Long- and short-term cover crop management effects on soil health in no-till dryland cropping systems in the semi-arid central Great Plains

by

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Abstract

Integrating cover crops (CCs) into dryland cropping systems in the semi-arid central Great Plains could improve soil health and provide forage for livestock. Two experiments were conducted in western Kansas to examine the effects of 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. A long-term study was initiated in 2007 near Garden City, KS to investigate CCs in a wheat-fallow (WF) rotation and was transitioned to WSF in 2012. Treatments included peas (*Pisum sativum* L.) for grain as well as one-, three-, and six-species CC mixtures compared to fallow. Half of each CC treatment was hayed to a height of 15 cm. A second study was initiated in 2015 near Brownell, KS, and treatments were oat (*Avena sativa* L.)/triticale (×*Triticosecale* Wittm.) CCs in place of fallow that were either hayed to a height of 15 cm, grazed by yearling heifers, or left standing. Forage accumulation and nutritive value were also determined in the experiment at Brownell. At Garden City, soil organic carbon (SOC) stocks were greater with CCs compared to fallow in 2012 after three cycles of the WF rotation. In 2018, after two cycles of the WSF rotation, SOC was similar among treatments, likely because CC residue was less following a succession of drought years. However, SOC had increased in all treatments since 2012 mostly due to the residue contribution of grain sorghum ($r^2 = 0.35$; $P = 0.0025$). 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 (WSA) was greater with standing CCs (1.11 mm) compared to peas (0.77 mm), and standing and hayed CCs (3.59 mm) had greater MWD of dry aggregates compared to fallow (2.75 mm). Water infiltration were greater with CCs compared to peas. Findings suggest simple CC mixtures and CCs managed for forage provide similar soil health benefits as diverse CC mixtures and CCs left standing. At Brownell, results showed forage accumulation averaged 3546 kg ha^{-1} for standing CCs. Hayed and grazed CCs removed 73 and 26% of the available forage. Greater nutritive value with grazed CCs was observed because of differences in maturity at harvest. In 2019, SOC stocks with standing and hayed CCs (27.54 Mg ha^{-1}) were greater than fallow (24.79 Mg ha^{-1}) which was similar to grazed CCs (26.87 Mg ha^{-1}). However, in 2020, SOC with hayed CCs (21.80 Mg ha^{-1}) was less compared to grazed or standing CCs (24.27 Mg ha^{-1}) which were similar to fallow (23.22 Mg ha^{-1}). The MWD of WSA was greater with standing and grazed CCs (2.89 mm) compared to fallow (1.67 mm) in both years, and hayed CCs were greater than fallow in only one year. Findings suggest that CCs can replace fallow to produce forage while improving soil health. However, residue management is critical such that grazing is more desirable than haying to maintain soil properties when CC productivity is low.

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Chapter 1 - Introduction and literature review

Introduction

Integrating cover crops (CC) in semi-arid dryland cropping systems in the central Great Plains (CGP) may provide several benefits to soil health in the region. These include such benefits as reduced bulk density and increased porosity, improved soil structure and aggregation, increased water infiltration, greater soil organic carbon stocks, as well as enhanced nutrient dynamics and microbial activity (Blanco-Canqui, Holman, Schlegel, Tatarko, and Shaver, 2013; Blanco-Canqui et al., 2015). However, even with these potential benefits and an increasing interest among CGP crop producers, CC adoption has been slow in the region. This is mostly due to the concern that CCs will deplete vital soil water and result in reduced yields of subsequent cash crops compared to chemically-controlled no-till fallow, where herbicides are used to manage weed growth to store soil moisture for the next crop.

Previous research conducted in the CGP region of Kansas and Colorado reported increased water usage and substantial decreases in winter wheat yields when CCs replaced fallow in the crop rotation (Holman et al., 2018; Nielsen et al., 2015a; Schlegel and Havlin, 1997). This is the predominant factor contributing to the low adoption rate of CCs in the CGP where crop production has relied heavily upon water storage during fallow as well as water withdrawals from the region's underlying Ogallala Aquifer for irrigation. However, continued depletion of the saturated thickness and associated higher pumping costs have already led some producers to transition previously irrigated acres back to dryland (Baumhardt, Staggenborg, Gowda, Colaizzi, and Howell, 2009; Cano et al., 2018).

