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Long-term cover crop management effects on soil properties in dryland cropping systems

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Abstract

Replacing summer-fallow by growing cover crops (CC) in semi-arid regions might provide several soil health benefits. This study examined the effects of long-term CC management in place of fallow on soil properties in a no-till (NT) winter wheat (*Triticum aestivum* L.)-grain sorghum (*Sorghum bicolor* Moench)-fallow (WSF) cropping system. Fallow replacement treatments were spring-planted and included peas (*Pisum sativum* L.) for grain as well as one-, three-, and six-species CC mixtures compared with summer-fallow. Half of each CC treatment was harvested for forage and the other half remained standing after termination. Soil organic carbon (SOC) stocks within the 0- to 15-cm soil depth increased by 0.14 Mg ha^{-1} yr^{-1} for each Mg ha^{-1} CC residue added from 2008 to 2012 and were unaffected by CC diversity. However, SOC stocks were not different than fallow in 2018 likely because CC residue inputs declined due to a succession of drought years. Residue contribution from grain sorghum in the WSF rotation best predicted SOC in 2018 compared to 2012. Soil aggregation was greater with CCs compared to peas or fallow and was unaffected by CC diversity. Mean weight diameter (MWD) of water stable aggregates in 2018 was greater with standing CCs (1.11 mm) compared to peas (0.77 mm) but was similar to fallow (0.84 mm). The MWD of dry aggregates with standing (3.55 mm) and hayed (3.62 mm) CCs were greater compared to fallow (2.75 mm). Our findings suggest simple CC mixtures and CCs managed for hay provide similar soil benefits as diverse CC mixtures or CCs left standing in this semi-arid environment.

Keywords: Cover crop, dryland cropping systems, soil organic matter, aggregate stability

1. Introduction

Growing cover crops (CCs) in dryland cropping systems in the semi-arid central Great Plains, USA has been promoted as a component of the movement toward regenerative agriculture and soil health (Cano et al., 2018; Kelly et al., 2021). This includes such benefits as reduced soil erosion, enhanced nutrient cycling, as well as increased microbial activity and abundance (Blanco-Canqui, 2018; Blanco-Canqui et al., 2013; 2015; Calderón et al., 2016). Despite these potential benefits as well as an increasing interest among producers, CC adoption has been slow in this water-limited region (Bergtold et al., 2017). This is largely due to concern that CCs may deplete stored soil water compared to that obtainable with chemically-controlled fallow which semi-arid regions such as the central Great Plains have historically relied upon for dryland crop production (Holman et al. 2018; Nielsen et al., 2005; Nielsen and Vigil, 2010).

Dryland crop production is prevalent in regions where precipitation accounts for only 20 to 35% of potential evapotranspiration and has been enhanced through increased crop residue retention by reduced or no-tillage (NT) to reduce soil erosion, increase soil water capture during fallow periods, and increase grain yields (Robinson and Nielsen, 2015; Stewart and Peterson, 2015). The practice of fallowing has been shown to stabilize grain crop yields and to prevent crop failure, particularly in drier years (Aiken et al., 2013; Nielsen and Vigil, 2010). However, precipitation storage efficiency during fallow is imperfect, ranging from 17 to 45%, depending primarily on tillage practice and associated residue management (Peterson and Westfall, 2004). Limited soil cover during fallow may lead to increased vulnerability to erosion even in fields under long-term NT management (Hansen et al., 2012). These situations may result in loss of topsoil, depletion of soil organic matter (SOM), declining soil fertility, and inefficient water storage (Baumhardt et al., 2015; Bowman et al., 1990). Replacing portions of the fallow period with short-season crops could provide cover to protect the soil and sustainably intensify dryland farming operations in the central Great Plains and similar semi-arid regions.

Adoption of CCs in dryland cropping systems may enhance residue cover and reduce the susceptibility of the soil to erosion and depletions in SOM (Blanco-Canqui et al., 2013, 2014). Reducing erosion is particularly important in semi-arid dryland cropping systems where residue levels are frequently low and fallow fields may be left exposed (Baumhardt et al., 2015; R. Ghimire et al., 2018). Incorporating CCs may increase SOC stocks, largely depending upon cumulative biomass production (B. Ghimire et al., 2017). In addition, it has been documented that increased root activity and associated carbon inputs from CCs may improve soil aggregation and water infiltration (Chalise et al., 2018; Franzluebbers et al., 2000; Nouri et al., 2019). However, many of these studies were conducted in regions that receive greater annual precipitation than is common in most semi-arid regions. Past research at this present long-term study site in southwest Kansas, USA showed replacement of fallow with CCs increased SOC content, reduced wind-erodible fraction, increased the stability of wet aggregates, and reduced run-off (Blanco-Canqui et al., 2013). These results indicate that CCs in semi-arid regions have the potential to improve soil health similarly to those reported in more humid regions at least in the short-term (<10 years) despite limited rainfall and high evaporative demand. However, information is still lacking regarding the long-term (>10 years) soil benefits of integrating CCs in dryland cropping systems (Blanco-Canqui et al., 2015).

A major consideration of CC management is species selection and the decision to plant a monoculture or diverse mixture. Interest in CC mixtures comes from the ecological theory of niche complementarity which could contribute to transgressive over-yielding, where a mixture yields more biomass than the best of its constituents (Schmid et al., 2008), and provide increased ecosystem services (multifunctionality) compared to monocultures. The results of Smith et al. (2014) suggest that a CC mixture could yield more than the average of its component species in monocultures but may not provide more ecosystem services than the most productive monoculture. Finney and Kaye (2017) suggested that rather than species diversity, functional diversity could be a better predictor of multifunctionality. However, these observations were made in more humid environments than the semi-arid central Great Plains. Previous studies with CCs in the semi-arid Great Plains concluded diverse mixtures of grass, legume, and other broadleaf species often yield the same or less than the most productive grass monocultures (Nielsen et al., 2015a; 2015b; Calderón et al., 2016). These authors further observed CC mixtures to have similar water use and effects on soil microbial properties as monocultures.

Growing CCs in dryland cropping systems offers great potential to improve soil properties, enhance precipitation use efficiency, and diversify markets when CCs are utilized as forage (Holman et al., 2021a; 2021b). Few studies have investigated the effect of managing CCs as annual forage on soil properties in dryland crop production (Blacno-Canqui et al., 2015). Haying and/or grazing of CCs for forage can provide an economic benefit to offset potential lost revenue associated with decreased crop yields when CCs are grown ahead of a cash crop in dry years (Holman et al., 2018; Holman et al., 2021a; 2021b; Kumar et al., 2020). However, there is concern that harvesting CCs as forages and the reduction in surface residue may negate the beneficial effects of CCs on soil health (Bergtold et al., 2017; Li et al., 2013). The short-term results of Blanco-Canqui et al. (2013) concluded no difference in SOC or water stable aggregates (WSA) when CCs were hayed for forage, leaving 15 cm of stubble, compared to when CCs were left standing.

To our knowledge, there is little or no information on the long-term (>10 years) effects of haying CCs for forage on soil health. The objective of this study was to assess the long-term effect of CC management in place of fallow on physical and chemical parameters of soil health.

Specifically, this study investigated the i) effect of CC species diversity and ii) effect of haying CCs as forage on soil properties in a NT dryland cropping system. Our hypothesis was that incorporating CCs would decrease bulk density while increasing SOC stocks, wet and dry aggregate stability, as well as water infiltration. It was predicted that increasing CC species diversity would not improve soil health beyond what is achievable with a simple grass monoculture CC due to the greater productivity of grasses compared to broadleaf crops under semi-arid dryland conditions. Furthermore, it was hypothesized that long-term haying of CCs as annual forage would result in similar soil health gains as when CCs were left standing because of retention of some above ground stubble after forage removal and contribution of the below-ground root biomass of CCs to soil health.

2. Materials and Methods

2.1. Experimental layout

This study was established in fall 2007 at the Kansas State University Southwest Research-Extension Center near Garden City, KS (37°58′31″ N, 100°51′51″ W) to investigate fallow replacement treatment effectsin semi-arid dryland cropping systems. The soil at the study location was a Ulysses silt loam (Fine-silty, mixed, superactive, mesic Torriorthentic Haplustolls) formed from loess material at an elevation of 865 m above sea level. Long-term (1981–2010) average annual precipitation at the study site was 489 mm (Table 1) with an open-pan evaporation (April through September) of 1810 mm. The initial study, from 2007 to 2012, was a split-plot randomized complete block design with crop phase as the main plot and eight fallow replacement CC treatments as sub-plots replicated four times and implemented during the fallow year of a winter wheat (*Triticum aestivum* L.)-fallow (WF) cropping system (Blanco-Canqui et al., 2013; Holman et al. 2018; 2021a). The eight sub-plot fallow replacement treatments from 2007 to 2012 were (1) fallow, (2) yellow spring peas (*Pisum sativum* L.) harvested for grain, (3) standing spring triticale (×*Triticosecale* Wittm.), (4) hayed spring triticale, (5) standing spring triticale/pea, (6) hayed spring triticale/pea, (7) standing spring triticale/lentil (*Lens culinaris*), and (8) hayed spring triticale/lentil CCs.

