Soil Health Response of Cover Crops in Winter Wheat–Fallow System

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ABSTRACT

Cover cropping has a potential to improve soil health in semi-arid regions. This research evaluated the effects of spring-planted cover crops on selected soil health indicators in limited-irrigated winter wheat (*Triticum aestivum* L.)–fallow system. Soil health parameters measured include soil water content (SWC), soil organic carbon (SOC), soil total nitrogen (STN), potentially mineralizable carbon (PMC), potentially mineralizable nitrogen (PMN), permanganate oxidizable carbon (POXC), inorganic N, and available P. Cover crops tested were pea (*Pisum sativum* L.), oat (*Avena sativa* L.), canola (*Brassica napus* L.), pea + oat (PO), pea + canola (PC), pea + oat + canola (POC), pea + oat + canola + hairy vetch (*Vicia villosa* L.) + forage radish (*Raphanus sativus* L.) + barley (*Hordeum vulgare* L.) (SSM), and a fallow. Cover crops were planted in February and terminated in May after 85 to 90 d. Cover crop biomass was 33 to 142% greater with oat, PO, PC, POC, and SSM than pea and canola. The SWC was 2 to 3% lower under cover crops than fallow plots at their termination, but was 2 and 4% greater in SSM and POC than fallow at wheat planting in October. Soil inorganic N was 41 to 49% lower with cover crops than fallow at termination date. Soil PMC and POXC varied with cover crop species and sampling dates. The SOC and STN contents were 18 to 20% greater with oat than PC. Oat and its mixture with other cover crops show promises to improve soil health and resilience.

Core Ideas

- Effect of cover crops on selected soil health indicators and wheat yield was monitored.
- Response of soil organic matter pools varied with cover crops and sampling dates.
- Oat and its mixtures as cover crops have potential to improve soil health.

THE OGALLALA Aquifer occupies 450,660 km^2 area in the eight High Plains states of the United States (Texas, New Mexico, Oklahoma, Colorado, Kansas, Nebraska, South Dakota, and Wyoming) and supplies water for agriculture, animal production, and public consumption (Alley et al., 1999). Depletion in water levels in the Ogallala Aquifer at an unsustainable rate in the last few decades had decreased water availability for irrigated crop production and challenged agricultural sustainability and profitability (Cano et al., 2018). The southern part of the Ogallala Aquifer underlying New Mexico and Texas can be exhausted early due to a low level of recharge while a large quantity of water pumped annually for agricultural production compared to other regions. A large portion of currently irrigated area is in transition to dryland or limited irrigation production in the next several years, and the rate of transition will be more rapid in the southern Ogallala Aquifer region than other parts of the aquifer (Cano et al., 2018). While conservation systems that reduce tillage, increase cropping intensity and diversity, cover cropping, and crop residue inputs can increase SOC and nutrient cycling in humid regions, little information is available regarding the impacts of these practices on soil health and agroecosystem resilience in semiarid agroecosystems with no or limited irrigation such as the southern Ogallala Aquifer region.

The USDA's Natural Resources Conservation Service (NRCS) has invested more than US$74 million in ~341,000 hectares of agricultural land in Ogallala Aquifer region since 2011 to initiate conservation programs that reduce soil disturbance, increase crop residue inputs, and enhance SOC accumulation and water holding capacity (Natural Resources Conservation Service, USDA-NRCS, 2015). Cover cropping can improve soil health and support sustainable crop production by increasing SOC and STN, reducing evaporation and N leaching, increasing soil water storage, and improving soil

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Table 1. Monthly average air temperature, total precipitation, and irrigation water applied during winter wheat and cover crop growing periods in 2016 and 2017.

Month	Avg monthly air temperature†		Total monthly precipitation		Irrigation water applied to winter wheat	
	2016	2017	2016	2017	2016	2017
	°C		mm			
Oct.	14.7	16.4	20.8	2.5	None	30.5
Nov.	6.94	9.72	21.8	25.4	None	None
Dec.	3.89	1.94	15.5	43.2	None	None
Jan.	2.08	2.50	2.0	28.2	None	None
Feb.	5.97	7.64	4.1	9.1	None	52.8
Mar.	9.61	10.9	0.0	23.6	38.1	76.2
Apr.	12.0	13.0	12.5	12.5	91.4	91.4
May	15.5	16.3	38.9	52.8	137	45.7
June	22.7	25.8	10.8	25.9	None	None
	Avg temperature/total precipitation‡					
Wheat period	10.4	11.6	126	223	267	297
Cover crop period	12.4	13.4	51	89	–	–

† Weather data was recorded at the weather station at the New Mexico State University Agricultural Science Center at Clovis, NM. The growing season for wheat in 2016 spanned from October 2015 to June 2016 and for 2017 spanned from October 2016 to June 2017. Cover crops were grown from the last week of February through early May (85–90 d).