Dryland agriculture is defined as crop production practiced in a region where producing an annual crop solely upon growing season precipitation is not possible (Robinson and Nielsen, 2015). Dryland crop production is prevalent in regions where precipitation accounts for only 20 to 35% of potential evapotranspiration (PET) (Stewart, 2016), and is made possible through the adoption of such management strategies as reduced tillage and crop residue retention to store water in the soil during the fallow period. Due to water limitations, winter wheat (*Triticum aestivum* L.)-fallow or winter wheat-summer crop [corn (*Zea mays* L.), grain sorghum (*Sorghum bicolor* Moench), or sunflower (*Helianthus annuus* L.)]-fallow are the dominant cropping systems throughout the CGP region (Peterson et al., 1998; Nielsen and Vigil, 2018).

Increased adoption of CCs by dryland producers in the semi-arid CGP can enhance residue cover to reduce the susceptibility of the soil to erosion (Blanco-Canqui, Mikha, Presley, and Claassen, 2011; Blanco-Canqui et al., 2013; 2014). Reducing erosion is particularly important in semi-arid dryland crop production systems where residue levels are often low and fallow fields are left exposed. In addition to this, it has been documented that the increased rooting activity and carbon inputs from CCs can improve soil aggregation and enhance water infiltration (Franzluebbers, Wright, and Stuedemann, 2000). However, most of these studies have been conducted in regions that receive relatively greater amounts of annual precipitation than is common for the semi-arid CGP.

Past research efforts in southwest Kansas have shown that replacement of fallow with CCs increased soil organic matter (SOM) content, reduced wind-erodible fraction, increased water stable aggregates (WSA), 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 lacking regarding the long-term (>10 years) soil health effects of integrating CCs in dryland crop production.

Grazing and or haying of CCs for forage can provide an economic benefit to offset potential lost revenue associated from decreased crop yields when CCs are grown ahead of a cash crop in dry years (Holman et al., 2018). However, there is concern that harvesting CCs as forages and the reduction in residue left on the soil surface may negate the beneficial effects of utilizing CCs for soil conservation. There is also potential that grazing CCs could increase soil compaction and degrade soil structure (Blanco-Canqui et al., 2013; Nielsen et al., 2015a). However, it is plausible that the alternate freeze and thaw events that occur annually in the CGP could eliminate any soil surface compaction due to CC grazing (Blanco-Canqui et al, 2016). Previous reports indicated that soil texture may be a contributing factor to the ability of soil to recover from compaction events with the presence of shrink-well clay particles such as smectites and vermiculites improving soil recovery following compaction (Baumhardt, Schwartz, MacDonald, and Tolk, 2011; Baumhardt, Johnson, Schwartz, and Brauer, 2017).

With all things considered, there is great motivation for researchers and others involved in production agriculture to develop and evaluate new and innovative crop production strategies and technologies to boost profitability and sustainability of dryland cereal-based cropping systems in the CGP. Despite risks of excessive water use by CCs and subsequent grain yield depressions, growing CCs offers great potential to improve soil health, enhance precipitation use efficiency, and diversify production when used for forage.

Crop production in the semi-arid Great Plains

The Great Plains (GPs) of the United States is characterized by vast, expansive semi-arid prairie, much of which has been cultivated for dryland crop production. The agricultural soils of the GPs were formed in loess and therefore are primarily characterized as being of the silt loam, silty clay loam, or loamy sand soil textural classes (Cano et al., 2018; R. Ghimire et al., 2018).

Stretching from the Canadian Prairie Provinces to southern Texas and bordered to the west by the Rocky Mountains along with higher rainfall areas to the east, the climate of the region changes dramatically as you move across it (Robinson and Nielsen, 2015). Generally, annual precipitation amounts decrease from east-to-west. The main contributing factors to this phenomenon include: i) the rain shadow effect of the Rocky Mountains, ii) the moisture flow from the Gulf of Mexico, and iii) the increasing north to south PET gradient (Nielsen, 2018). Periodic wet cycles are contrasted by sustained droughts often not confined to a single season of the year. In addition to the great variability between years, unpredictable, short-term drought periods within a cropping season are also quite common (R. Ghimire et al., 2018). A major challenge for dryland crop producers is the implementation of best management practices that can effectively and efficiently utilize available soil water while minimizing risk of crop failure when precipitation is sparse.