This experiment was modified to a three-year NT winter wheat-grain sorghum (*Sorghum bicolor* Moench)-fallow (WSF) cropping system in 2013 (6 years of fallow replacement in the cropping system) to better align with the typical producer practice in the region (Holman et al., 2021b). Converting from WF to a three-year WSF rotation was accomplished by incorporating a third crop phase to the study perpendicular to the existing two blocks of the WF system. This third phase of the rotation was phased in over a period of three years starting in of 2010 in order for all main crop phases (WSF) to be completely randomized by 2013. For the current study, fallow replacement treatments were sampled during the fallow phase of the rotation in fall 2018 before wheat planting in those replications which had been present in the study since 2007 (12 years of fallow replacement in the cropping system). In summer 2019, these same plots were sampled again after the wheat planted in fall 2018 had been harvested. Similar to the initial study, CC and pea treatments were grown only in the fallow phase of the crop rotation as replacement options compared to the traditional NT fallow.

Fallow replacement treatments from 2013 to 2019 were similar to those from 2007 to 2012 with slight modifications to include more diverse CC mixtures . The fallow replacement treatment plots sampled in 2018 as well as 2019 and held consistent since 2007 (12 years in the study) were: (1) fallow, (2) yellow spring peas harvested for grain, (3) standing triticale, and (4) hayed triticale. In 2013, spring oat (*Avena sativa* L.) was added to the standing and hayed triticale/pea hay treatments, converting them to (5) standing and (6) hayed oat/triticale/pea treatments. Similarly, a (7) standing and (8) hayed cocktail mixture of oat/triticale/pea/buckwheat (*Fagopyrum esculentum* Moench) /turnip (*Brassica ra pa* L.) /radish (*Raphanus sativus* L.) replaced standing and hayed triticale/lentil, respectively. This resulted in eight fallow or fallow replacement treatments similar to the original treatments. Modifying the spring triticale/pea and spring triticale/lentil treatments did not change the overall productivity because the three and six species CC mixtures were dominated by grass species in the mix, which contributed most of the biomass produced from these treatments (Holman et al., 2021b). All the CC treatments were divided into standing and hayed management groups in all years. No fertilizer was applied to any fallow replacement treatment at any time since study initiation. The individual plot size was 9 m × 36 m (for fallow and spring pea treatments), and the standing and hayed CCs were 4.5 m × 36 m with four replications. Crops grown as cover were terminated with herbicides and left standing, crops grown for hay were harvested at a height of 15-cm, and peas were allowed to grow to maturity and harvested for grain. The fallow treatment was maintained as NT using appropriate chemical weed control methods.

All phases of the WF (2007 to 2012) or WSF (2013 to 2019) rotations were present in each of the four replications every year of the study. Therefore, each phase of the rotation (wheat and fallow or fallow replacement from 2007 to 2012; wheat, sorghum, and fallow or fallow replacement from 2013 to 2019) was present each year of the study (Supplementary Table 1). Over the years, this study was repeated in the same plots such that the wheat planted in the fall of 2012 grew on soil that experienced three cycles of the two-year WF rotation. The plots sampled in 2018 and 2019 had those three cycles of the WF rotation followed by additional two cycles of the three-year WSF rotation with fallow replacement treatments applied to the same plots since

2007 (Supplementary Table 1). Therefore, each plot has had five cycles of fallow replacement crops.

2.2. Crop management

Every year winter wheat was planted in early October and harvested in early July. Following an 11-month fallow period after wheat harvest, grain sorghum was planted in June and harvested between mid-October through early November. Fallow replacement crops followed grain sorghum in the crop rotation and were planted between the end of February and mid-March as field conditions allowed. Cover crops were hayed for forage and/or chemically terminated in early June to minimize negative effects on subsequent wheat yields (Schlegel and Havlin, 1997; Holman et al., 2018). Peas grown for grain were harvested in mid-July though they often failed to produce grain and plots were often infested by kochia [*Kochia scoparia* (L.) Schrad.]. Haying and termination of CCs coincided with triticale heading, which was selected as a harvest stage to optimize forage yield and quality. Wheat and peas were harvested with a small plot combine (Model Delta, Wintersteiger Inc., Salt Lake City, UT) equipped with a stripper header (Model CX, Shelbourne Reynolds Inc., Colby, KS) from a 2.4-m by 36-m area at grain maturity, which occurred approximately the first week of July. A stripper header was used to maximize stubble height and residue retention. Grain sorghum was harvested similarly using the same small plot combine equipped with a row crop header. Grain yields were used to estimate crop residue production assuming a harvest index of 0.45 and 0.46 for wheat (Dai et al., 2016) and sorghum (Unkovich et al., 2010), respectively. Biomass yields for forage crops were estimated by cutting to a 15-cm stubble height using a small plot forage harvester (Carter Manufacturing Company, Inc., Brookston, IN). Harvesting the CCs at a 15-cm stubble height provided about 70 to 80% residue cover to protect the soil surface against wind and water erosion.

2.3. Soil sampling and analysis

Soil sampling took place at study initiation in fall 2007, in fall 2012 during actively growing winter wheat, in fall 2018 before wheat planting, and summer 2019 after wheat harvest for determination of soil physical and chemical properties. Soil bulk density in 2007 and 2012 sampling was determined by collecting undisturbed soil cores (5-cm in diameter) from two random locations in each plot using a truck mounted Giddings hydraulic probe (Giddings Machine Co, Windsor, CO) from the 0- to 15-cm depth. Similarly, in 2018 and 2019, two intact soil cores (5-cm diameter) were randomly taken from the 0- to 15-cm depth from each plot using an AMS bulk density sampler (AMS, Inc., American Falls, ID) for determination of bulk density. Additionally, ten soil cores (2.5-cm diameter) were taken with a hand probe from the 0- to 15-cm depth, combined, and thoroughly mixed for determination of pH, available nitrogen (NO_3 and NH_4), and SOC concentration at each sampling time. Samples collected for bulk density were dried at 105 °C for 48-hr, and bulk density was calculated by mass of oven-dry soil divided by volume of the core. Data for the two cores were averaged to obtain one bulk density value for the plot. Soil samples collected for determining soil chemical properties were air-dried and ground to pass through a 2-mm sieve after carefully removing any large pieces of crop residue and fine plant roots that may have been collected with the soil sample. The soil at the study site does not contain very coarse soil particles and mineral fragments >2-mm. Hence, sieving the ground air-dried soil sample through 2-mm sieve was to get homogenous samples and not meant to remove rocks. Soil pH was analyzed using a 1:1 (soil/water) ratio with deionized water on an OAKTON PC 700 Benchtop pH Meter (OAKTON Instruments, Vernon Hills, IL). Soil N concentrations were determined colorimetrically using a Seal AQ2 discrete autoanalyzer (Seal Analytical Inc., Mequon, WI) following extraction with 2 M KCl. A portion of the samples were ground with a mortar and pestle to pass through a 0.25-mm sieve, and SOC concentration was determined by dry combustion using a CN analyzer after pretreating samples with 10% (v/v) HCl to remove carbonates (Nelson and Sommers, 1996). Carbon concentrations were converted to stocks by multiplying concentrations by soil bulk density and the thickness of the soil layer on a fixed depth basis as described by Benjamin et al. (2010). The SOC stocks were calculated on fixed depth basis because our previous research showed SOC stocks calculated on fixed depth or equivalent mass basis from soil samples were taken at 0 to 15 cm were not different (Mikha et al., 2018).

Additional samples were collected from the 0- to 5-cm soil depth with a flat shovel for the determination of aggregate stability. This sampling depth was chosen because the upper soil layer is the most vulnerable to the impacts of wind and water erosion in dryland environments and is the depth most responsive to changes in soil management (Blanco-Canqui et al., 2013; Sherrod et al., 2018). The samples collected were passed through sieves with 4.75- to 8.0-mm mesh and then allowed to air-dry. The 4.75- to 8.0-mm aggregate samples were used to estimate WSA by the wet-sieving method (Nimmo and Perkins, 2002) by placing a 50 g sample on top of a stack of nested sieves of 2- and 0.25-mm sized openings in a water column. Samples were allowed to wet by capillarity for 5 minutes. Subsequently, sieve stacks were oscillated a vertical distance of 3.7 cm at 30 oscillations minute^{-1} for 5 minutes. Aggregate fractions were transferred into glass beakers, dried at 105°C, and weighed to determine the proportion of aggregates within each size fraction. Each dry sample was then corrected for coarse sand by mixing the oven-dried aggregates with 30 ml of 5g L^{-1} sodium hexametaphosphate solution to disperse soil particles.

Samples were allowed to soak for a minimum of four hours and were then swirled on an orbital shaker for an additional four hours. Each sample was then poured back though individual sieves with the same sized openings. The recovered sand was oven-dried and weighed to correct for coarse particles. Sand-corrected values were then used to compute the mean weight diameter (MWDWSA) and aggregate size distribution of WSA (ASDWSA).