‡ Annual average air temperature and total annual precipitation.

structure compared to no cover cropping (Sainju et al., 2003; Blanco-Canqui et al., 2013, 2015). However, use of cover crops in arid and semiarid regions is controversial for their excessive water use and associated potential negative impacts on the subsequent crop yields (Nielsen et al., 2002; Nielsen and Vigil, 2005). Studies have reported that cover crop residues can reduce water loss by providing soil cover, reducing evaporation, and increasing soil aggregation and water infiltration, although cover crops use soil water during their growth (Blanco-Canqui et al., 2013).

The effect of cover crops on soil water use and soil health depend on the agro-climatic region, soil type, cover crop planting and termination time, and method of cover crop residue placement in the soil (Ghimire et al., 2018). Cover crops in regions with high precipitation or low evapotranspiration can reduce nutrient leaching and erosion by scavenging residual nutrients and recycling back to the following crop (Dabney et al., 2001; Burgess et al., 2014). In addition, legume cover crops fix atmospheric N and reduce N fertilizer requirement for subsequent crops (Pikul et al., 1997). Cover crops can also absorb and convert inorganic N and available P into organic forms, thereby reducing N and P concentration in the soil during the non-crop period (Villamil et al., 2006). However, it may take several years to see these benefits from cover cropping on SOC accumulation, nutrient cycling, and subsequent crop yields in arid and semiarid agroecosystems. Successful integration of cover crops with low or no yield penalty to subsequent crops in semiarid regions require the development of cover cropping practices that do not exhaust limited water resources, enhance soil nutrient availability, and reduce nutrient loss during the fallow period (Ghimire et al., 2018).

Improved understanding of soil health impacts due to cover cropping in the southern Ogallala region can support the development of a resilient agroecosystem while transitioning from limited irrigation to dryland production. A global meta-analysis of cover crop effects on soil C sequestration revealed an increase in SOC by 0.32±0.08 Mg ha^{-1} yr^{-1}, with improvements in soil health (Poeplau and Don, 2015). However, it is often difficult to see changes in SOC due to cover cropping in a short period

(Kaspar and Singer, 2011) and even more so in arid and semiarid environments where low precipitation limits crop growth and biomass C inputs (Wang et al., 2018). Increases in active organic matter fractions, such as permanganate oxidizable carbon (POXC) and potentially mineralizable carbon (PMC), can suggest improved soil health and nutrient cycling in response to recent field management (Franzluebbers et al., 2000; Culman et al., 2012). Studies on the effect of cover crops on soil water content, nutrient dynamics, and SOM can help farmers in designing a sustainable cropping system in the semiarid southern Ogallala Aquifer region of the United States. Therefore, we studied these parameters for the region using single and mixed groups of cover crops in a limited irrigation winter wheat-based rotation.

This study evaluated the effects of cover crops on soil water, SOC pools, and nutrient cycling in no-tillage winter wheat–fallow system. Successful integration of diverse cover crops in the southern Ogallala region may diversify cropping systems transitioning from irrigated to limited irrigation or dryland production and improve soil health and agroecosystem resilience.

MATERIALS AND METHODS
Study Site and Treatments

The study was conducted during crop years 2016 and 2017 at the New Mexico State University Agricultural Science Center, Clovis, NM (34°35′ N, 103°12′ W, elev. 1348 m). The study site had a semiarid climate with long-term (110-yr) mean annual temperature of 15°C and mean annual precipitation of 470 mm, 70% of which occurs between May and September. Average monthly temperature and total precipitation in 2016 and 2017 recorded at the study site is presented in Table 1. The soil at the site is Olton clay loam (fine, mixed, superactive, thermic, Aridic Paleustoll) according to USDA soil classification. Soil bulk density measured at the beginning of the study ranged from 1.1 to 1.3 Mg m^{-3}, gravimetric water content from 14.2 to 20.7%, pH 8.1, electrical conductivity from 0.28 to 0.51 ds m^{-1}, SOM from 13 to 16 Mg ha^{-1}, inorganic N from 2.24 to 8.97 kg N ha^{-1}, and available P from 24.9 to 34.5 P kg ha^{-1} at the 0- to 15-cm depth.