In the CGP, the 12- to 14-month fallow period between cash crops was historically introduced as a method to store soil water. Fallow has been proven to stabilize cash crop yields and to prevent devastating crop failure, particularly in drier years (Nielsen and Vigil, 2010; Aiken, O'Brien, Olson, and Murray, 2013). However, precipitation storage efficiency during fallow is imperfect, ranging only from 17 to 45% efficiency depending mainly upon the tillage and residue management strategies of the given producer (Peterson and Westfall, 2004). Limited soil cover during fallow leads to increased vulnerability to erosion even in fields under long-term no-till (NT) management (Hansen, Allen, Baumhardt, and Lyon, 2012). This situation causes loss of topsoil, depletion of SOM, declining soil fertility, and inefficient water storage in the region.

Due to ever-present water limitations in the CGP, the standard dryland cropping system has been winter wheat-fallow, utilizing sweep tillage to maintain fallow (Nielsen and Vigil, 2005, 2010). However, conversion to NT production as an alternative to tillage has been accomplished through the use of multiple herbicide applications, including residual formulations, to keep weeds controlled during the 14-month fallow period between crops (Schlegel and Havlin, 1997; Nielsen and Vigil, 2010). Long-term research near Tribune, KS (average annual precipitation of 455 mm) has shown that NT winter wheat yielded more on average than conventionally-tilled (CT) wheat after 5 to 6 years of sustained NT practices (Schlegel, Assefa, Haag, Thompson, and Stone, 2018a). This is most likely due to the improved water storage efficiency of NT fallow. Nevertheless, producing a single crop every other year makes it inherently challenging to generate enough income to cover the expenses of production and to sustain farm operations.

Over the past decades, with the spread of NT, more intensive cropping systems have developed throughout the region including winter wheat-summer crop (corn, grain sorghum, or sunflower)-fallow (Schlegel, Assefa, Haag, Thompson, and Stone, 2017; Nielsen and Vigil, 2018). Efforts to incorporate legume grain crops into dryland crop rotations in the CGP have been met with mixed success. This is documented by multiple studies across the CGP that showed the combination of low yields and high costs of seed made profiting from dryland legumes for grain challenging in semi-arid regions (Felter, Lyon, and Nielsen, 2006; Lyon, Nielsen, Felter, and Burgener, 2007; Schlegel, Assefa, Haag, Thompson, and Stone, 2018b). Increased diversity in crop rotations has provided several benefits to producers including better overall water use efficiency, more surface residue input, additional herbicide options for weed control, and improved profitability potential (Peterson et al., 1998; Schlegel et al., 2018b).

Cover crops in semi-arid dryland cropping systems

Previous research on the incorporation of CCs in semi-arid regions of the United States has utilized diverse grass and broadleaf species to address a wide variety of resource concerns. In the semi-arid CGP region of western Kansas, western Nebraska, and eastern Colorado; areas that experience an average annual precipitation of 450, 435, and 400 mm respectively; Austrian winter pea (*Pisum sativum* L.), barley (*Hordeum vulgare* L.), berseem clover (*Trifolium alexandrinum* L.), common vetch (*Vicia sativa* L.), flax (*Linum usitatissimum* L.), hairy vetch (*Vicia villosa* Roth), lentil (*Lens culinaris* L.), oat (*Avena sativa* L.), phacelia (*Phacelia tenacetifolia* L.), rapeseed [*Brassica napus* L.]), safflower (*Carthamus tinctorius* L.), spring pea and triticale (×*Triticosecale* Wittm.) were utilized as cover or annual forage crops with mixed success, often dependent upon species mixture and soil water content at planting (Nielsen et al., 2015a; Holman et al., 2018). The authors of these reports determined that grass species often dominated multi-species CC mixtures. In the northern Great Plains (NGP), barley, oat, pea, proso millet (*Panicum milliaceum* L.), radish (*Raphanus sativus* L.), red clover (*Trifolium pratense* L.), and triticale were tested for use as CCs or annual forages (Carr, Horsley, and Poland, 2004; Sanderson, Johnson, and Hendrickson, 2018). Results were similar to those reported in the CGP, in that grass species appeared as the dominant contributors to total biomass in the various CC mixtures.