In 2019, before sieving for WSA, half of each sample was separated and air-dried to determine dry aggregate stability using a system of nested rotary sieves having 19-, 6.3-, 2-, 0.84-, and 0.42-mm diameter openings (Chepil, 1962). Samples were shaken for 5 minutes using a portable sieve shaker (W.S. Tyler Model RX-812, Mentor, OH). The soil particles remaining on each sieve was weighed and the data was used to compute dry aggregate size distribution (ASDDA) and mean weight diameter of dry aggregates (MWDDA) as well as wind-erodible fraction (WEF) which is the fraction of soil particles with a diameter less than 0.84 mm (Blanco-Canqui et al., 2013).

Infiltration rate measurements were conducted after winter wheat harvest in summer 2019 using the Cornell sprinkle infiltrometer, a device designed to estimate water infiltration rates (WIR), saturated infiltrability rate (SIR), and time-to-runoff (TTR) under simulated rainfall conditions (Ogden et al., 1997). Briefly, a Cornell sprinkle infiltrometer consists of a water reservoir with a perforated bottom that delivers simulated rainfall onto a 241-mm-diameter area delimited by a metal ring. An outflow tubing is fitted to the metal ring that allows water to runoff from the device when surface ponding occurs. When a steady state in the water outflow is achieved, the field saturated infiltration rate is then estimated as the difference between the applied rainfall rate and the runoff rate (Ogden et al, 1997). In the present study, the infiltrometer was calibrated to deliver simulated rainfall of 25 cm hr^{-1} and measurements were taken for one hour. The time to runoff was recorded. Additionally, runoff volume was measured every 3 minutes with a 1000-ml measuring cylinder and recorded. Two infiltration measurements were taken at two positions located approximately 12-m part within non-trafficked rows in each plot.

2.4. Statistical analysis

Data analysis for soil physical and chemical properties was performed using PROC GLIMMIX in SAS ver. 9.4 (SAS Institute, Cary, NC). In this study, the fallow replacement treatments by management combination resulted in eight different treatments that were implemented in the fallow phase of the crop rotation as sub-plots. Data collection occurred only in the fallow or wheat phase of the rotation so the main plot factor was not included in the model. The fallow replacement treatments and sampling year were considered fixed effects and replication (blocks) as random for the analysis of fallow management effects. Treatment effects were considered significant at $P \leq 0.05$. In addition, five single-degree of freedom contrasts were performed to compare fallow vs. standing CCs, fallow vs. hayed CCs, pea vs. standing CCs, pea vs. hayed CCs, and standing CCs vs. hayed CCs. Mean values presented for standing and hayed CCs were averaged across CC treatments of triticale, oat/triticale/pea, and cocktail to compare CC management effects. Regression analyses were performed using PROC REG in SAS to characterize the relationship between residue inputs from grain crops and CCs with accrued SOC stocks for each sampling period: 2007 to 2018, 2007 to 2012, and 2013 to 2018.

3. Results

3.1. Long-term weather patterns

Average annual precipitation from 2007 to 2012 was 446 mm or 83% of the 30-year average (489 mm) (Table 1). However, spring precipitation (February-May) was relatively reliable and favorable for the cool-season crops, winter wheat and fallow replacement treatments, in the crop rotation at the time. Average annual precipitation from 2013 to 2018 was 497 mm or 102% of the 30-year average. Although cumulative precipitation was near normal, this period had distinctly less reliable spring precipitation (117 mm) than the first six years (149 mm) and the 30-year average (167 mm). In the last six years of this study, on average, cumulative spring precipitation was 50-mm less compared with the 30-year average and did not reach near normal until the month of July, which was favorable for grain sorghum production, but too late to benefit the cool-season fallow replacement treatments or winter wheat in the rotation.

3.2. Soil organic carbon and crop residue input

In 2012, growing a CC increased SOC stocks compared to fallow though this did not persist to later sampling times in 2018 and 2019 (Table 2). For example, in 2012, SOC stocks were greater with standing (20.9 Mg ha^{-1}) or hayed CCs (19.9 Mg ha^{-1}) compared to fallow (17.9 Mg ha^{-1}). However, SOC stocks in 2012 was not significantly different among the CC treatments. These observations were made six years after study initiation and during a period when precipitation distribution was relatively favorable for the fallow replacement treatments (Table 1). When left standing, CCs had greater SOC compared to peas in 2012 but this difference did not persist into subsequent SOC stock measurements in 2018 and 2019 (Table 2). Averaged across CC mixture and monoculture treatments, SOC with hayed CCs was not different from standing CCs. Differences in SOC among treatments were not present in 2018 and 2019 samplings. Averaged across treatments, SOC stocks were 21.8 and 20.0 Mg ha^{-1} in 2018 and 2019, respectively. Soil organic carbon stocks within the 0- to 15-cm was not different among CCs with increased species diversity in 2012 and 2018.. However, in 2019, the hayed cocktail treatment was significantly greater than the standing or hayed oat/triticale/pea treatments. These were similar to all other treatments including fallow.

Regression analyses showed a positive relationship between SOC stocks in 2018 and annual total crop residue inputs (main crops plus fallow replacement crops) across the twelve years of this study (Fig. 1a). From 2008 to 2012, SOC stocks were unaffected by winter wheat residue (Fig.1 b). However, CC residue produced during this same period did positively affect SOC stocks measured in 2012 (Fig. 1c). Within this period, each additional Mg ha^{-1} CC residue input increased SOC stocks by 0.14 Mg C ha^{-1} yr^{-1}. Again, SOC stocks measured in 2018 were unaffected by winter wheat residue inputs from 2013 to 2018 (Fig. 1d). However, there was a significant positive relationship between SOC stocks measured in 2018 and grain sorghum residue input from 2013 to 2018 (Fig. 1e). The SOC stocks increased by 0.21 Mg C ha^{-1} yr^{-1} for each additional Mg ha^{-1} grain sorghum residue inputs from 2013 to 2018. Unlike 2008 to 2012, CC residue from 2013 to 2018 had no significant effect on SOC stocks measured in 2018 (Fig. 1f).

3.3. Physical and hydraulic properties

In 2018, bulk density was less with the average of standing (1.41 g cm^{-3}) and hayed CCs (1.42 g cm^{-3}) compared to fallow (1.48 g cm^{-3}), and both were similar to peas (1.39 g cm^{-3}) (Table 3). This effect of CCs was clearest with triticale and was less so with increased diversity and inclusion of broadleaf-species in the oat/triticale/pea and cocktail CC mixtures. Bulk density was not influenced differently when CCs were hayed versus when they were left standing. Differences in bulk density among treatments were not present in samples obtained after winter wheat harvest in summer 2019 and averaged 1.39 g cm^{-3} (Table 3). Water infiltration rate and SIR measured in summer 2019 increased with the average of standing or hayed CCs compared to peas but were both similar to fallow (Table 4). Interestingly, peas had significantly lower WIR and SIR as well as a trend toward lower TTR compared to fallow (Table 4). Greatest WIR and

SIR were observed with the oat/triticale/pea (4.84 cm hr^{-1} and 0.06 cm min^{-1}) and cocktail CCs (4.16 cm hr^{-1} and 0.06 cm min^{-1}) and less so with triticale (2.33 cm hr^{-1} and 0.03 cm min^{-1}). There were no statistical differences in WIR, SIR, or TTR between the average of hayed and standing CC treatments.

3.4. Soil pH and N stocks

Soil pH in the 0- to 15-cm soil depth in 2018 tended to be lower with the average of standing CCs (mean of 7.0) compared to fallow (7.3) or hayed CCs (7.3). This reduction in soil pH was most pronounced with the cocktail (6.9) and oat/triticale/pea (7.0) CCs compared to triticale alone (7.1). Soil pH in the pea treatment was similar to all other treatments. Soil pH was not different among fallow replacement treatments in 2019 after winter wheat harvest and averaged 7.5. Measured in 2018 and 2019, soil NO_3-N in the 0- to 15-cm soil depth was not significantly different across treatments although stocks tended to be greater with the average of standing (28.8 kg ha^{-1}) and hayed CCs (26.6 kg ha^{-1}) compared to fallow (23.0 kg ha^{-1}) (Table 5). Additionally, in both sampling periods, soil NO_3-N stocks tended to be less with the triticale CC compared to the oat/triticale/pea or cocktail CCs. Soil NH_4-N was not different among treatments at either sampling period and averaged 5.0 and 1.8 kg ha^{-1} in 2018 and 2019, respectively (Table 5).

3.5. Water and Wind Erodibility

Mean weight diameter of WSA in 2018 was 44% greater with the average of standing CCs (1.11 mm) compared to peas (0.77 mm) (Table 6) but was similar to fallow (0.84 mm). The greatest difference came with the triticale CC and was less so with the more diverse oat/triticale/pea and cocktail CCs. Interestingly, haying of CCs did not affect MWDWSA differently compared to when CCs were left standing averaged across mixtures and monocultures. Although MWDWSA with CCs was not statistically different from fallow, there were differences within aggregate size fractions. The proportion of aggregates in the >2-mm size fraction was greater with both standing and hayed CCs compared to fallow, 52 and 51%, respectively (Table 7). The proportion of aggregates in the <2-mm size fraction was less with standing or hayed CCs compared to fallow, 16 and 17%, respectively. In 2019, few treatment differences were evident though there was a trend with the standing triticale CC (2.57 mm) increasing MWDWSA compared to peas (1.78 mm). In 2019, the average of standing CCs (3.55 mm) had greater MWDDA compared to fallow (2.75 mm). Average of standing CCs were similar to both peas (3.81 mm) and the average of hayed CCs (3.62 mm) (Table 6). Likewise, WEF in 2019 tended to be less with both standing and hayed CCs compared to fallow. Although MWDDA was decreased and WEF increased by haying with the triticale CC, this was not observed for the other CC treatments.