The study design was a randomized complete block with eight treatments, two phases of crop rotations, and three replications in a split-plot arrangement in which crop rotation phases (winter wheat–cover crop [WW–CC] and cover crop–winter wheat [CC–WW]) was the main plot factor and cover crop treatment was the subplot factor. The first phase of the rotation (WW–CC) was started by planting wheat in October 2015 and harvested in July 2016 (crop year 2016), followed by planting cover crops in February 2017 that was terminated in May 2017. The second phase of the crop rotation (CC–WW) was started in the fallow field by planting cover crops in February 2016 that was terminated in May 2016, followed by winter wheat planting in October 2016 and harvesting in July 2017 (crop year 2017). Both phases of the rotation were present each year. Cover crop treatments included a fallow that had no cover crop, three monoculture cover crops: pea, oat, canola, and four mixtures: pea and oat (PO); pea and canola (PC); pea, oat, and canola (POC); and six species mixture (SSM) of pea, oat, canola, hairy vetch, forage radish, and barley. The plot size for each treatment was 18 by 12 m. Both phases of the rotations were established in previous year's sorghum (*Sorghum bicolor* L.) stubble. Cover crops were planted using a no-till drill (Great Plains 3P600, Moline, IL). The seeding rates for pea, oat, and canola were 22.4, 44.8, and 4.5 kg ha^{-1}, respectively. Canola emergence in 2016 was only 61% of the seeding rate, which may have affected its biomass yield and associated soil biogeochemical properties. The monoculture seeding rates for hairy vetch, forage radish, and barley were 11.21, 4.48, and 44.84 kg ha^{-1}, respectively. Cover crop species used in two-, three-, and six-species mixtures used only 50, 33, and 17% of the monoculture seeding rates. Cover crops received one irrigation (38 mm) for seed germination, after which no irrigation was applied. Each year, experimental plots were treated with glyphosate [N-(phosphonomethyl) glycine] 53.8% at 0.38 L ha^{-1} and 2,4-D [(2,4-dichlorophenoxy) acetic acid] Ester 0.72 kg L^{-1} (LV-6) at 0.87 L ha^{-1}, with ammonium sulfate (AMS) and non-ionic surfactant (NIS) at 20 g L^{-1} and 5 mL L^{-1}, respectively, 2 wk before cover crop planting. Fallow plots were sprayed once in March and again at the time of cover crop termination in May to control weeds. All cover crops were chemically terminated at the flowering stage of oat (85–90 d).

The experiment was maintained under no-tillage system. However, the study site was under conventional tillage winter wheat–sorghum–fallow rotation before the establishment of the experiment in October 2015. Winter wheat cultivar TM113 was planted using a no-till drill (Great Plains 3P600, Moline, IL) at 0.25 m spacing at a seeding rate of 62 kg ha^{-1}. Weeds and pests were controlled by applying herbicides and pesticides during wheat growth as needed. All treatments received 67 kg N ha^{-1} and 12.1 kg S ha^{-1} in 2016, and 70 kg N ha^{-1} and 12.5 kg S ha^{-1} in 2017. The experiment was maintained under limited irrigation. In fully irrigated wheat, water is typically applied at 400 to 450 mm, but each treatment in this study received a total of 267 and 300 mm irrigation water in 2016 and 2017 growing seasons, respectively, at critical growth stages of wheat; for example, jointing, booting, heading, and grain filling stage.

Soil Sampling and Laboratory Analysis

Soil samples were collected at cover crop planting in February and at termination in May for both years (2016 and 2017).

Additional samples were collected from CC–WW phase of the rotation at wheat planting in October 2016, early growth in February 2017, and harvest in July 2017. At each sampling date, 2-cm diam. soil cores using a hand probe were collected from five randomly selected spots within each plot to a 15-cm depth, composited, and brought to the laboratory for analysis. The baseline samples collected before establishing cover crops in February 2016 were composited by treatment (composite of three replications). All soil samples were stored at 4°C until laboratory analysis, which occurred within 2 wk of sampling.

Soil measurements assessed included bulk density, pH, electrical conductivity (EC), gravimetric water content, and inorganic N, available P, PMN, PMC, and POXC concentrations. Soil bulk density was determined by collecting three undisturbed soil cores (2.3 cm diam. × 15- cm depth) using a hand probe, oven-drying soil samples at 110°C for 24 h, and dividing the weight of the oven-dried sample by the volume of the core (Blake and Hartge, 1986). Soil texture was determined using the hydrometer method (Gee and Bauder, 1979). Gravimetric soil water content was determined by oven-drying 10 g field-moist soil at 105°C for 24 h. Soil pH and EC were determined in a 1:5 soil to water suspension using electrodes (Thomas, 1996). Inorganic N concentration was analyzed as the sum of KCl-extractable NO_3^-–N and NH_4–N in an autoanalyzer (Timberline Instruments, LLC, Boulder, CO). For this, 5 g soil was extracted with 25 mL of 1 mol L^{-1} KCl. Available P concentration was analyzed by extracting 2.5 g soil with 50 mL, 0.5 mol L^{-1} sodium bicarbonate and measuring the concentration with a spectrophotometer (Olsen, 1954). The PMC concentration was analyzed by aerobic incubation of approximately 20 g soil samples for 2 wk (Zibilske, 1994) and measuring CO_2 release from incubation jars using infrared gas analyzer (LICOR Inc., Lincoln, NE). The PMN concentration was analyzed by extracting the incubated samples with KCl and determining inorganic N concentration as above. The POXC concentration was analyzed by chemical oxidation of organic matter with 0.2 mol L^{-1} $KMNO_4$ solution (Weil et al., 2003) and analyzing the reflectance of the supernatant at 550 nm with a spectrophotometer (United Products and Instrumentals Inc., Dayton, NJ). The STN and SOC concentrations were analyzed by dry combustion method in a LECO CNS analyzer (Ellington and Associates, Inc., Houston, TX). The contents of soil inorganic N, available P, PCM, POXC, SOC, and STN (kg or Mg ha^{-1}) were determined by multiplying their concentrations (mg or g kg^{-1}) by soil bulk density and the thickness of the soil layer.

