0-30 cm soil depth (table 3). Although not significant, there was a small increase (0.09 g cm^{-3}) in ρ_b in the bare soil plots from 2013 to 2016; however, the SCCC treatment maintained ρ_b at the same level as at the beginning of the research. This might be because the increase in OMC (only 0.03%) due to cover crops over this short duration (2013-2016) was not sufficient to impact ρ_b, as ρ_b is highly and negatively correlated with OMC (De Kimpe et al., 1982). Haruna and Nkongolo (2015a) observed only a 3% decrease in ρ_b in cover crop plots as compared with no cover crops in a maize-soybean rotation with silt loam soil. Changing the soil ρ_b in real-world production fields (as compared to laboratory, greenhouse, or other controlled environments) by altering soil and crop management practices is a difficult and prolonged process because the magnitude of change (increase or decrease) in ρ_b is smaller than the magnitude of change in OMC. Thus, the impact of cover crop cultivation on soil ρ_b, especially in deeper soil layers, would be a slow process. Similar results were reported for a continuous no-till maize-cover crop in a fine sandy loam soil by Wagger and Denton (1989), who did not observe an increase in ρ_b in an untrafficked hairy vetch cover crop treatment from 1985 to 1987, even in the top 2.5 to 10 cm soil layer. In contrast, Haruna and Nikongolo (2015b) reported significant interactions ($p < 0.05$) between cover crop and crop rotation with ρ_b and gravimetric and total pore space of the soil. In addition, cover crop also significantly interacted with tillage for ρ_b and total pore space. All soil physical properties studied were significantly ($p < 0.0001$) affected by the depth of sampling, except for ρ_b, the pore tortuosity factor and total pore space in 2012, and the volumetric water content in 2013. When the ρ_b values in the bare soil and SCCC treatments that were measured in our research in 2016 were compared with the USDA-NRCS values measured in 1974 in the experimental fields, slight increases of only 0.02 g cm^{-3} for SCCC and 0.09 g cm^{-3} for bare soil were observed, indicating that incorporating the cover crops in maize-soybean rotations did not have a long-term impact on soil ρ_b.

Table 3. Soil bulk density (ρ_b) in the 0-30 cm depth measured in the 2013 and 2016 growing seasons in comparison to NRCS-determined bulk density values measured in 1974 in the experimental fields.[a]

Treatment[b]	Soil Bulk Density (ρ_b, g cm^{-3})		
	NRCS	2013	2016
SCCC	1.38[c]	1.42 (0.11) a	1.41 (0.08) a
Bare soil	-	1.37 (0.13) a	1.47 (0.15) a

[a] Means between years for the same treatment followed by the same letter are not significantly different at the 5% significance level.

[b] SCCC = seed maize followed by cover crop, and bare soil = bare soil with no residue cover.

[c] The 1974 NRCS bulk density value was measured in a maize-soybean rotation.

Saturated and Unsaturated Hydraulic Conductivity

The double-ring and single-ring infiltrometer-measured saturated hydraulic conductivity (K_s) at the topsoil exhibited interannual variation for the same treatments, and there were no significant differences ($p > 0.05$) between treatments in any year nor for the same treatment between years (table 4; each value in table 4 is an average of five measurements). In general, the K_s exhibited moderate to very small changes for all treatments, which were within experimental error or expected soil variability. The K_s for SC remained similar (decreased only by 6%) from 2013 to 2015; however, the K_s for SCCC increased by 50%, from 1.93 cm h^{-1} in 2013 to 2.90

Table 4. Measured saturated hydraulic conductivity (K_s) of four land cover treatments.[a]

Treatment[b]	Saturated Hydraulic Conductivity (K_s, cm h^{-1})		
	2013	2014	2015
CC	2.77 ±2.17 a	2.25 ±0.34 a	1.50 ±0.12 a
SCCC	1.93 ±1.37 a	3.11 ±1.33 a	2.90 ±1.68 a
Bare soil	2.06 ±0.57 a	1.67 ±0.28 a	1.40 ±0.87 a
SC	3.42 ±2.43 a	2.33 ±1.58 a	3.20 ±3.38 a

[a] Means in the same column followed by the same letter are not significantly different at the 5% significance level.