Sanderson et al. (2018) further reported that CC multi-species mixtures did not yield more than the average of all monocultures (proso millet, triticale, red clover, and radish) with spring plantings being more successful than late-summer plantings. The triticale monoculture produced the most biomass of all CC treatments in the study. Similar results were observed in the southern GP (SGP) where a single-species rye (*Secale cereal* L.) CC generally produced greater biomass when compared to a multi-species CC (Lewis et al., 2018). Averaged across years, the authors reported that the rye monoculture yielded 4433 kg dry matter ha^{-1} compared to 3568 kg DM ha^{-1} for the multi-species CC.

In southwest Kansas, winter triticale, spring triticale, and triticale–legume mixtures produced the most biomass across all CC treatments (Holman et al., 2018). Fall-planted legumes were found to have some successes when grown in a mixture but showed significant levels of winterkill when grown in monoculture. Additionally, the authors reported substantial year-to-year variability in biomass production due to variable precipitation, which is typical of the CGP. The biomass produced ranged from 780 kg DM ha^{-1} when precipitation during the CC growing period was 46% less than the 30-yr average to 2690 kg DM ha^{-1} when precipitation was at or above the 30-yr average. These results suggest that CC successes may be determined by precipitation more so than any other factor in semi-arid dryland systems (Reese et al., 2014; Nielsen et al., 2015a; Holman et al., 2018).

Many CC proponents have suggested growing multi-species mixtures with the theory that they will be able to increase biomass production, residue cover, water use efficiency and soil health compared to single-species CCs. However, there is little or no data to support such a recommendation in semi-arid regions. Previous research showed residue cover at CC termination was not significantly different when a 10-species mixture was compared with an average of single-species plantings over multiple years at two sites in eastern Colorado and western Nebraska (Nielsen et al., 2015b). The authors further reported that averaged across data sets, precipitation storage efficiency was not significantly different for the mixture (30.4%) when compared to single species plantings (29.7%). With consideration to the fact that precipitation is the single most limiting factor in both dryland and limited irrigation cropping systems in the

CGP region (Robinson and Nielsen, 2015; R. Ghimire et al., 2018; Nielsen, 2018), there is great motivation for the development of CC management strategies that can more efficiently utilize stored soil water as well as growing-season precipitation to sustain farm productivity and profitability.

Water use and flex-cover cropping

Cover crops have frequently been found to have either no effect or to reduce cash crop yields in water-limited regions by reducing available water for the subsequent crop (Blanco-Canqui et al., 2015). Termination date can be critical for minimizing the potential risk of reduced cash crop germination, stand density, and yield due to deficit soil moisture (Svoma and Gantzer, 2016). This is of greatest importance when CCs are grown in low water-holding-capacity soils such as those with high levels of sand-sized particles or in regions with low precipitation (<500 mm yr^{-1}) (Blanco-Canqui et al., 2011). In an analysis of the water storage efficiency of the 14-month fallow period in the CGP crop rotations, Peterson and Westfall (2004) described stage III of fallow, or the 4.5 months ahead of winter wheat planting to be –4% efficient in water storage. This was speculated to be due to high air temperatures and greater evaporation rates at this time of year in the CGP in addition to the soil profile having already reached field water holding capacity. This indicates room for improvement as crop producers in the CGP seek sustainable intensification in their farming operations.

In southwest Kansas, growing CCs or forages during the fallow period reduced subsequent winter wheat yields in dry years but had little effect in wet years (Holman et al., 2018). The authors reported that for every 125 kg ha^{-1} of CC biomass grown, plant available water at wheat planting was reduced by 1 mm, subsequently reducing the yield of that crop by 5.5 kg ha^{-1}. Similarly, studies in northeastern Colorado have shown a direct negative relationship between CC water use during fallow and subsequent winter wheat yields (Nielsen et al., 2015b). In another study at two semi-arid sites in South Dakota, Reese et al. (2014) reported high CC biomass production (>2000 kg ha^{-1}) that resulted in subsequent corn yields being reduced by 1610 to 2950 kg ha^{-1} due to lower soil water content at corn planting as well as a reduction in available soil N.

Lewis et al (2018) reported reduced cotton lint yield in response to CCs included in a continuous cotton production system in the Texas Panhandle. The authors reported cotton under CT without CCs yielded 170 and 79 kg ha^{-1} more lint compared to when a rye CC and a CC mixture, respectively, were grown under NT management. Even with early termination dates, legumes grown for green manure between winter wheat crops in northeastern Colorado used significant amounts of soil water, leading to a wheat yield reduction of 900 to 1650 kg ha^{-1} (Nielsen and Vigil, 2005). The authors reported that wheat yields were linearly related to available soil water at the time of planting and varied with the severity of water stress conditions.