Cover Crop Biomass and Wheat Yield

Cover crop biomass yield was determined by harvesting aboveground biomass from 1 m^2 area within each plot, oven-drying at 65°C for 72 h and weighing. Winter wheat was harvested at physiological maturity in June 2016 and 2017 by harvesting an area of 3.05 by 1.2 m with a Sickle Bar mower (Santa Fe Equipment Sales Inc., Santa Fe, NM). Wheat aboveground biomass (straw and grain) was collected in cloth bags, brought to the laboratory, and thrashed using a plot combine to separate grain and straw. The moisture content of wheat grain was determined with a moisture meter, while straw was oven dried at 65°C for 72 h to determine moisture content. From this, grain and biomass yields were determined, and wheat grain yield was adjusted to 14% moisture for comparing yields. Harvest index (HI) was

Table 2. Cover crop biomass, wheat grain yield, and harvest index (2016–2017) under diverse cover cropping treatments.

Treatment	Cover crop biomass	Wheat yield 2016	Wheat yield 2017	HI 2016	HI 2017
	——— kg ha^{-1} ———				
Fallow	–	3609	6268	0.28	0.33ab
Pea	951c	3363	6168	0.31	0.34ab
Oat	2302a	3198	6270	0.33	0.35a
Canola	994c	2720	5682	0.32	0.33ab
PO	2112a	3252	6187	0.29	0.32ab
PC	1326bc	3684	6361	0.54	0.33ab
POC	1937ab	3518	5955	0.53	0.32ab
SSM	1923ab	3438	6609	0.46	0.31b
Year					
2016	923b	3348b		0.38	
2017	2375a	6187a		0.33	
Analysis of variance		2016	2017	2016	2017
Treatment (T)	<0.001	0.88	0.89	0.29	0.05
Year (Y)	0.002	–		–	
T × Y	0.11	–		–	

calculated by dividing grain yield by total biomass (grain + straw) after adjusting grain yield on an oven-dried basis.

Statistical Analysis

Data on soil properties that were measured at the time of cover crop termination in 2016 and 2017 cover crop biomass, and crop yields were analyzed by using the PROC MIXED program in SAS (SAS v.9.3, SAS Institute, Cary, NC) for a randomized complete block design experiment with split-plot arrangement of treatments. This analysis used cover crop treatment as the fixed factor, year as the split-plot in time factor (second fixed factor) and replication as the random term in the model. Soil properties measured at different sampling dates in the CC–WW rotation were analyzed using treatment as the fixed factor, sampling date as the split-plot in time factor (second fixed factor), and replication as the random term in the model. The soil properties monitored at the end of the 2-yr study period, such as SOC and STN, were also analyzed using PROC MIXED in SAS for a randomized complete block experiment. Cover crop biomass data were analyzed by using cover crop treatment as the fixed factor, year as the split-plot in time (second fixed factor) and replication as the random term in the model. Winter wheat yield and harvest index data were analyzed separately for 2016 and 2017 using cover crop treatment

as the fixed factor and replication as the random factor in the model. Treatment means were compared at a significant probability of ≤0.05 using a Tukey test unless otherwise stated.

RESULTS

Cover Crop Biomass

Cover crop biomass varied among treatments and years. Averaged across years, cover crop biomass for oat (2302 kg ha^{-1}) and PO mixture (2102 kg ha^{-1}) was significantly greater than other cover crop species (Table 2). Averaged across treatments, cover crop biomass at termination was 2375 kg ha^{-1} in 2017, which was 1649 kg ha^{-1} greater than 923 kg ha^{-1} in 2016. While two-, three-, and six-species mixtures used 50, 33, and 17% of the monoculture seeding rate, respectively, for each crop in the mixture, oat covered ~75% biomass in PO mixture and ~64% in POC mixture at the time of cover crop termination. Oat and barley in six species mixture covered ~60% biomass, whereas legumes (pea and hairy vetch mixture) covered only ~15% and the rest ~25% biomass with brassica. Variation in cover crop biomass may have affected soil properties and wheat yield.