4.0. Discussion

Differences observed in 2012 supported our hypothesis that CCs would have greater SOC stocks compared to fallow and agreed with the results of others (Blanco-Canqui et al., 2011; Delaune et al., 2019; Lewis et al., 2018). However, the lack of differences in SOC stocks at the time of sampling in 2018 and 2019 with CCs compared to fallow did not support this hypothesis. In an earlier study at this same location, SOC stocks measured at 0- to 7.5 cm increased with spring or winter triticale CCs compared to fallow when soil samples were taken two to three months after CC termination but CC effects on SOC stocks diminished 9 months post-termination (Blanco-Canqui et al., 2013). The authors speculated that increases in SOC with CCs may be transient mostly because of the variability in CC residue inputs in this water-limited environment. In the present study, regression analyses showed effects of CC residue input on

SOC stocks were greatest in the early years of this study (Fig. 1c). This occurred because of the relatively more favorable spring precipitation (Table 1) that favored the productivity of the cool-season fallow replacement treatments and increased residue inputs. However, effect of CCs on SOC were diminished in the later years of the study due to less favorable precipitation distribution (Table 1) that limited CC biomass production and residue retention (Fig. 1f). For instance, most of the precipitation from 2013 to 2019 occurred in late May through July which was too late for the fallow replacement treatments or winter wheat in the rotation. Notwithstanding, SOC stocks increased from 2012 to 2018 mostly because of cropping system intensification with the introduction of grain sorghum. In eastern Colorado, Sherrod et al. (2018) reported increases in SOC stocks with the transition from WF to wheat-corn-fallow or continuous cropping during wet years did not continue to increase at the same rate after a period of extended drought, though SOC did not decrease.

The observation of SOC stock changes by Sherrod et al. (20218) agrees with findings in the present study where SOC stocks with CCs was not greater compared to fallow in 2018 and 2019 but had increased after the transition from WF to WSF. Regression analysis showed the increased in SOC stocks measured in 2018 was positively related to the total amount of residue input from grain and CCs with an r^2 of 0.17 (Fig. 1a). However, the addition of grain sorghum in the cropping system had the greatest influence on SOC stocks observed between 2012 and 2018 (Fig. 1e). This finding suggests that rather than CCs, the intensification of the cropping system had the greatest contribution to the long-term maintenance of SOC at this semi-arid study site during this time. Averaged across CC treatments, SOC stocks did not differ between hayed CCs compared to CCs left standing in any of the sampling periods. This suggests that the below-ground biomass contribution of CCs may play a greater role in SOC dynamics and may facilitate increases and maintenance of SOC even when above-ground biomass is removed with forage harvest. Further, these findings support dual-purpose use of CCs for forage (hayed in the present study) in dryland systems where producers are concerned about yield and revenue lost following CCs in dry years. Relatively less SOC stocks measured in 2019 with the oat/triticale/pea and cocktail treatments compared to 2018 were likely due to SOC decomposition in plots with CC mixtures that contain broadleaf species. Additionally, the 2019 soil samples were taken one year after CC termination, enough time for residue decomposition to occur especially in the CC mixtures with broadleaves that tend to have lower carbon: nitrogen ratio.

Yield limiting compaction is a major concern for crop producers especially in long-term NT systems. Results from the present study agreed with our hypothesis that CCs would have lower bulk density compared to fallow. In the earlier study from the same plots, Blanco-Canqui et al. (2013) reported CCs had no effect on soil bulk density measured within the top 0 to 7.5 cm soil depth, through there was a trend in decreasing bulk density with triticale CCs compared to fallow. Our results agree with findings reported by Blanco-Canqui et al. (2011) in south central Kansas, USA as well as Villamil et al. (2006) in east central Illinois, USA. This influence of CCs on bulk density in the present study was most evident with triticale and less so with increased diversity and inclusion of broadleaf-species in the CC mixtures. This was likely due to the greater biomass and root production of triticale relative to broadleaf species in semi-arid drylands (Holman et al., 2018). In this semi-arid environment, broadleaf CCs are best suited for irrigated systems (Holman et al., 2021c) while grasses tend to be best suited for dryland systems (Holman et al., 2018; 2021a; 2021b). Differences in soil bulk density among treatments were not present in 2019 after winter wheat harvest and was most likely due to the alternate wet-dry and freeze-thaw cycles that would have occurred at the study site between the times of sampling in

2018 and 2019. Alternate wet-dry and freeze-thaw cycles are typical of the Great Plains region of the US and has been previously cited as a possible cause of diminishing effects of management on near-surface soil compaction (Baumhardt et al., 2011; 2017).

Many have reported either increased WIR, SIR, or TTR with CCs in a variety of cropping systems (Blanco-Canqui et al., 2011; DeLaune et al., 2019; Nouri et al., 2019). Results from the present study did not agree with our hypothesis that CCs would increase WIR, SIR, and TTR compared to fallow. However, they were similar to those reported by Blanco-Canqui and Jasa (2019) in eastern Nebraska, USA where no significant difference was observed with grass or legume CCs in a long-term NT system. Six years earlier using simulated rainfall at this long-term study site, Blanco-Canqui et al. (2013) reported increased time-to-runoff with a winter triticale CC compared to fallow in a WF cropping system. However, the authors showed no differences with spring triticale or peas compared to fallow. The lack of treatment differences in time to runoff between spring triticale CCs or spring pea and fallow in the present study was similar to that previously reported from this same study area (Blanco-Canqui et al., 2013). Moreover, the infiltration measurements in the present study were conducted after wheat harvest with significant residue cover that could delay time to runoff and mask treatment effects. Nevertheless, spring CCs had greater WIR and SIR compared to peas. Peas grown in place of fallow in this semi-arid environment contributed little surface residue and soil disturbance from planting peas and destruction of existing crop residues is the likely cause of detrimental long-term soil hydraulic properties compared to CCs and fallow. However, results suggest that CCs may not significantly alter soil hydraulic properties compared to fallow in similar long-term NT cropping systems. Blanco-Canqui et al. (2013) in an earlier study reported infiltration rates measured with a double ring infiltrometer 9-month post CC termination was not different compared to fallow. This agrees with results of infiltration measurements in the present study taken 12-month after CC termination.

Reports of soil pH alteration with CCs are infrequent with pH either being reduced (Dozier et al., 2017; Lewis et al., 2018) or more frequently unaffected (Blanco-Canqui et al., 2015). In west Texas, USA, Lewis et al. (2018) reported decreased pH with long-term CCs in a continuous cotton (*Gossypium hirsutum* L.) system. In that study, rye (*Secale cereale* L.) CCs caused greater reductions in pH compared to a multi-species CC and was attributed to the greater biomass production of rye. In east central Illinois, USA, there was a trend of decreased pH with CCs that was most pronounced with radish CCs despite radishes producing less biomass than the most productive species in the study (Dozier et al., 2017). In the present study, there was a trend of greatest reductions in pH with the cocktail and oat/triticale/pea CCs compared to triticale measured about four months after CC termination. However, changes in soil pH associated with CCs appeared to be transient and were diminished by the time of winter wheat harvest in 2019.

Cover crops in intensively managed cropping systems may influence soil nutrients by fixing atmospheric N, scavenging nutrients, as well as reducing nutrient loss due to erosion (Blanco-Canqui et al., 2015; Blanco-Canqui, 2018; Thapa et al., 2018). Many have reported reductions in soil NO_3-N with CCs and concerns of asynchronous N mineralization from CC residues at peak N demand of subsequent crops (DeLaune et al., 2019; Lewis et al., 2018; R. Ghimire et al., 2019). Results from the present study suggest that N immobilization by and/or mineralization from CCs and peas were limited and were similar to those reported by others at similar sampling points relative to CC termination (Blanco-Canqui and Jasa, 2019; Burgess et al., 2014; Miller et al., 2018). Further, in the present study, recommended rates of N fertilizer were applied each year to the primary crops, wheat and sorghum, and residual N built up in this semi-arid dryland system may have masked any potential observable differences in soil N among CC treatments.