Developing climate-specific CC management options for dryland farmers could improve adoption of CC use in the CGP. Flex-cover cropping is the concept of planting CCs or forages only when soil moisture levels are adequate, and the precipitation outlook is favorable. Under drought conditions, flex-cover copping should help minimize negative impacts (Felter et al., 2006; Lyon et al., 2007; Holman et al., 2018). This method, coupled with the incorporation of select crops that produce greater amounts of persistent residues, can lead to more water-use-efficient dryland cropping systems for the CGP (Nielsen, Unger, and Miller, 2005). In southwest Kansas, Holman, Roberts, and Maxwell (2017) began utilizing flex-cover copping by planting CCs or forages only when a minimum of 4 inches of plant available water was determined at spring planting. The alternative would be to leave the area fallow. The goal of flex-cover cropping as a management strategy is to take advantage of available moisture in wet years but maintaining fallow in dry years to minimize risk.

Utilizing cover crops as a forage resource

Previous research in western Kansas has shown that most of the plant species utilized as CCs have excellent forage quality attributes in terms of crude protein (CP), digestibility, and DM production (Obour and Holman, 2016). Due to the significant regrowth potential, especially of grass species, hayed or grazed CCs can regrow to provide significant residue cover compared to fallow. With this in mind, opportunity certainly exists for dual-purpose use of CCs in dryland cropping systems to provide high-quality forage as well as residue cover to reduce erosion and build soil health (Blanco-Canqui et al., 2013; Farney, Sassenrath, Davis, and Presley, 2018). However, these CCs should be managed with an ultimate goal of leaving >30% residue to meet soil health objectives. Grazing time, duration, and stocking rate are key considerations to prevent soil degradation when CCs are used as forage (Blanco-Canqui et al., 2016; Rakkar et al., 2018). Such cropping systems can take advantage of available soil moisture, defer cattle grazing from native perennial grasslands, and provide forage for the livestock industry in the GPs (Sanderson et al., 2018; Holman et al., 2018).

Over three years in central North Dakota, the average DM yield of spring-planted CC mixtures (2400 kg ha^{-1}) was greater than the average of CC monocultures (1720 kg ha^{-1}) (Sanderson et al., 2018). However, mixtures did not yield more than the most productive monoculture, triticale (3165 kg ha^{-1}). Crude protein of triticale forage averaged 111 g kg^{-1} and was less than the average mixture (129 g kg^{-1}) likely due to the addition of broadleaf species, clover and radish, in the mixture. Also in North Dakota, Carr et al. (2004) reported average DM yields of 2.91 Mg ha^{-1} and 3.84 Mg ha^{-1} as well as CP concentrations of 90 and 61 g kg^{-1} for monoculture barley and oat forages, respectively. The authors went on to state that on average, DM and CP were increased with the inclusion of peas in mixtures with barley or oats compared to either grass crop in monoculture.

In the NGP region of Montana, Miller, Glunk, Holmes, and Engel (2018) assessed annual forage production in place of fallow in rotation with dryland winter and spring wheat. They reported average barley and pea forage yields from 2.68 to 4.28 Mg ha^{-1} when harvested at the time of flowering. A monoculture of spring peas (3.61 Mg ha^{-1}) produced more forage than winter peas (2.41 Mg $ha-^{1}$) across two growing seasons and was similar to when grown in mixture with barley (3.57 Mg ha^{-1}). In one growing season, the barley monoculture (6.21 Mg ha^{-1}) out yielded peas (4.2 Mg ha^{-1}) but yielded slightly less (2.45 and 2.97 Mg ha^{-1}, respectively) in the other season. Across years, CP averaged 110, 123, 177, and 225 g kg^{-1} for monoculture barley, pea-barley, monoculture spring pea, and monoculture winter pea, respectively.