Soil Properties

The SWC at cover crop termination was significantly influenced by treatment and treatment × year interaction (Table 3). The SWC in fallow treatment was 1.6 to 2.7% and 4.5 to 6.7% greater in 2016 and 2017, respectively, than SWC in cover crop treatments (Fig. 1). Among cover crop treatments, SWC was 0.21% lower under pea than canola in 2016, and 0.56 to 2.32% lower under oat than pea and canola in 2017 (Fig. 1). The analysis of SWC at different sampling dates in CC–WW rotation revealed a significant effect of sampling date and treatment × sampling date interaction only at the $p = 0.06$ level (Table 3). The SWC was 1.82% greater in fallow than cover crop treatments in May 2016, but 2.49 and 4.18% greater in SSM and POC than fallow in October 2016 (Fig. 2). The SWC was similar among treatments at other sampling dates.

Soil inorganic N content at cover crop termination differed among treatments and years, and there was a significant treatment × year interaction (Table 3). Inorganic N content was 1.8 to 3.4 times greater in fallow than cover crop treatments; however, inorganic N was similar among cover crop treatments within a year (Fig. 1). Inorganic N within CC–WW rotation varied among treatments and sampling dates, with significant interaction for treatment × sampling date (Table 3). Soils under cover crops had 41 to 49% less inorganic N than under fallow in

Table 3. Analysis of variance for treatments × year interaction at cover crop termination time and treatments × sampling date effects in CC–WW rotation on soil water content (SWC), inorganic N, available P, potentially mineralizable carbon (PMC), permanganate oxidizable carbon (POXC), soil organic carbon (SOC), and soil total nitrogen (STN).

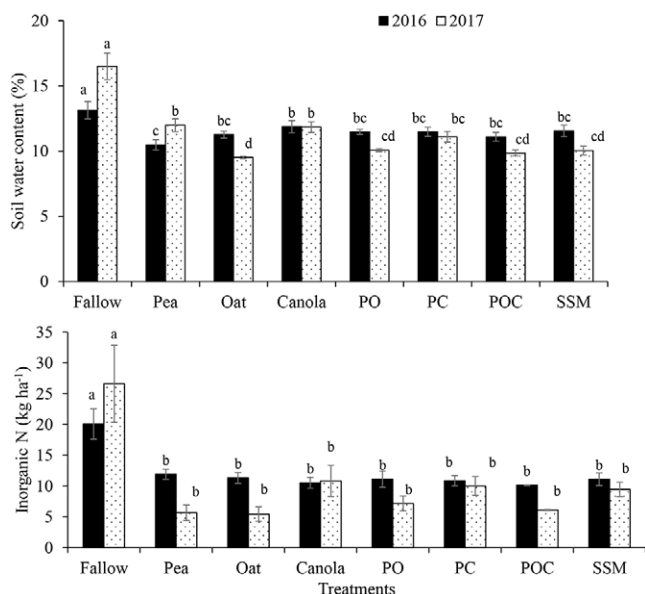| Response	P-value SWC	Inorganic N	Available P	PMC	POXC	SOC	STN
	Comparison between years						
Treatment (T)	<0.001	<0.01	0.19	<0.001	<0.001	0.007	0.001
Year (Y)	0.39	0.03	<0.001	0.01	0.63	–	–
T × Y	<0.001	0.03	0.43	<0.001	<0.001	–	–
	Treatments × sampling date interaction in CC–WW rotation						
T	0.61	0.001	0.15	0.007	<0.001	–	–
Sampling date (D)	<0.001	<0.001	0.001	<0.001	0.01	–	–
T × D	0.06	0.006	0.15	0.01	0.004	–	–

Fig. 1. Soil water content (SWC) and inorganic N under different cover crops and fallow plots at cover crop termination in 2016 and 2017. Bars above the mean are ± standard error. Bars with a common lowercase letters indicate no significant difference between treatments within a year (*P* < 0.05, Tukey test).
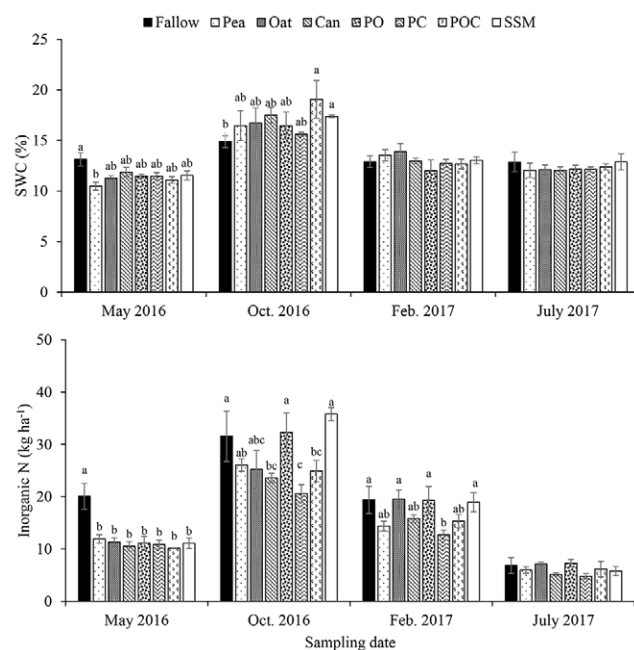
Fig. 2. Soil water content (SWC) and soil inorganic N at different sampling dates in a cover crop–winter wheat (CC–WW) rotation. Bars above the mean are ± standard error. Bars with a common lowercase letters are not significantly different between treatments within sampling date (*P* < 0.06 for SWC and *P* < 0.05 available N, Tukey test).