Soil structure and aggregation are important properties that influence the many physical processes of the soil. Well-aggregated soils have greater resistance to the forces of wind and water erosion which is a major environmental concern in semi-arid soils such as those of the central Great Plains (Colazo and Buschiazzo, 2010; Fultz et al., 2013). In the present study, CCs increased MWDDA and decreased WEF compared to fallow. This is consistent with earlier reports from this site that showed growing CCs increased water stable aggregates and decreased susceptibility of dryland soils to wind and water erosion (Blanco-Canqui et al., 2013). This finding is significant because, in the study region, soil is most susceptible to erosion in late winter and early spring when primary crops are often absent and the potential for extreme weather is high (Baumhardt et al., 2015; Hansen et al., 2012). Similar reductions in WEF have been reported by others with long-term CC management (Blanco-Canqui et al., 2011; Blanco-Canqui and Jasa 2019; Nouri et al., 2019). Differences in MWDWSA were only observed between triticale and peas, with fallow having intermediate values (Table 6). These results suggest that CCs, especially productive grasses, may improve soil physical properties while broadleaf monoculture crops are unlikely to provide benefits compared to grasses in similar semi-arid environments and may even be detrimental in the long-term. Differences observed for MWDWSA, MWDDA, and WEF in 2019 indicate that long-term CC management may develop a lasting effect on soil physical properties in contrast to the seemingly transient effect observed earlier by Blanco-Canqui et al. (2013).

Most interestingly, management of CCs for hay did not negatively affect improvements in soil structure and aggregation made with CCs in this study. These results are similar to those reported at this same study sites six years earlier by Blanco-Canqui et al. (2013) when no differences in MWDWSA or MWDDA were observed when CCs were hayed compared to when left standing. However, the authors did speculate that differences with haying could appear after long-term management. Results from the present study suggest that haying of CCs for annual forage, where carefully implemented to leave 15-cm of stubble, may not negate the beneficial effects of CCs in similar NT dryland systems in either the short- or long-term.

5.0. Conclusions

After 12 years of fallow replacement in the semi-arid central Great Plains of the US, soil physical properties were enhanced with greater soil aggregation both when CCs were hayed and when left standing. The SOC stocks in 2018 with CCs were not different compared to fallow. Grain sorghum residues in the rotation was best at predicting SOC stocks measured in 2018, suggesting that intensification of the cropping system from WF to WSF was more important than CCs for SOC grains from 2012 to 2018. Our findings also showed CC residue input contributed significantly to SOC stocks from 2008 to 2012 during a period of relatively greater spring precipitation that favored cool-season fallow replacement treatments in the first six-years of this study. Notwithstanding, findings suggest SOC gains could be sustained even during extended periods of drought that reduce total residue inputs when crop productivity is limited by very dry conditions. Furthermore, results showed that, with careful management, CCs could be utilized for forage (hayed in the present study) without long-term detrimental effects to soil health. Peas were poor yielding and often failed to produce grain. The low-productivity of peas in semi-arid regions like southwest Kansas may be detrimental to long-term soil physical properties compared to fallow. Findings from this study suggest that CC mixtures should be simple and dominated by productive grass species and that dual-purpose CCs managed for annual forage production could provide similar soil health benefits compared to CCs left standing in similar NT dryland systems.

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Figure Captions

Figure 1. Influence of annual crop residue inputs from 2008 to 2018, 2008 to 2012, and 2013 to 2018 on soil organic carbon (SOC) stocks in the 0- to 15-cm soil depth in 2012 and 2018 near Garden City, KS.

†A. Annual crop residue from 2008 to 2018 against SOC in 2018, B. Wheat residue from 2008, 2010, and 2012 against SOC in 2012, C. Cover crop residue from 2009 and 2011 against SOC in 2012, D. Wheat residue from 2013 and 2016 against SOC in 2018, E. Sorghum residue from 2014 to 2017 against SOC in 2018, and F. Cover crop residue from 2015 and 2018 against SOC in 2018.

References

Aiken, R.M., D.M. O'Brien, B.L. Olson, and L. Murray. 2013. Replacing fallow with continuous cropping reduces crop water productivity of semiarid wheat. Agronomy Journal. 105, 199-207. https://doi.org/10.2134/agronj2012.0165.

Baumhardt, R.L., B.A. Stewart, and U.M. Sainju. 2015 North American soil degradation: Processes, practices, and mitigating strategies. Sustainability. 7, 2936-2960. https://doi.org/10.3390/su7032936.

Baumhardt, R.L., G.L. Johnson, R.C. Schwartz, and D.K. Brauer. 2017. Grazing and tillage effects on soil properties, rain infiltration, and sediment transport during fallow. Soil Science Society of America Journal. 81, 1548-1556. https://doi.org/10.2136/sssaj2017.04.0133.

Baumhardt, R.L., P.H. Gowda, P.D. Colaizzi, T.A. Howell, and S.A. Staggenborg. 2009. Modeling irrigation management strategies to maximize cotton lint yield and water use efficiency. Agronomy Journal. 101, 460-468. https://doi.org/10.2134/agronj2008.0041xs.

Baumhardt, R.L., R.C. Schwartz, J.C. MacDonald, and J.A. Tolk. 2011. Tillage and cattle grazing effects on soil properties and grain yields in a dryland wheat-sorghum-fallow rotation. Agronomy Journal. 103, 914-922. https://doi.org/10.2134/agronj2010.0388.

Benjamin, J.G., A.D. Halvorson, D.C. Nielsen, and M.M. Mikha. 2010. Crop management effects on crop reside production and changes in soil organic carbon in the central Great Plains. Agronomy Journal. 102, 990-997. https://doi.org/10.2134/agronj2009.0483.

Bergtold, J.S., S. Ramsey, L. Maddy, and J.R. Williams. 2017. A review of economic considerations for cover crops as a conservation practice. Renewable Agriculture and Food Systems. 34, 62-76. https://doi.org/10.1017/S1742170517000278.

Blanco-Canqui, H. 2018. Cover crops and water quality. Agronomy Journal. 110, 1633-1647. https://doi.org/10.2134/agronj2018.02.0077.

Blanco-Canqui, H., J.D. Holman, A.J. Schlegel, J. Tatarko, and T.M. Shaver. 2013. Replacing fallow with cover crops in a semiarid soil: Effects on soil properties. Soil Science Society of America Journal. 77, 1026-1034. https://doi.org/10.2136/sssaj2013.01.0006.

Blanco-Canqui, H., M.M. Mikha, D.R. Presley, and M.M. Claassen. 2011. Addition of cover crops enhances no-till potential for improving soil physical properties. Soil Science Society of America Journal. 75, 1-12. https://doi.org/10.2136/sssaj2010.0430.

Blanco-Canqui H. and P.J. Jasa. 2019. Do grass and legume cover crops improve soil properties in the long term? Soil Science Society of America Journal. 83, 1181-1187. https://doi.org/10.2136/sssaj2019.02.0055.

Blanco-Canqui, H., R.B. Ferguson, V.L. Jin, M.R. Schmer, B.J. Wienhold, and J. Tatarko. Can cover crop and manure maintain soil properties after stover removal from irrigated no-till corn? Soil Science Society of America Journal. 78, 1368-1377. https://doi.org/10.2136/sssaj2013.12.0550.

Blanco-Canqui, H., T.M. Shaver, J.L. Lindquist, C.A. Shapiro, R.W. Elmore, C.A. Francis, and G.W. Hergert. 2015. Cover crops and ecosystem services: Insights from studies in temperate soils. Agronomy Journal. 107, 2449-2474. https://doi.org/10.2134/agronj15.0086.

Bowman, R.A., J.D. Reeder, and R.W. Lober. 1990. Changes in soil properties in a central plains rangeland soil after 3, 20, and 60 years of cultivation. Soil Science. 150, 851-857. https://doi.org/10.1097/00010694-199012000-00004.

Burgess, M., P. Miller, C. Jones, and A. Bekkerman. 2014. Tillage and cover crops affects soil water, nitrogen, and wheat yield components. Agronomy Journal. 106, 1497-1508. https://doi.org/10.2134/agronj14.0007.

Calderón F.J., D. Nielsen, V. Acosta-Martínez, M. F. Vigil, and D. Lyon. 2016. Cover crop and irrigation effects on soil microbial communities and enzymes in semiarid agroecosystems of the central Great Plains of North America. Pedosphere. 26, 192-205. https://doi.org/10.1016/S1002-0160(15)60034-0.

Cano, A., A. Núñez, V. Acosta-Martinez, M. Schipanski, R. Ghimire, C. Rice, and C. West. 2018. Current knowledge and future research directions to link soil health and water conservation in the Ogallala Aquifer region. Geoderma. 328, 109-118. https://doi.org/10.1016/j.geoderma.2018.04.027.

Chalise, K.S., S. Singh, B.R. Wegner, S Kumar, J.D. Pérez-Gutiérrez, S.L. Osborne, T. Nleya, J. Guzman, and J.S. Rohila. 2018. Cover crop and returning residue impact on soil organic carbon, bulk density, penetration resistance, water retention, infiltration, and soybean yield. Agronomy Journal. 110, 99-108. https://doi.org/10.2134/agronj2018.03.0213.

Chepil, W.S. 1962. A compact rotary sieve and the importance of dry sieving in physical soil analysis. Soil Science Society of America Proceedings. 26, 4-6. https://doi.org/10.2136/sssaj1962.03615995002600010002x.