[b] CC = cover crop without seed maize, SCCC = seed maize followed by cover crop, bare soil = bare soil with no residue cover, and SC = seed maize without cover crop.

cm h^{-1} at the end of 2015. There was a 46% decrease in K_s for CC, from 2.77 to 1.50 cm h^{-1}, and a 32% decrease for the bare soil treatment, from 2.06 to 1.40 cm h^{-1}, at the end of the research. Even though not significant, these results indicate that including cover crops with seed maize as a rotational crop aided in increasing the soil K_s, probably due to adding more OMC to the surface soil than other treatments. However, the decrease in K_s for the CC treatment might be due to inadequate cover crop or row crop residue that might have aided in increasing K_s. This indicates that incorporating cover crops into a seed maize rotation had moderate to small impacts on K_s. Among all treatments, the bare soil (1.40 cm h^{-1}) and CC treatments (1.50 cm h^{-1}) had the lowest K_s at the end of the research, whereas the SC treatment had the highest K_s (3.20 cm h^{-1}).

The K_{us} values were not significantly different ($p > 0.05$) between treatments for a given year. All treatments exhibited an increasing trend in K_{us} (table 5) during the research period. Because K_{us} is strongly correlated to soil compaction, an increasing trend in K_{us} may indicate increasing compaction in the topsoil. In the process of compaction, the macroporosity decreases, whereas the microporosity often increases (Richard et al., 2001; Dec et al., 2008). This results in larger water contents for a wide range of matric potentials in compacted soil versus uncompacted soil, which results in a higher K_{us} in compacted soil than in uncompacted soil (Van den Akker and Soane, 2005). The lowest K_{us} values were observed in 2014 for all treatments, except for SC. At the end of the research in 2015, the highest K_{us} was observed in CC (0.98 cm h^{-1}), whereas the lowest K_{us} was observed in the bare soil treatment (0.78 cm h^{-1}). Similar to K_s, as expected, large standard deviations were observed in K_{us} because hydraulic conductivity is one of the most variable soil properties and can vary substantially for the same soil due to many factors, including non-uniform presence of decayed root channels, worm holes, variation in soil structure and texture,

Table 5. Measured unsaturated hydraulic conductivity (K_{us}) of four land cover treatments.[a]

Treatment[b]	Unsaturated Hydraulic Conductivity (K_{us}, cm h^{-1})		
	2013	2014	2015
CC	0.38 ±0.08 a	0.11 ±0.07 a	0.98 ±0.62 a
SCCC	0.26 ±0.12 a	0.11 ±0.00 a	0.86 ±0.67 a
Bare soil	0.61 ±0.23 a	0.20 ±0.15 a	0.78 ±0.06 a
SC	0.23 ±0.01 a	0.59 ±0.71 a	0.83 ±0.23 a

[a] Means in the same column followed by the same letter are not significantly different at the 5% significance level.

[b] CC = cover crop without seed maize, SCCC = seed maize followed by cover crop, bare soil = bare soil with no residue cover, and SC = seed maize without cover crop.

Figure 6. Impact of soil compaction on turnip growth.

cracks below the soil surface, differences in soil temperature, potential non-uniformity in initial soil-water content where measurements are taken, and other factors.

The relationship between the K_{us} values observed in this research and soil compaction was confirmed independently with visual observations in the field. In figure 6, a turnip pulled out of field F1 clearly shows evidence of soil compaction in the top 8 to 15 cm soil layer. This level of soil compaction changed the turnip's shape and was observed numerous times. More than 30 turnip tubers were pulled from the soil, and they all showed the same or similar shapes in the top 8 to 15 cm of their length. Similar observations were made for more than 25 radish tubers (pictures not available) that were visually inspected.