May 2016 (Fig. 2). In October 2016, inorganic N was 25 to 74% greater under fallow, PO, and SSM than canola, PC, and POC. Inorganic N in February 2017 was 49 to 54% greater in fallow, pea, oat, and SSM than canola. In July 2017, inorganic N did not differ among cover crops and the fallow treatment.

Available P varied with sampling dates (Table 3). Averaged across treatments, available P at cover crop termination was 17.1 kg ha^{-1} in 2016, which was 81% greater than 2017. Available P content was similar among treatments and no significant treatment × year interaction was observed (Table 3).

Soil PMC content at cover crop termination differed among treatments and years, with an interaction of treatment × year (Table 3). Soil PMC content was 22% greater in 2016 than the value of 170 kg ha^{-1} recorded in 2017, mainly due to difference among fallow, POC, and SSM treatments. The PMC in 2017 varied among treatments, with 99 to 163% greater under pea, oat, canola, and two-species cover crop mixtures (PO and PC) than fallow (Fig. 3). Analysis of PMC at different sampling dates in CC–WW rotation revealed that PMC varied among treatments and sampling dates, with a significant interaction for treatment × sampling date (Table 3). The PMC was 39% greater under SSM than fallow in May 2016 (Fig. 4). In October 2016, PMC was 90 to 145% greater under fallow, pea, oat, and PO than the value of 56.8 kg ha^{-1} observed under POC. In July 2017, PMC was 55 to 57% greater under SSM than PC and POC.

Soil POXC content was different among treatments, with significant treatment × year interaction at cover crop termination (Table 3). Soil POXC under SSM was greater (33 and 25%, respectively) than canola and PC mixture in 2016, and 22% greater under oat than pea in 2017 (Fig. 3). Soil POXC at different sampling dates in CC–WW rotation also revealed differences among treatments and sampling dates, with significant interaction of treatment × sampling date (Table 3). Soil POXC was generally lower under canola and PC than SSM, fallow, oat, or PO at all sampling dates (Fig. 4).

The SOC at the end of the experiment in July 2017 was 18% greater under oat than PC (Fig. 5). Similarly, STN was 8 to 20% greater under oat than pea, canola, PC, POC, and SSM.

Wheat Yield

Winter wheat yield was not affected by the treatments in both years. Wheat yield ranged from 2720 to 3684 kg ha^{-1} in 2016 which were significantly lower than the yields of 5682 to 6609 kg ha^{-1} observed in 2017 (Table 2). Harvest index was similar among treatments in 2016, but was greater in oat than in SSM in 2017.