Planted mid-summer, after winter wheat harvest, oats, radish, and CC mixtures yielded >4000 kg DM ha^{-1} with a 1 November harvest date in central South Dakota (average annual precipitation of 504 mm) (Hansen, Owens, Beck, and Sexton, 2013). Oats and radish also yielded >4000 kg ha^{-1} in southeastern South Dakota (average annual precipitation of 604 mm) with a 1 November or 1 December harvest date, respectively. Forage quality tended to decrease somewhat as harvest was delayed. Except for cowpeas (*Vigna unguiculata* L.), due to low productivity, all CCs were viable forages in South Dakota through the late fall when good establishment was achieved. In a complementary study, broadleaf or legume CCs grown in mixtures produced substantial late-season growth and showed great potential to fill late-autumn or early-winter grazing deficits (Hansen, Owens, Beck, and Sexton, 2015).

In the Nebraska Panhandle, Titlow, Luebbe, Lyon, Klopfenstein, and Jenkins (2014) reported an average CC mixture DM yield of 1.4 Mg ha^{-1} and CP of 100 g kg^{-1}. Though CC mixtures did not consistently produce DM yields greater than the average of crested wheatgrass (*Agropyron cristatum*) pasture (1.9 Mg ha^{-1}), CP was substantially greater for CCs than crested wheatgrass (69 g kg^{-1}). Replacing the fallow phase of a dryland winter wheat-corn-fallow (WCF) cropping system, spring-planted forage triticale averaged 4698 kg DM ha^{-1} across six site-years in northeast Colorado and the Nebraska Panhandle (Nielsen, Lyon, and Miceli-Garcia, 2017). Across site-years, forage yields ranged from 2967 to 6724 kg ha^{-1}.

In southwest Kansas, average DM production from CCs ranged from a low of 780 kg ha^{-1} when precipitation was 46% less than the 30-year average to a high of 2690 kg ha^{-1} when precipitation was at or near the 30-year average during the CC growing period (Holman et al., 2018). The authors reported winter and spring triticale as well as triticale–legume mixtures to have the greatest biomass production in their study. Winter triticale and winter triticale-legume mixtures averaged 4100 kg ha^{-1}, but spring triticale and spring triticale–legume mixtures averaged 1700 kg ha^{-1}. Fall-seeded monoculture legumes were susceptible to winterkill resulting in some years without any biomass production. In southeast Kansas, a relatively wetter environment than much of the CGP region, multi-species CC mixtures were planted in August of each year and evaluated with the goal of producing forage for livestock (Davis, Presley, Farney, and Sassenrath, 2016; Farney et al., 2018). The authors reported that, across years, oats and barley produced 1737 and 1264 kg ha^{-1}, respectively, but wheat and rye produced only 446 and 225 kg ha^{-1}, respectively. Crude protein concentrations tended to be higher for mixtures containing wheat or rye, and less for those containing oat or barley. However, the overall range of CP between the mixtures was small, ranging only from 180 to 247 g kg^{-1}.

Soil health benefits with cover crops

Cover crops have great potential to benefit soil health in agricultural systems. Documented impacts of CCs include reduced bulk density and increased porosity, improved soil structure and aggregation, increased water infiltration, greater soil carbon stocks, as well as enhanced nutrient dynamics and microbial activity (Blanco-Canqui et al., 2015). Cover crops may enhance all these properties, largely depending upon species selection as it relates to biomass production potential and the persistence of residue remaining on the soil surface (B. Ghimire, R. Ghimire, VanLeeuwen, and Mesbah, 2017). Few studies have assessed the effect of managing CCs as grazed or hayed forages on soil health (Blanco-Canqui et al., 2015). A major concern of livestock grazing in NT systems is the potential development of soil compaction which may limit crop yield (Baumhardt et al., 2011, 2017).

Bulk density and porosity

Yield limiting soil compaction is a major concern for crop producers. Compaction, observed as increased bulk density and decreased porosity, is often exacerbated by the use of larger and heavier farm equipment and performance of field activities when the soil is too wet in an effort to be timely with operations. Cover crops have been recommended as one possible management practice to alleviate these issues. In a summary of six studies, Blanco-Canqui et al. (2015) concluded that CCs did not always reduce soil bulk density. In four studies, CCs were shown to reduce bulk density with two studies showing no effect by CCs. Two of the studies showing differences were 15- and 13-year experiments suggesting that CCs may reduce bulk density in the long-term.