Cumulative Infiltration and Infiltration Capacity (Infiltrability)

In addition to ρ_b, K_s, K_{us}, FC, PWP, and SWHC, the potential impacts of cover crops on soil infiltration capacity, which is also referred to as infiltration rate or infiltrability, were investigated. During the double-ring, single-ring, and Mini Disk infiltrometer measurements, the decrease in water level (infiltrated into the soil) was recorded, and cumulative values of infiltration versus time for each treatment for three years are presented in figures 7a, 7c, and 7e. As the amount of water added with time, the cumulative infiltration, which is the time integral of the infiltration rate (Hillel, 1998), exhibited a curvilinear response to time and water added in all three years (figs. 7a, 7c, and 7e). In general, SCCC had the lowest cumulative infiltration and SC and CC had the highest cumulative infiltration in all three years. The trends in cumulative infiltration were similar for all treatments in 2013 and 2014 (except for SCCC), with cumulative infiltration increasing gradually and reaching a maximum value of

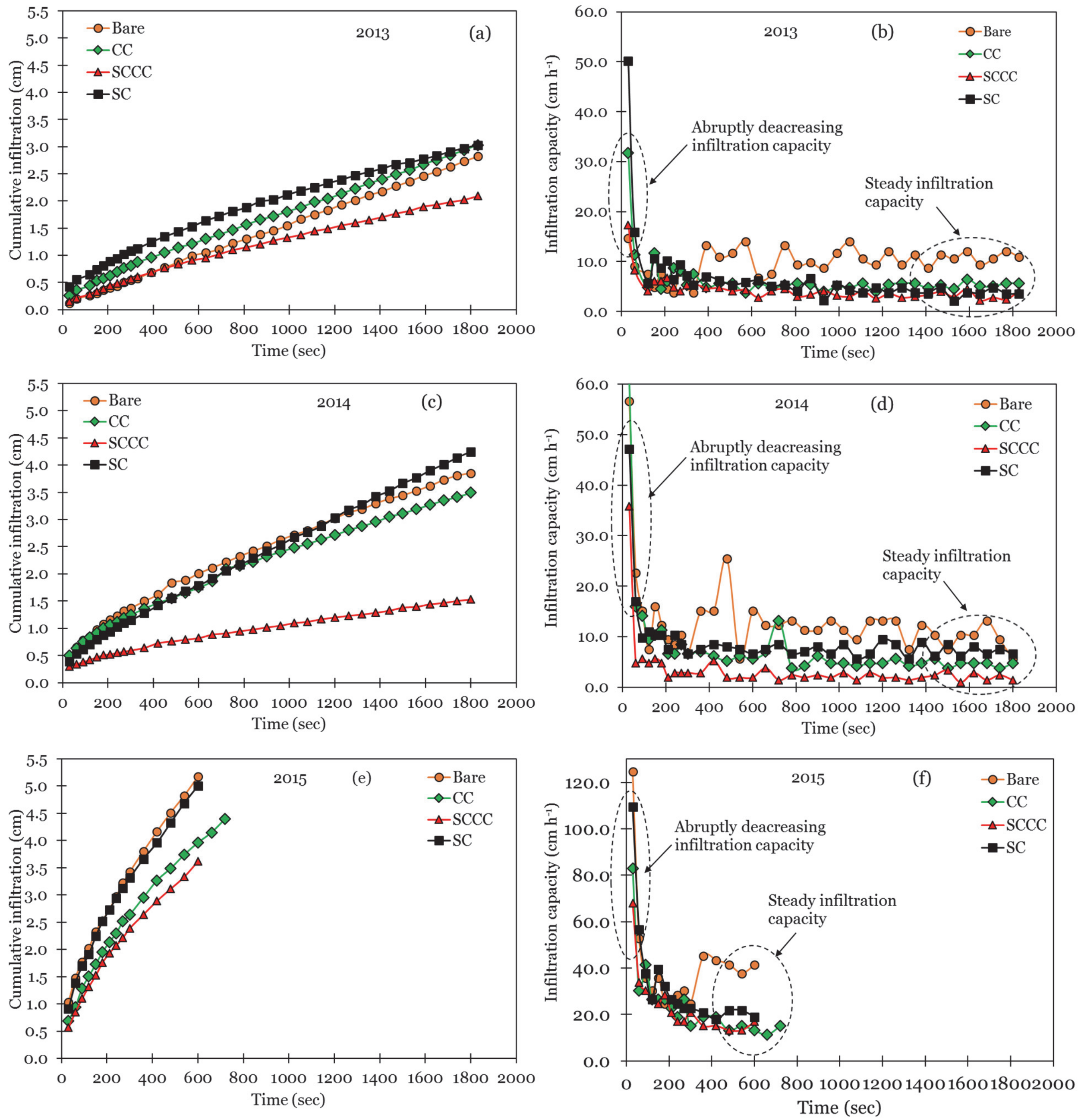

Figure 7. Measurements of (a, c, and e) cumulative infiltration and (b, d, and f) infiltration capacity for the four land cover treatments in 2013, 2014, and 2015. Land cover treatments: CC = cover crop without seed maize, SCCC = seed maize followed by cover crop, bare soil = bare soil with no residue cover, and SC = seed maize without cover crop.

about 3 cm at about 1830 s in 2013 and reaching a greater maximum value of 4.2 cm (for SC) at the same time in 2014. The order of the magnitude of cumulative infiltration (from highest to lowest) was similar in all three years: SC or CC > bare soil > SCCC. In 2015 (fig. 7e), all treatments reached their maximum cumulative infiltration values in a much shorter time (600 to 800 s) than in 2013 and 2014, resulting in greater increasing rates of cumulative infiltration. This could be due, in part, to drier surface soil conditions during the infiltration measurements in 2015 than in other years. On a three-year average basis, the cumulative infiltration values were 4.1, 3.9, 3.6, and 2.4 cm for the SC, bare soil, CC, and SCCC treatments, respectively, with standard deviations of 0.99, 1.18, 0.70, and 1.08 cm, respectively, with SCCC having the lowest cumulative infiltration among all treatments. The SCCC treatment had 59% lower cumulative infiltration than SC, indicating that incorporating cover crops into the seed maize rotation substantially decreased the cumulative infiltration capacity in these research settings.