DISCUSSION

Conservation systems that reduce tillage and increase cropping intensity, diversity, and crop residue inputs have the potential to improve soil health and agroecosystem resilience in the southern Ogallala Aquifer region. However, increasing cropping intensity through cover cropping should be implemented carefully, because cover crops may use water and affect subsequent crop yields (Nielsen and Vigil, 2005). In this study, treatments did not interact with sampling dates for SWC when the significance level (*P*) was considered at 0.05, but there was a significant interaction at *P* = 0.06, with the fallow treatment having higher SWC than cover crop treatments at cover crop termination. Absence of crops may have increased SWC in the fallow treatment while water uptake by cover crops during their growth resulted in lower SWC under cover crops at the time of termination. This is similar to those reported by several researchers (Nielsen et al., 2002; Nielsen and Vigil, 2005) that growing cover crops can reduce soil water content when compared to leaving the land under fallow. Inserting a crop between wheat and fallow periods under the no-tillage system neither affected soil water content at wheat planting, nor subsequent wheat yield, but completely replacing fallow
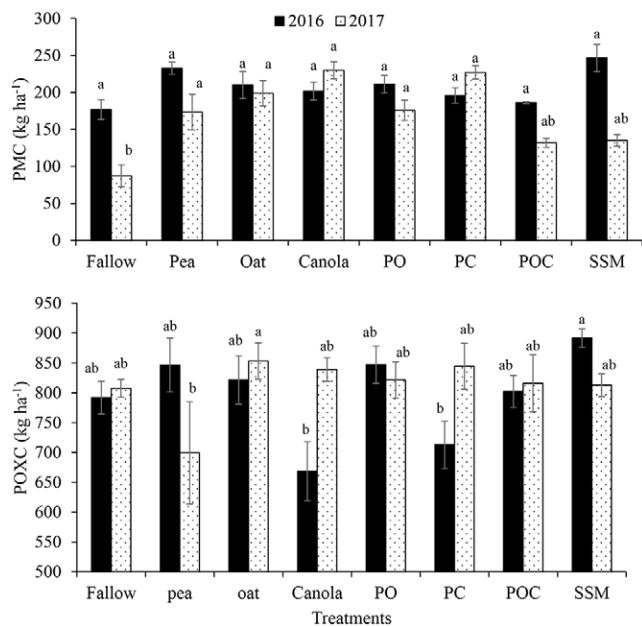
Fig. 3. Potentially mineralizable carbon (PMC) and permanganate oxidizable carbon (POXC) under different cover crops and fallow plots in 2016 and 2017. Bars above the mean are ± standard error. Bars with a common lowercase letters indicate no significant difference between treatments within a year (*P* < 0.05, Tukey test).
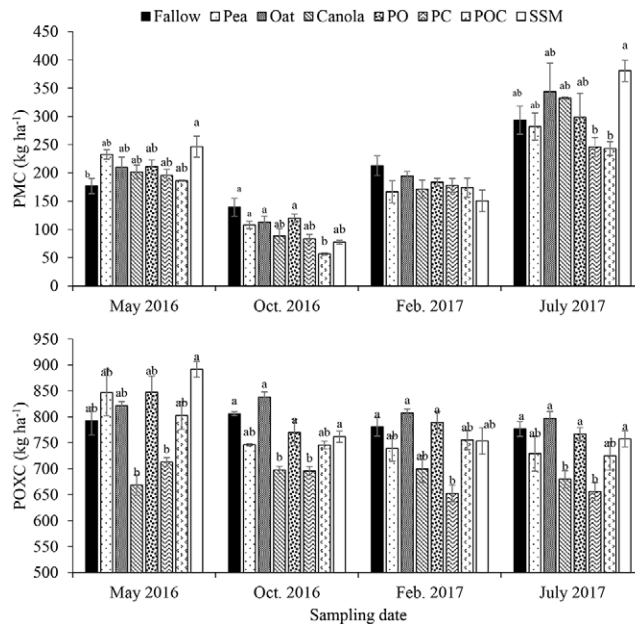
Fig. 4. Potentially mineralizable carbon (PMC) and permanganate oxidizable carbon (POXC) at different sampling dates in cover crop–winter wheat (CC–WW) rotation. Bars above the mean are ± standard error. Bars with a common lowercase letters indicate no significant difference between treatments within a sampling date (*P* < 0.05, Tukey test).

with cover crops reduced soil water as well as subsequent wheat yield (Nielsen and Vigil, 2005). In our study, cover cropping for few months and leaving residues during the summer, likely conserved more water in cover crop than the fallow treatment, thereby showing greater SWC in cover crop. Soil water recharge due to precipitation in the summer may have resulted in similar SWC among treatments at wheat planting in July. The SWC was comparable among treatments during wheat growth and development in the CC–WW rotation.

The early indication of changes in soil health and nutrient cycling was evaluated by monitoring labile SOM components, such as inorganic N and P, PMC, PMN, and POXC. The greater PMC and POXC under oat, PO, and SSM than other treatments at most sampling dates in our study were associated with increased C input from cover crop residue, as the biomass was greater with these cover crops than other treatments (Table 2). Various researchers (Broadbent, 1986; Wu et al., 1993; Lou et al., 2007) have reported similar findings. As cover crop and crop residue inputs provide C sources for microbes, lack of crop C inputs in the fallow treatment resulted in the lowest PMC content, specifically at the time of cover crop termination. Studies showed that SOC decomposition depends on the quality as well as quantity of residues added to the soil (Shahbaz et al., 2017). Analysis for pea, oat, and canola biomass samples for their quality at the time of cover crop termination showed C/N ratios of 10.3, 18.2 and 7.8 and lignin content of 5.16, 2.85, and 3.30%, respectively (Ghimire et al., 2017). Higher C/N ratio of oat than pea and canola may have reduced mineralization rate of the residue, thereby increasing SOC and STN with this cover crop. Increased soil inorganic N with fallow in May and October 2016 may have also affected PMC and PMN contents.

Several researchers (Pikul et al., 1997; Sainju et al., 2003) have reported that soil inorganic N was greater under fallow than cropped soils due to the absence of plants for N uptake.