Colazo, J.C. and D.E. Buschiazzo. 2010. Soil dry aggregate stability and wind erodible fraction in a semiarid environment of Argentina. Geoderma. 159, 228-236. https://doi.org/10.1016/j.geoderma.2010.07.016.

Dai, J., B. Bean, B. Brown, W. Bruening, J. Edwards, M. Flowers, R. Karow, C. Lee, G. Morgan, M. Ottman, J. Ransom, and J. Wiersma. 2016. Harvest index and straw yield of five classes of wheat. Biomass and Bioenergy. 85, 223-227. https://doi.org/10.1016/j.biombioe.2015.12.023.

Deines, J.M., M.E. Schipanski, B. Golden, S.C. Zipper, S. Nozari, C. Rottler, B. Guerrero, and V. Sharda. 2020. Transitions from irrigated to dryland agriculture in the Ogallala Aquifer: Land use suitability and regional economic impacts. Agricultural Water Management. 223, 1-10. https://doi.org/10.1016/j.agwat.2020.106061.

DeLaune, P.B., P. Mubvumba, K.L. Lewis, and J.W. Keeling. 2019. Rye cover crop impacts soil properties in a long-term cotton system. Soil Science Society of America Journal. 83, 1451-1458. https://doi.org/10.2136/sssaj2019.03.0069.

Dozier, I.A., G.D. Behnke, A.S. Davis, E.D. Nafziger, and M.B. Villamil. 2017. Tillage and cover cropping effects on soil properties and crop production in Illinois. Agronomy Journal. 109, 1261-1270. https://doi.org/10.2134/agronj2016.10.0613.

Finney, D.M. and J.P. Kaye. 2017. Functional diversity in cover crop polycultures increases multifunctionality of an agricultural system. Journal of Applied Ecology. 54, 509-517. https://doi.org/10/1111/1365-2664.12765.

Franzluebbers, A.J., S.F. Wright, and J.A. Stuedemann. 2000. Soil aggregation and glomalin under pastures in the southern Piedmont USA. Soil Science Society of America Journal. 64, 1018–1026. https://doi.org/10.2136/sssaj2000.6431018x.

Fultz, L.M., J. Moore-Kucera, T.M. Zobeck, V. Acosta-Martínez, and V.G. Allen. 2013. Aggregate carbon pools after 13 years of integrated crop-livestock management in semiarid soils. Soil Science Society of America Journal. 77, 1659-1666. https://doi.org/10.2136/sssaj2012.0423.

Ghimire, R., B. Ghimire, A.O. Mesbah, O.J. Idowu, M. K. O'Neill, S. V. Angadi, and M.K. Shukla. 2018. Current status, opportunities, and challenges of cover cropping for sustainable dryland farming in the southern Great Plains. Journal of Crop Improvement. 32, 579-598. https://doi.org/10.1080/15427528.2018.1471432.

Ghimire, R., B. Ghimire, A.O. Mesbah, U.M. Sainju, and O.J. Idowu. 2019. Soil health response of cover crops in winter wheat-fallow system. Agronomy Journal. 111, 1-8. https://doi.org/10.2134/agronj2018.08.0492.

Ghimire, B., R. Ghimire, D. VanLeeuwen, and A. Mesbah. 2017. Cover crop residue amount and quality effects on soil organic carbon mineralization. Sustainability. 9, 1-14. https://doi.org/10.3390/su9122316.

Hansen, N.C., B.L. Allen, R.L. Baumhardt, and D.J. Lyon. 2012. Research achievements and adoption of no-till, dryland cropping in the semi-arid U.S. Great Plains. Field Crops Research. 132, 196-203. https://doi.org/10.1016/j.fcr.2012.02.021.

Holman, J.D., K. Arnet, J. Dille, S. Maxwell, A. Obour, T. Roberts, K. Roozeboom, and A. Schlegel. 2018. Can cover or forage crops replace fallow in the semiarid central Great Plains? Crop Science. 58, 932-944. https://doi.org/10.2135/cropsci2017.05.0324.

Holman, J. D., A. Schlegel, A.K. Obour, and Y. Assefa. 2020. Dryland cropping system impact on forage accumulation, nutritive value, and rainfall use efficiency. Crop Science. 60, 3395-3409. https://doi.org/10.1002/csc2.20251.

Holman, J. D., A. Obour, and Y. Assefa. 2021a. Cover-crop water use and productivity in the High Plains wheat-fallow crop rotation. Crop Science. 61, 1374-1385. https://doi.org/10.1002/csc2.20365.

Holman, J.D., A. Obour, Y. Assefa. 2021b. Fallow replacement cover crops in a semi-arid High Plains cropping system. Crop Science. 2021, 1-16. https://doi.org/10.1002/csc2.20543.

Holman, J. D, Y. Assefa, M. Stamm, and A. Obour. 2021c. Canola yield, forage accumulation, and nutritive value in dual-purpose and companion cropping. Crop Science. 63, 814-824. https://doi.org/10.1002/csc2.20291.

Kelly, C., Schipanski, M. E., Tucker, A., Trujillo, W., Obour, A., Holman, J. D., Johnson, S. K., Brummer, J. E., Haag, L., & Fonte, S. J. (2021). Dryland cover crop soil health benefits are maintained with grazing in the U.S. High and Central Plains. Agriculture, Ecosystems & Environment, 313, 107358. https://doi.org/10.1016/j.agee.2021.107358.

Kumar, V., A. Obour, P. Jha, R. Liu, M.R. Manuchehri, J.A., Dille, J. Holman, and P.W. Stahlman. 2020. Integrating cover crops for weed management in the semiarid U.S. Great Plains: Opportunities and challenges. Weed Science. 68, 311-323. https://doi.org/10.1017/wsc.2020.29.

Lewis, K.L., W.S. Keeling, J.W. DeLaune, Paul B. Keeling, J.A. Burke, and D.M. McCallister. 2018. Soil benefits and yield limitations of cover crop use in Texas High Plains cotton. Agronomy Journal. 110, 1616-1623. https://doi.org/10.2134/agronj2018.02.0092.

Li, Y., A.F. Hou, J. Chen, and C.P. Brown. 2013. Steers grazing a rye cover crop influence growth of rye and no-till cotton. Agronomy Journal. 105, 1571-1580. https://doi.org/10.2134/agronj2013.0020.

Mikha, M.M., **A**.K. Obour, and J.D. Holman. 2018. Soil nutrients status after fifty years of tillage and nitrogen fertilization. Communication Soil Science Plant Analysis. 49:1953-1973

Miller, P., E. Glunk, J. Holmes, and R. Engel. 2018. Pea and barley forage as fallow replacement for dryland wheat production. Agronomy Journal. 110, 833-841. https://doi.org/10.2134/agronj2017.02.0087.

Nelson, D.W. and L.E. Sommers. 1996. Total carbon, organic carbon, and organic matter. In: D.L. Sparks et al. (Eds.), Methods of soil analysis, Part 3: Chemical methods. Soil Science Society of America & American Society of Agronomy, Madison, WI, pp. 961-1010.

Nielsen, D.C. 2018. Influence of latitude on the US Great Plains east–west precipitation gradient. Agricultural and Environmental Letters. 3, 1-5. https://doi.org/10.2134/ael2017.11.0040.

Nielsen, D.C., D.J. Lyon, G.W. Hergert, R.K. Higgins, F.J. Calderón, and M. F. Vigil. 2015a. Cover crop mixtures do not use water differently than single-species plantings. Agronomy Journal. 107, 1025-1038. https://doi.org/10/2134/agronj14.0504.

Nielsen, D.C., D.J. Lyon, G.W. Hergert, R.K. Higgins, and J.D. Holman. 2015b. Cover crop biomass production and water use in the central Great Plains. Agronomy Journal. 107, 2047-2058. https://doi.org/10.2134/agronj15.0186.

Nielsen, D.C., P.W. Unger, and P.R. Miller. 2005. Efficient water use in dryland cropping systems in the Great Plains. Agronomy Journal. 97, 364-372. https://doi.org/10.2134/agronj2005.0364.

Nielsen, D.C. and M.F. Vigil. 2010. Precipitation storage efficiency during fallow in wheat-fallow systems. Agronomy Journal. 102, 537-543. https://doi.org/10.2134/agronj2009.0348.

Nimmo, J.R., and K.S. Perkins. 2002. Aggregate stability and size distribution. In: J.H. Dane , G.C. Topp (Eds.), Methods of soil analysis, Part 4. Physical Methods. Soil Science Society of America, Madison, WI, pp. 317-327.

Nouri, A., J. Lee, X. Yin, D.D. Tyler, and A.M. Saxton. 2019. Thirty-four years of no-tillage and cover crops improve soil quality and increase cotton yield in Alfisols, Southeastern USA. Geoderma. 337, 998-1008. https://doi.org/10.1016/j.geoderma.2018.10.016.

Ogden, C.B., H.M. van Es, and R.R. Schindelbeck. 1997. Miniature rain simulator for field measurement of soil infiltration. Soil Science Society of America Jounrnal. 61, 1041-1043. https://doi.org/10.2136/sssaj1997.03615995006100040008x.