Sharp decreases in infiltration rate were observed for all treatments in the initial stage of the infiltration measurements for all three years (figs. 7b, 7d, and 7f). Infiltration rates exhibited interannual variation between treatments and for the same treatment between years. During the measurements, the soil surface was usually dry (or drier than the subsoil), and the infiltration rate was high. As the topsoil became wetter with the addition of water during the measurements, the soil infiltration rate declined (abruptly in some cases) for all treatments in all years. After the initial wetting of the surface soil, the infiltration rate decreased to a certain value and then remained relatively stable (with some fluctuations, which also varied between treatments in a given year and for the same treatment between years) until the end of the measurements. Infiltration rates were greater in 2015 than in 2013 and 2014. After an abrupt initial decline, the infiltration rate exhibited larger fluctuations between measurements in the bare soil treatment. On a three-year average basis, the infiltration rates were 9.7, 22.0, 8.6, and 6.1 cm h^{-1} for the SC, bare soil, CC, and SCCC treatments, respectively, with standard deviations of 7.9, 16.9, 5.8, and 6.5 cm h^{-1}, respectively, with the SCCC treatment resulting in about a 64% lower infiltration rate than the SC treatment, indicating that incorporating cover crops into a seed maize-soybean rotation decreased the infiltration rate of the soil under these experimental conditions in 2015. The highest infiltration rate for the bare soil treatment can be attributed to the lower soil-water status in the surface soil as compared to the other treatments, in which the surface soil was shaded with seed maize and/or cover crop residue, reducing the radiation interception at the surface, which reduced soil evaporation and resulted in greater soil-water status as compared to the bare soil plots.