Higher inorganic N in the summer also results from increased soil temperature and water content, leading to increased SOM mineralization. It is not clear how different cover crops affected N dynamics in semiarid environments. Longer-term study may reveal the effect of specific legume and non-legume cover crops on soil N availability. However, greater soil inorganic N under PO and SSM in October 2016 in this study may be associated with legumes, such as pea and hairy vetch, present in the mixtures. Mineralization of the N-rich residue may have increased soil inorganic N in October 2016. Legume residues with higher N concentration and lower C/N ratio mineralize more rapidly and increase soil inorganic N than non-legume residue or the absence of cover crop (Soon and Arshad, 2002; Constantin et al., 2010). As cover crop and the fallow treatments did not receive P fertilizer, soil available P was low and similar across the sampling dates and treatments.

Although differences in the response of some labile components of SOC and STN occurred in this short-term study, it may take several years to realize the sustained improvement in soil health due to hot, dry environment. Increased SOC and STN under oat than other cover crops may be related to the quality and quantity of cover crop residue returned to the soil. Cover crop biomass was greater with oat than pea, canola, and PC (Table 2). A previous study at the same experimental site revealed higher C/N ratio of oat residue than pea and canola residues (Ghimire et al., 2017). Pea, canola and PC mixture, however, resulted in lower soil labile C fractions and nutrient availability, possibly due to lower biomass residue returned to the soil. Canola emergence was only 61% of the seeding rate in the first year. Even with such a low emergence, canola biomass was comparable with pea biomass, which was relatively lower in both years, thereby affecting C inputs. It has been known that SOC and STN are usually greater with non-legume than legume cover
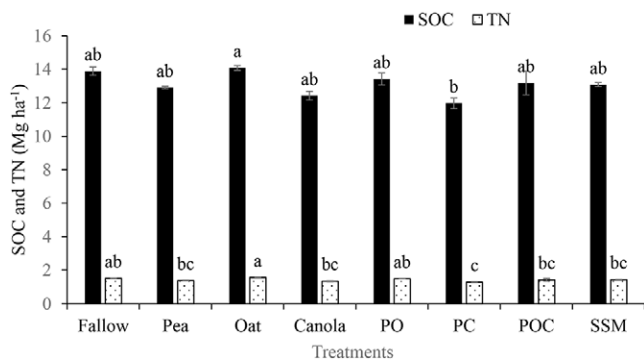
Fig. 5. Soil organic carbon (SOC) and soil total nitrogen (STN) in response to the cover crop (CC) treatments after wheat harvesting in 2017. Bars above the mean are ± standard error. Means with a common lowercase letters are not significantly different ($P < 0.05$, Tukey test).

crops due to their greater C/N ratio (Kuo et al., 1997a, 1997b; Sainju et al., 2003). Long-term evaluation of SOC and STN pools, dynamics, and their stabilization under diverse cover cropping practices will improve our understanding of agroecosystem resilience with cover cropping in the semiarid environment, such as the southern Ogallala Aquifer region. Nonsignificant difference in winter wheat yields among cover crops and the fallow treatment also suggests the need for long-term study. Cover crop, as well as wheat yield, was greater in 2017 than in 2016, possibly due to improvements in soil environment over the years by adopting no-tillage. No-tillage was adopted across all treatments with the establishment of this study in a field previously under conventional tillage management for several years. Change in management from conventional to no-tillage may have improved the water storage in the soil profile throughout all treatments and supported high cover crop biomass and wheat yield in the second year of the study. Increased winter wheat yield in 2017 than 2016 was also due to greater precipitation, as growing season (October–July) precipitation was 279 mm in 2017 compared to 139 mm in 2016 (Table 1). Nevertheless, this study revealed improvements in early indicators of changes in soil health and highlights the need for long-term research. Although cover crops provide multiple benefits, economic analysis is needed to evaluate the ecosystem services because cover crop seeding can increase the cost of crop production.

CONCLUSIONS

Results from this 2-yr study reveal positive influence of cover crops on labile components of SOC and STN pools in a winter wheat-based cropping system with minimum impacts on SWC in the southern Ogallala Aquifer region. Oat and its mixture with other cover crops had higher biomass yield and increased soil inorganic N, PMC, POXC, SOC, and STN compared to pea and canola. Though SWC was lower with cover crops than the fallow treatment at cover crop termination, SWC at winter wheat planting was not different among treatments. Breaking a long fallow period with short-season cover crops could be a good strategy to improve soil health and the resilience of winter wheat-based crop rotations in the southern Ogallala Aquifer region. Cover cropping with oat and its mixture with other species have the potential to improve soil health and fertility, increase C and N sequestration, and sustain winter wheat yields. Further research

on diverse cover cropping practices will improve the understanding of water use and soil health effects in semiarid regions.

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