Peterson, G.A. and D.G. Westfall. 2004. Managing precipitation use in sustainable dryland agroecosystems. Annals of Applied Biology. 144, 127-138. https://doi.org/10.1111/j.1744-7348.2004.tb00326.x.

Robinson, C. and D. Nielsen. 2015. The water conundrum of planting cover crops in the Great Plains: When is an inch not an inch? Crops & Soils (January-February 2015). https://doi.org/10.2134/cs2015-48-1-7.

Schlegel, A.J. and J.L. Havlin. 1997. Green fallow for the central Great Plains. Agronomy Journal. 89, 762-767. https://doi.org/10.2134/agronj1997.00021962008900050009x.

Schmid, B, A. Hector, P. Saha, and M. Loreau. 2008. Biodiversity effects and transgressive overyielding. Journal of Plant Ecology. 1, 95-102. https://doi.org/10.1093/jpe/rtn011.

Sherrod, L.A., G.S. McMaster, J.A. Delgado, M.E. Schipanski, S.J. Fonte, R.L. Montenieri, and K. Larson. 2018. Soil carbon pools in dryland agroecosystems as affected by several years of drought. Journal of Environmental Quality. 47, 766-773. https://doi.org/10.2134/jeq2017.09.0371.

Smith, R.G., L.W. Atwood, and N.D. Warren. 2014. Increased productivity of a cover crop mixture is not associated with enhanced agroecosystem services. PLos ONE, 9. https://doi.org/10/1371/journal.pone.0097351

Stewart, B.A. and G.A. Peterson. 2014. Managing Green Water in Dryland Agriculture. Agronomy Journal. 107, 1544-1553. https://doi.org/10.2134/agronj14.0038.

Thapa, R, S.B. Mirsky, and K.L. Tully. 2018. Cover crops reduce nitrate leaching in agroecosystems: A global meta-analysis. Journal of Environmental Quality. 47, 1400-1411. https://doi.org/10.2134/jeq2018.03.0107.

Unkovich, M., J. Baldock, and M. Forbes. 2010 Variability in harvest index of grain crops and potential significance for carbon accounting: Examples from Australian agriculture. Advances in Agronomy. 105, 173-219. https://doi.org/10.1016/S0065-2113(0)05005-4.

Villamil, M.B., G.A. Bollero, R.G. Darmody, F.W. Simmons, and D.G. Bullock. 2006. No-till corn/soybean systems including winter cover crops: Effects on soil properties. Soil Science Society of America Journal. 70, 1936-1944. https://doi.org/10.2136/sssaj2005.0350.

Table 1. Monthly precipitation from 2007 to 2019 near Garden City, KS.

Month	Precipitation													
	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	30-yr avg.[†]
	mm													
Jan.	15	8	2	18	5	0	7	0	12	1	39	0	9	12
Feb.	15	15	2	10	11	21	4	0	8	7	0	0	19	14
Mar.	46	8	29	46	17	47	2	3	8	1	70	10	53	33
Apr.	74	42	111	57	45	40	7	13	9	120	111	21	2	44
May	30	49	47	99	29	6	24	14	160	27	27	57	149	76
Jun.	64	79	94	37	43	30	41	239	36	101	29	98	28	79
Jul.	43	30	80	33	14	48	77	76	123	147	53	217	49	71
Aug.	66	64	56	69	62	24	87	45	74	44	59	45	34	64
Sept.	53	18	41	8	9	27	38	62	1	4	81	47	4	36
Oct.	5	119	76	19	11	22	20	39	64	0	47	92	9	31
Nov.	3	9	10	2	11	0	18	1	22	2	0	6	6	14
Dec.	34	1	5	2	52	11	3	6	29	6	0	41	31	15
Annual	448	440	552	400	308	277	327	499	546	458	516	634	393	489

[†] 30-year averages are for the period 1981-2010.

Table 2. Cover crop management effect on soil organic carbon (SOC) stocks in the 0- to 15-cm soil depth in fall 2007, fall 2012, fall 2018, and summer 2019 near Garden City, KS.

Treatment	Management	2007	2012	2018	2019
		SOC			
		Mg ha^{-1}			
Fallow		18.0abB†	17.9cB	21.0aA	19.5abA
Pea	Grain	19.7aA	18.5bcA	21.6aA	20.6abA
Triticale	Standing	18.6abA	21.0aA	21.0aA	19.9abA
	Hayed	18.7abA	19.2abcA	20.5aA	20.7abA
Oat/Triticale/Pea	Standing	16.6bC	20.9abA	21.9aA	19.0bB
	Hayed	16.5bC	20.2abcAB	20.9aA	19.2bB
Cocktail	Standing	17.4abB	20.9abAB	23.0aA	19.8abAB
	Hayed	16.6bB	20.2abcAB	24.5aA	21.4aAB
Contrasts		p-value			
Fallow vs. Standing CC		0.59	**<0.01**	0.66	0.96
Fallow vs. Hayed CC		0.39	**0.06**	0.66	0.30
Pea vs. Standing CC		0.10	**0.02**	0.85	0.22
Pea vs. Hayed CC		0.05	0.16	0.86	0.81
Standing CC vs. Hayed CC		0.64	0.13	0.99	0.17

†Means within a column followed by the same lower-case letter are not different (α =0.05) among treatments within each year and means within a row followed by the same upper-case letter are not significantly different (α =0.05) among years within each treatment.

Table 3. Effect of cover crop management on bulk density in the 0- to 15-cm soil depth in fall 2012, fall 2018 and summer 2019 near Garden City, KS.

Treatment	Management	2012	2018	2019
			Bulk density	
			g cm^{-3}	
Fallow		1.41bAB†	1.48aA	1.39aB
Pea	Grain	1.42abA	1.39bA	1.39aA
Triticale	Standing	1.42abA	1.39bA	1.40aA
	Hayed	1.43aA	1.40bA	1.41aA
Oat/Triticale/Pea	Standing	1.43aAB	1.44abA	1.36aB
	Hayed	1.42abA	1.44abA	1.38aA
Cocktail	Standing	1.43aA	1.41bA	1.40aA
	Hayed	1.42abA	1.42abA	1.40aA
Contrasts			p-value	
Fallow vs. Standing CCs		**0.03**	**0.02**	0.99
Fallow vs. Hayed CCs		0.11	**0.04**	0.67
Pea vs. Standing CCs		0.74	0.43	0.94
Pea vs. Hayed CCs		0.74	0.29	0.71
Standing CCs vs. Hayed CCs		0.35	0.69	0.53

†Means within a column followed by the same lower-case letter are not different (α =0.05) among treatments within each year and means within a row followed by the same upper-case letter are not significantly different (α =0.05) among years within each treatment.

Table 4. Cover crop management effect on water infiltration rate (WIR), saturated infiltrability rate (SIR) and time-to-runoff (TTR) in Summer 2019 near Garden City, KS.

Treatment	Management	WIR	SIR	TTR
		cm hr^{-1}	cm min^{-1}	min
Fallow		4.90ab[†]	0.07ab	6.14a
Pea	Grain	1.23d	0.02d	3.45a
Triticale	Standing	3.56bc	0.05bc	7.05a
	Hayed	1.10d	0.01d	2.75a
Oat/Triticale/Pea	Standing	5.41a	0.07a	7.40a
	Hayed	4.27abc	0.06abc	7.56a
Cocktail	Standing	2.84c	0.04c	7.95a
	Hayed	5.49a	0.07a	5.89a

Contrasts		p-value	
Fallow vs. Standing CCs	0.17	0.16	0.64
Fallow vs. Hayed CCs	0.07	0.06	0.79
Pea vs. Standing CCs	**<0.01**	**<0.01**	0.14
Pea vs. Hayed CCs	**<0.01**	**<0.01**	0.50
Standing CCs vs. Hayed CCs	0.49	0.47	0.27

[†] Means followed by the same lower-case letter within the same column are not significantly different (α =0.05) among cover crop treatments.

Table 5. Cover crop management impact on soil NO_3-N and NH_4-N stocks for the 0- to 15-cm soil depth in Fall 2018 and Summer 2019 near Garden City, KS.

Treatment	Management	Fall 2018		Summer 2019	
		NO_3-N	NH_4-N	NO_3-N	NH_4-N
		kg ha^{-1}			
Fallow		33.83aA[†]	3.94bA	12.18cB	0.16aB
Pea	Grain	44.57aA	5.57abA	14.70abcB	1.90aB
Triticale	Standing	33.48aA	4.67abA	13.51abcB	1.14aB
	Hayed	35.94aA	4.67abA	12.99bcB	3.12aA
Oat/Triticale/Pea	Standing	45.59aA	5.45abA	13.82abcB	1.71aB
	Hayed	37.36aA	6.11aA	16.09abcB	1.27aB
Cocktail	Standing	49.53aA	4.98abA	16.74aB	3.39aA
	Hayed	42.33aA	4.52abA	15.02abcB	1.45aB
Contrasts		p-value			
Fallow vs. Standing CCs		0.26	0.15	0.09	0.21
Fallow vs. Hayed CCs		0.55	0.13	0.09	0.24
Pea vs. Standing CCs		0.83	0.47	0.99	0.90
Pea vs. Hayed CCs		0.45	0.53	1.00	0.97
Standing CCs vs. Hayed CCs		0.44	0.90	0.99	0.90

[†] Means within a column followed by the same lower-case letter are not different (α =0.05) among treatments within each year and means within a row followed by the same upper-case letter are not significantly different (α =0.05) among years within each treatment.