In a NT winter wheat-grain sorghum system, the addition of summer CCs including sunn hemp (*Crotalaria juncea* L.) and late-maturing soybean [*Glycine max* (L.) Merr.] reduced near-surface compactibility by 5% after 15 years of management (Blanco-Canqui et al., 2011; Blanco-Canqui, Claassen, and Presley, 2012). Soil compactibility in this study were correlated with increases in SOC concentration at the 0- to 7.5-cm soil depth. Blanco-Canqui et al. (2013) reported no difference in bulk density with CCs in a wheat-fallow system and that bulk density was not different when CCs were hayed for forage. Similar results were found for CCs in a continuous cotton system (Lewis et al., 2018).

After 12 years of CC management in a NT corn-soybean-winter wheat cropping system, no difference in bulk density was observed with rotations intensified with either grass or legume CCs (Blanco-Canqui and Jasa, 2019). This lack of differences even after long-term use of CCs was attributed, at least in part, to the 15 years of continuous NT that this study had been under before the initiation of the experiment. Similar results were found in a continuous cotton system where bulk density was unaffected by CCs after 34 years of NT (Nouri, Lee, Yin, Tyler, and Saxton, 2019). Results from these studies suggest that long-term NT may be more influential than CCs in managing soil compaction.

Aggregation and structure

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 CGP. With the Dust Bowl years as a reminder of the consequences of severe wind erosion upon agriculture and society, the inclusion of CCs in current cropping systems offers great promise for the conservation of soils in the CGP. In this region, soil is most susceptible to erosion in late winter and early spring when primary crops are often absent and wind speeds are high (Hansen et al., 2012). Cover crops have the potential to reduce erosion risks by physically protecting the soil surface, improving soil structural properties, increasing SOC, as well as by anchoring the soil in place through active root growth (Bilbro, 1991; Blanco-Canqui et al., 2011).

One of the soil physical properties that has been frequently measured under CCs is WSA. Seven of eleven studies observed by Blanco-Canqui et al. (2015) showed an increase in WSA with CCs. The other four studies showed no effect. In south central Kansas, mean weight diameter (MWD) of WSA was increased 80% with CCs (Blanco-Canqui et al., 2011). This was attributed to an increase in macro-sized aggregates in the 8- to 4.75-mm and 4.75- to 2-mm size fractions by 3.6 times and 1.8 times, respectively, along with corresponding reductions in the 0.5- to 0.25-mm and <0.25-mm size fractions. Blanco-Canqui et al. (2013) reported an increased geometric mean diameter (GMD) of WSA with winter and spring triticale as well as spring pea compared to fallow in southwest Kansas. Geometric mean diameter of WSA was increased by 70% with winter triticale and 50% with spring triticale or peas compared to fallow. In this same study, winter and spring triticale CCs significantly reduced the wind-erodible fraction (<0.84-mm diameter) and increased the GMD of dry aggregates. Most interestingly, both GMD of dry aggregates and WSA as well as wind-erodible fraction were unaffected by haying of CCs in this study.

In western Tennessee, aggregate size distribution in the 0–15 cm depth was significantly affected after 34 years of CCs (Nouri et al., 2019). Mean weight diameter of WSA was increased 22% with wheat or vetch CCs. This can largely be attributed to a 12% increase in the proportion of macro-sized aggregates (>2-mm) with CCs and subsequent reductions in the size fractions <0.5-mm. After 12 years of CC management in eastern Nebraska, Blanco-Canqui and Jasa (2019) reported that grass CCs grown in between grain crops in a NT cropping system increased MWD of WSA by 34% compared to legume CCs or a NT system without CCs. These results indicate that grass CCs have the potential to improve soil physical properties, but legume CCs may not because of limited biomass production.

Water infiltration

Cover crops may improve soil water infiltration and hydraulic conductivity through greater aggregation of the soil and increased porosity (Blanco-Canqui et al., 2015; Blanco-Canqui, 2018). In a NT winter wheat-fallow cropping system, simulated rainfall induced time-to-runoff was delayed with a winter triticale CC compared to fallow (Blanco-Canqui et al., 2013). The authors reported spring triticale and spring pea CCs to be similar to fallow. Sediment loss was 3.7 times lower with winter triticale and spring pea compared to losses from fallow. Although sediment loss with spring triticale was numerically less than fallow, the results were not significant.

Cumulative water infiltration was increased after 34 years of CCs in a NT continuous cotton system (Nouri et al., 2019). The authors reported 96 and 70% increases with vetch and wheat CCs, respectively. However, this was not the case after 12 years of CCs in a NT corn-soybean-winter wheat cropping system where neither legume nor grass CCs altered water infiltration (Blanco-Canqui and Jasa, 2019). These results were surprising and suggest that CCs may not necessarily alter water infiltration after long-term NT in all environments.