Comparison of FC, PWP, and SWHC with NRCS Historical Measured Values

Comparisons of FC, PWP, and SWHC measured in this research for the SCCC treatment (which represented the crop practices in the research fields since 2002 and a maize-soybean rotation for several decades before 2002) with the NRCS historical (1974) data are presented in figure 8. The changes in FC, PWP, and SWHC exhibited interannual variations for the same field as well as between fields and years. Overall, the FC, PWP, and resulting SWHC data for the research fields in 1974 did not show changes at the end of the current research in 2015 after long-term cultivation of cover crops. There were some slight increases and decreases in FC and PWP in the current measured data as compared with the NRCS data at the 0-5 cm soil depth. On a three-field average basis, a 5% increase in FC and 20% increase in PWP were observed for the topsoil (0-5 cm). At the end of the current research in 2015, on average, the SWHC at 0-60 cm soil depth was almost exactly the same as reported by the NRCS in 1974. Although cover crops might increase the OMC of the soil, this increase does not always result in improved SWHC, as mentioned by Jamison (1953), who found an increase in aggregation of the soil due to an increase in OMC that resulted in decreased available water. Jamison (1953) reported that this result was due to an increase in moisture retention at permanent wilting point (-15 bar).

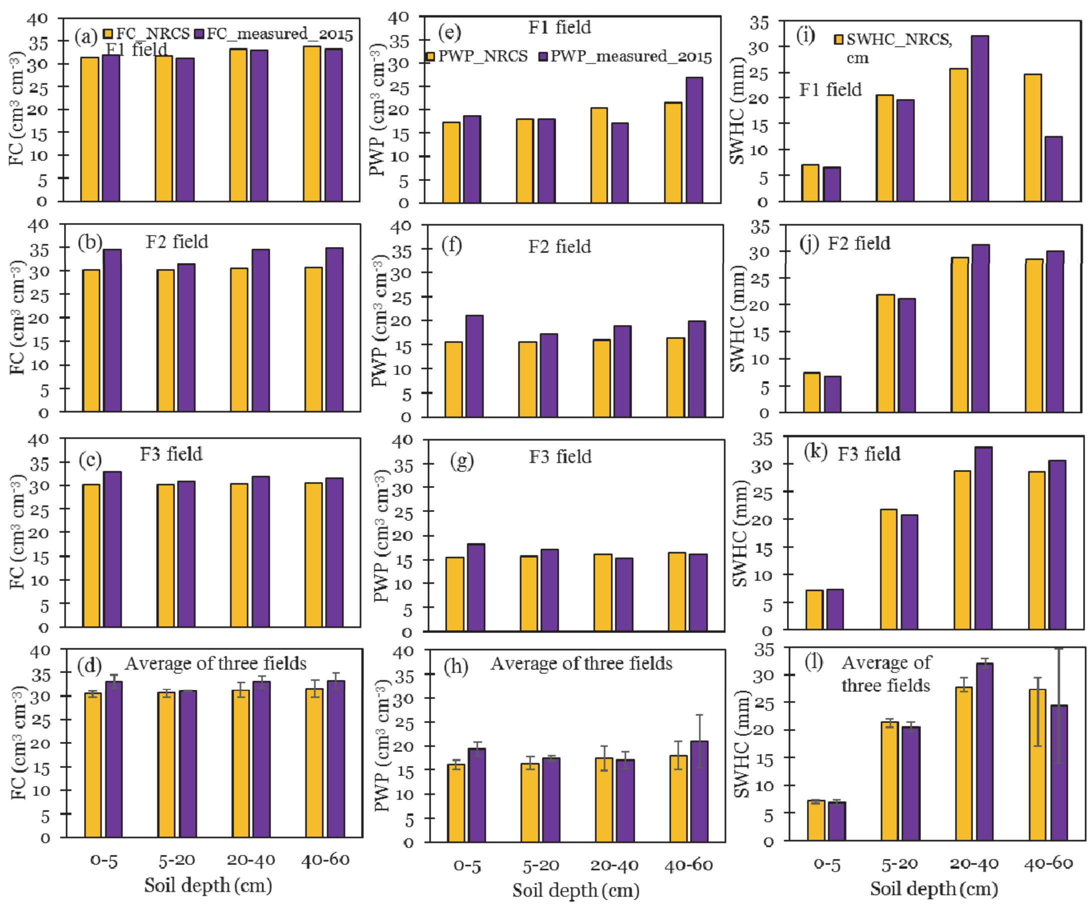

Figure 8. Comparison of (a through d) field capacity (FC), (e through h) permanent wilting point (PWP), and (i through l) soil-water holding capacity measured in this study with NRCS historical (1974) data at 0-5, 5-20, 20-40 and 40-60 cm soil depths for field F1 (a, e, and i), field F2 (b, f, and j), field F3 (c, g, and k), and average of the three fields (d, h, and l).

On a three-field average basis, the SWHC measured at all depths in this research was less than the NRCS values, except in the 20-40 cm soil layer, where it was 4 mm higher (fig. 8). While there were slight increases in FC on a three-field average basis, there were increases in PWP as well, which resulted in not affecting the SWHC. An increase in FC (fig. 8d) and a decrease in PWP (fig. 8h) were observed only in the 20-40 cm soil layer, in which a small (4.3 mm) increase in SWHC (fig. 8l) was also observed. The largest increase in SWHC was observed in the 20-40 cm soil layer in field F1 (fig. 8i), in which the SWHC increased from 25.6 mm in 1974 to 31.9 mm at the end of this research. The largest decrease in SWHC was also observed in field F1 in the 40-60 cm soil layer, in which the SWHC decreased from 24.6 mm in 1974 to 12.5 mm in 2015. The reason for little or no increase in SWHC