Table 6. Impact of cover crop management on mean weight diameter of water stable aggregates (MWDWSA), mean weight diameter of dry aggregates (MWDDA), and wind-erodible fraction (WEF) in the 0- to 5-cm soil depth in fall 2018 and Summer 2019 near Garden City, KS.

		2018	2019		
Treatment	Management	MWDWSA	MWDWSA	MWDDA	WEF
		mm			%
Fallow		0.84abB[†]	2.09abA	2.75d	50.79a
Pea	Grain	0.77bB	1.78bA	3.81abc	43.03bc
Triticale	Standing	1.21aB	2.57aA	3.95a	42.56c
	Hayed	1.13abB	2.11abA	3.28c	47.87ab
Oat/Triticale/Pea	Standing	1.08abB	2.43abA	3.29c	46.72abc
	Hayed	1.03abB	2.12abA	3.88ab	43.17bc
Cocktail	Standing	1.04abB	1.82abA	3.42bc	46.67abc
	Hayed	1.04abB	1.89abA	3.69abc	42.01c

Contrasts	p-value			
Fallow vs. Standing CCs	0.10	0.54	**<0.01**	**<0.01**
Fallow vs. Hayed CCs	0.17	0.88	**<0.01**	**<0.01**
Pea vs. Standing CCs	**0.04**	0.11	0.24	0.26
Pea vs. Hayed CCs	0.07	0.40	0.38	0.51
Standing CCs vs. Hayed CCs	0.68	0.29	0.68	0.50

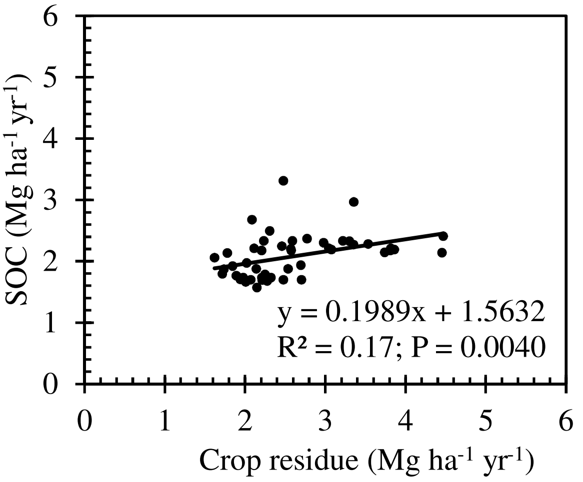
[†] Means within a column followed by the same lower-case letter are not different (α =0.05) among treatments within each year and means within a row followed by the same upper-case letter are not significantly different (α =0.05) among years within each treatment.

Table 7. Effect of cover crop management on the size distribution (ASD) of water stable aggregates in the 0- to 5-cm soil depth in fall 2018 and summer 2019 near Garden City, KS.

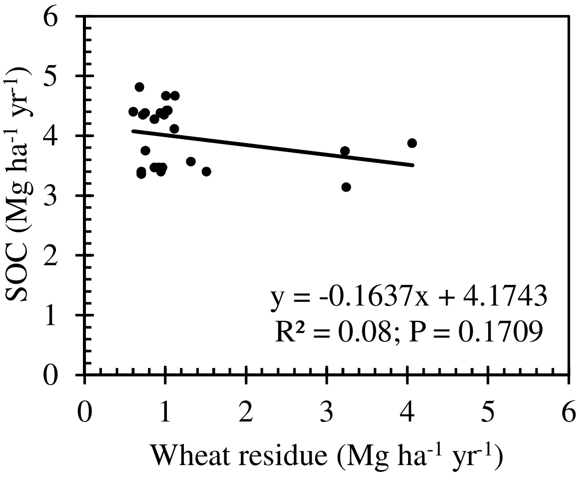
Sample Period	Treatment	Management	2- to 8-mm	0.25- to 2-mm	<0.25-mm
				%	
Fall 2018	Fallow		24.16ab[†]	52.74a	23.10a
	Pea	Grain	21.23b	49.20ab	29.57a
	Triticale	Standing	40.69a	36.67bc	22.64a
		Hayed	36.46ab	41.92abc	21.63a
	Oat/Triticale/Pea	Standing	36.56ab	33.11c	30.32a
		Hayed	40.21a	38.53abc	21.26a
	Cocktail	Standing	33.09ab	42.95abc	23.97a
		Hayed	33.08ab	40.64abc	26.28a
	Contrasts			p-value	
	Fallow vs. Standing CCs		0.07	**0.02**	0.65
	Fallow vs. Hayed CCs		0.08	**0.04**	0.99
	Pea vs. Standing CCs		**0.03**	0.06	0.48
	Pea vs. Hayed CCs		**0.03**	0.15	0.24
	Standing CCs vs. Hayed CCs		0.97	0.51	0.51
Summer 2019	Fallow		33.22ab	47.11a	19.68ab
	Pea	Grain	26.18b	52.54a	21.28ab
	Triticale	Standing	45.65a	31.76b	22.59a
		Hayed	35.72ab	41.18ab	23.10ab
	Oat/Triticale/Pea	Standing	41.85ab	39.79ab	18.36b
		Hayed	36.28ab	38.27ab	25.45ab
	Cocktail	Standing	28.71b	42.22ab	31.63ab
		Hayed	30.57ab	47.54a	21.89ab
	Contrasts			p-value	
	Fallow vs. Standing CCs		0.41	0.12	0.37
	Fallow vs. Hayed CCs		0.88	0.42	0.45
	Pea vs. Standing CCs		0.06	0.02	0.57
	Pea vs. Hayed CCs		0.23	**0.09**	0.66
	Standing CCs vs. Hayed CCs		0.34	0.29	0.84

[†]Means with the same lower-case letter within the same column are not significantly different (α =0.05) among cover crop treatments.

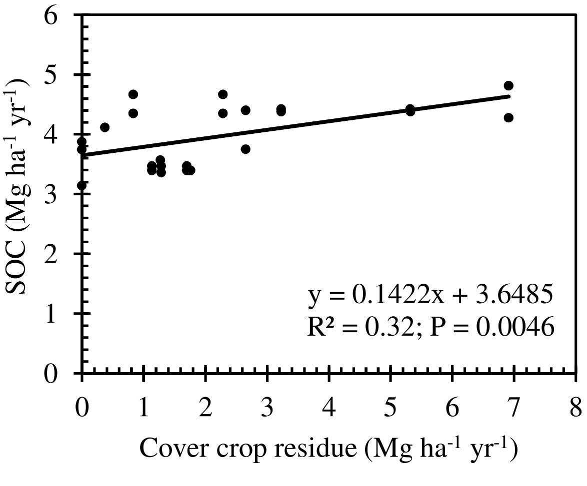
A. 2007 to 2018[†]



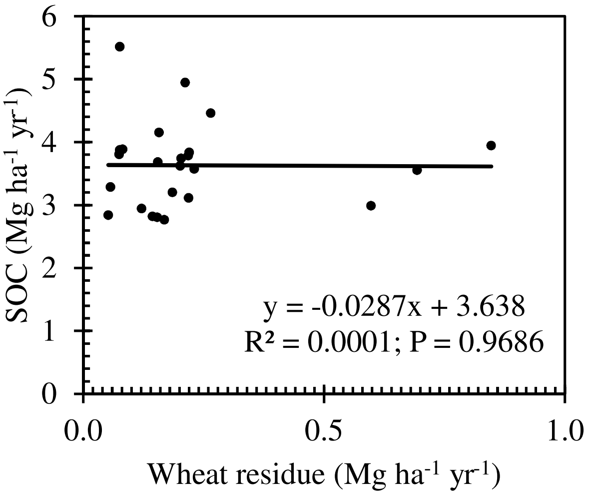
B. 2007 to 2012



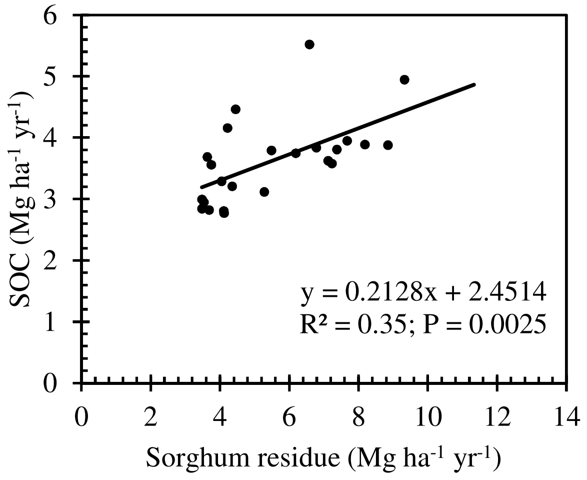
C. 2007 to 2012



D. 2013 to 2018



E. 2013 to 2018



F. 2013 to 2018