with the adoption of cover crops for about 14 years since 2002 might be that cover crops do not always increase the OMC and/or the increase in OMC does not always translate into enhancing the SWHC. There is a significant and complex relationship between OMC and available water in soils with relatively low clay content (13% to 20%) (MacRae and Mehuys, 1985; Jamison and Kroth, 1958). MacRae and Mehuys (1985) and Jamison and Kroth (1958) observed that in soils with more than 15% clay, factors other than clay content can become dominant in determining available soil-water. Because the soils at this research site have clay content greater than 19% (except in the 0-30 cm soil layer in field F1), little or no change in SWHC can be expected with the inclusion of cover crops into the row crop rotation. Another reason for essentially little or no change in SWHC is that the change (increase) in PWP (20% in the topsoil based on three-field average) was greater than the change (increase) in FC (5%), which resulted in a reduction of SWHC in many cases under these experimental conditions.

In some cases, it is assumed that cover crops increase OMC and that this increase translates into increased SWHC, which is not a correct assumption. Considering that soil physical properties can change very little, or not at all, over short durations (and even over long durations such as decades), changing the soil properties, including FC, PWP, and SWHC, in natural conditions is a slow and difficult process. While FC and PWP, and in turn SWHC, are impacted by soil and crop management practices, primarily through increasing the soil OMC (depending on clay content and the interactions of other soil properties), impacting FC and PWP by increasing the OMC is a slow process, and increasing the OMC even by large magnitudes impacts these properties only by low magnitudes. Furthermore, increasing the OMC can influence FC and PWP by different magnitudes, e.g., a percent or unit change in OMC does not influence FC and PWP by the same magnitude. To demonstrate the impacts of changes in OMC on FC, PWP, and SWHC, we used the Soil-Water Characteristics Software and quantified the impact of changing the OMC on FC, PWP, and SWHC for a silt loam soil that had similar characteristics as the research site soils. The OMC was increased from 0% to 10% in 0.2% increments, and the changes in FC, PWP, and SWHC per 30 cm soil layer were quantified (fig. 9). The increase in OMC resulted in a slow increase in both FC and PWP. The response (increase) in FC, PWP, and SWHC to the increase in OMC was linear. A 0.2% increase in OMC resulted in only a 0.20 and 0.10 $cm^3\ cm^{-3}$ increase in FC and PWP, respectively, and only a 0.30 mm increase in SWHC per 30 cm soil layer.

In total, when the OMC was increased from 0% to 8%, FC increased from 29.7 to 37.7 $cm^3\ cm^{-3}$ with a total increase of 8 $cm^3\ cm^{-3}$ (a 27% increase), and PWP increased from 12.4 to 16.4 $cm^3\ cm^{-3}$ with a total increase of 4 $cm^3\ cm^{-3}$ (a 32.2% increase). Thus, the increase in OMC resulted in a greater magnitude increase in FC than in PWP, which is the primary reason for the expected positive impact of an increase in OMC for increasing the SWHC. If both FC and PWP increased by the same magnitude in response to the increase in OMC, the increase in OMC would not have any impact on enhancing SWHC. The SWHC increased from 51.9 to 63.9 mm per 30 cm, with a total increase of 12 mm (a 23% increase). When considering the increase in OMC by 8%, these increases in FC and PWP, as well as enhancing the SWHC by 12 mm, are extremely small enhancements because increasing OMC by 8% can take decades, depending on numerous factors, if it can even be accomplished in real-

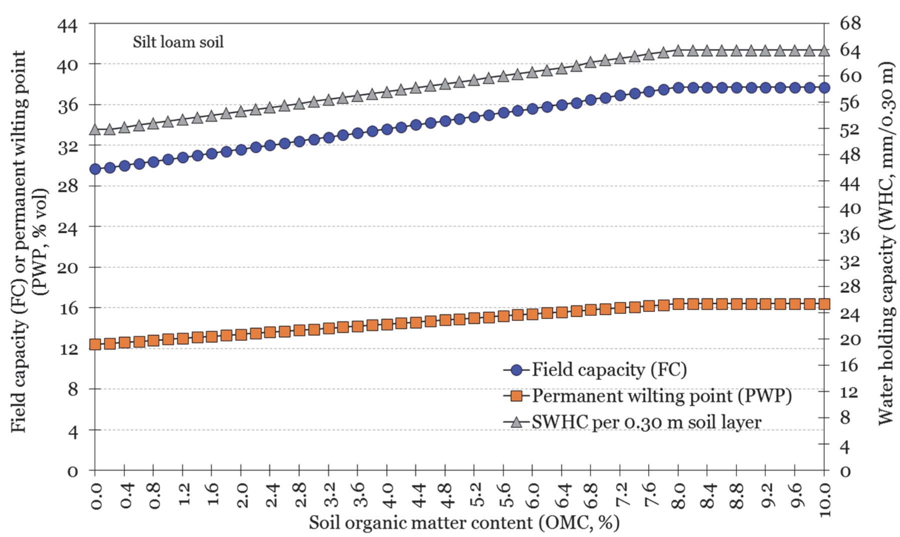

Figure 9. Relationship between soil organic matter content (OMC) and field capacity (FC), permanent wilting point (PWP), and soil-water holding capacity (SWHC, per 30 cm soil layer) for a silt-loam soil.

world production fields. Given that most cover crop studies, including this research, have indicated small or no change in soil physical properties or some small changes only in the topsoil (e.g., 0 to 10 or 15 cm), a 12 mm improvement in SWHC per 30 cm soil layer, as shown in figure 9, would be only half of that amount (~6 mm) in the top 15 cm soil layer, resulting in much lesser impact of an increase in OMC on SWHC if the typical 90 cm root zone depth for most agronomic crops and the 60-90 cm (or shallower) root zone depth for most cover crops were considered.

The relationships between OMC and FC, PWP, and SWHC presented in figure 9 clearly indicate that changing the soil physical properties, especially SWHC, is an extremely slow and difficult process. Thus, the impacts of cover crops in changing these properties should not be expected to occur over short durations or even a few decades. In addition, there may be expectations that increasing the OMC can only increase the FC, and that this can result in increased SWHC, which is not accurate because increasing the OMC also increases the PWP. Thus, the impact of incorporating cover crops into agronomic row crop cultivation depends heavily on the rate of change in both FC and PWP for any expected improvements in SWHC. Because both FC and PWP increase linearly with increasing OMC, improvements in SWHC cannot be expected to occur in several years or even several decades. Another observation based on figure 9 is that while all three soil properties responded linearly to an increase in OMC up to 8%, diminishing returns occurred beyond 8% (at FC, PWP, and SWHC values of 37.7 cm^3 cm^{-3}, 16.4 cm^3 cm^{-3}, and 63.9 mm, respectively) when FC, PWP, and SWHC did not respond to a further increase in OMC for the silt loam soil used in this example, indicating an upper limit of potential improvements in SWHC by increasing OMC.

Summary and Conclusions

Field experiments were carried out to quantify the effects of cover cropping on soil physical properties. FC, PWP, SWHC, ρ_b, K_s, K_{us}, and infiltration rates were measured and compared for four land cover treatments (CC, SCCC, bare soil, and SC) in three large-scale production fields (~64 ha each) with silt loam soil in south central Nebraska in the 2012-2013, 2013-2014, 2014-2015, and 2015-2016 cover crop growing seasons. Some of the field-measured soil properties in the SCCC treatment were also compared with historical values measured by the USDS-NRCS in the three research fields in 1974. The research conclusions are summarized as:

- In general, soil physical properties were unaffected by incorporating cover crops into the rotation of row crop cultivation. No significant differences in FC and PWP were observed among the four treatments, and they were not significantly different from the historical values measured by the NRCS in 1974. As a result, no significant differences ($p > 0.05$) in SWHC in the 0-60 cm soil profile were observed between treatments in any of the periods (seasons).
- Incorporating cover crops into seed maize rotations had moderate to small impacts on K_s. The K_s values at the topsoil exhibited interannual variation for the same treatment, and there were no significant differences ($p > 0.05$) neither between land cover treatments in any of the years nor for the same treatment between years. Among all treatments, the bare soil (1.40 cm h^{-1}) and CC treatments (1.50 cm h^{-1}) had the lowest K_s at the end of the research, whereas the SC treatment had the highest K_{us} (3.20 cm h^{-1}). The K_{us} values were not significantly different ($p > 0.05$) neither between treatments for a given year nor between years. At the end of the research, the highest K_{us} was observed in the CC treatment (0.98 cm h^{-1}), whereas the lowest K_{us} was observed in the bare soil treatment (0.78 cm h^{-1}).
- Infiltration rate exhibited interannual variation between treatments and for the same treatment between years. The order of magnitude of cumulative infiltration (from highest to lowest) was similar for all three years: SC or CC > bare soil > SCCC. The SCCC treatment had 59% to 64% lower cumulative infiltration than the SC treatment, indicating that incorporating cover crops into the rotation substantially decreased the cumulative infiltration capacity in these research conditions.
- The ρ_b values in the bare soil and SCCC treatments that were measured in our research in 2016 were essentially the same as the values measured in 1974, indicating that long-term incorporation of cover crops into maize-soybean rotations did not have any impact on soil ρ_b.

While cover crops could be beneficial for soil fertility, for using excess water in drainage-prone regions, for adding organic matter content, for grazing due to their nutritional values, and for other benefits, these impacts depend on numerous factors. In this extensive and comprehensive research, no sufficient evidence was found to suggest that cover crops can significantly or even considerably alter the soil physical properties that were investigated in these experimental conditions. In addition to soil physical properties, further research that investigates potential changes in soil biological properties and their potential implications for soil physical properties is needed to more comprehensively understand the potential interactions between cover crops and soil biological and physical properties.

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