Soil carbon

Soil organic carbon (SOC) makes up ~50% of the SOM faction and is a source and a sink for plant nutrients. Soil organic carbon is important in maintaining tilth, aiding gaseous exchange as well as solute and nutrient transport, promoting water retention, and reducing erosion (Blanco-Canqui et al., 2015; Colazo and Buschiazzo, 2010). Because of this, SOC has long been considered a key factor in the assessment of soil health. Cover crops may increase SOC in agricultural soils though the degree of effect is site-specific and dependent upon CC biomass input, above and below ground, as well as the number of years CCs have been a part of the cropping system (B. Ghimire et al., 2017). By reducing soil erosion, NT management will increase ambient SOC meaning the addition of CCs may be less influential after many years of NT (Blanco-Canqui and Ruis, 2018).

On a Ulysses silt loam, CCs increased SOC stocks and concentration in the 0- to 7.5-cm soil depth but not at deeper depths relative to chemical fallow (Blanco-Canqui et al., 2013). Winter and spring triticale as well as spring lentil CCs increased SOC stocks by an average of 1.2 times compared with fallow. Differences were not significant for winter lentil and spring peas. These results were attributed to the greater residue input from triticale than from the legume species. Averaged across treatments, triticale CCs increased SOC stocks by 2.48 Mg ha^{-1}, or a 23% increase, which is consistent with other reports that grasses yield greater and more persistent residue than legumes (Rosolem, Li, and Garcia, 2016; Sanderson et al., 2018). Soil organic carbon stocks were not different when CCs were hayed for annual forage compared to when CCs were left standing (Blanco-Canqui et al., 2013).

On a Geary silt loam, SOC concentration was increased in the upper 0- to 7.5-cm soil depth after 15 years of legume CCs (Blanco-Canqui et al., 2011). This difference was not present in the 7.5- to 15-cm depth. In two studies on an Amarillo fine sandy loam, a naturally low SOC containing soil, authors reported that long-term cereal rye and multi-species CC management increased SOC near the soil surface, but differences were not present at deeper depth (Lewis et al., 2018; DeLaune, Mubvumba, Lewis, and Keeling, 2019). Similar results were observed on an Aksarben silty clay loam where grass CCs increased the SOM concentration in the 0- to 7.5-cm depth after 12 years of management though this was not the case with legume CCs (Blanco-

Canqui and Jasa, 2019). These results suggestions that CCs may increase SOC and SOM after many years of management.

Nutrient dynamics

Cover crops in intensively managed cropping systems may influence soil nutrient accumulation, recovery, storage, and cycling by fixing atmospheric N, scavenging nutrients, as well as reducing nutrient lose due to leaching and erosion (Blanco-Canqui et al., 2015; Blanco-Canqui, 2018; Thapa, Mirsky, and Tully, 2018). Research in eastern Kansas found that summer legume CCs grown after winter wheat harvest and ahead of corn resulted in total corn N uptake similar to that of a complementary fallow system with 45 kg applied N ha^{-1} (Mahama, Prasad, Roozeboom, Nippert, and Rice, 2016b). Similar results were found when legume CCs were grown ahead of grain sorghum. Total grain sorghum N uptake was found to be similar to that of a complementary fallow system with 45 or 90 kg applied N ha^{-1} (Mahama, Prasad, Roozeboom, Nippert, and Rice, 2016a). In south central Kansas, a significant soil N accumulation was observed with legume CCs (Blanco-Canqui et al., 2012) though the authors speculated that the benefits of summer legume CCs may be limited in areas of lower average annual precipitation.

Cover crops may also absorb and convert available P into organic forms. Scavenged nutrients are subsequently released gradually after termination, which may reduce nutrient losses due to leaching and erosion. In southwest Kansas with simulated rainfall, total sediment loss with winter triticale and spring pea CCs was 3.7 times lower than with fallow (Blanco-Canqui et al., 2013). Further, the loss of total dissolved P and NO_3–N in runoff was 3.4 to 4.2 times less in winter triticale and spring pea than in fallow. Spring triticale and winter lentils numerically reduced sediment and dissolved nutrients compared to fallow thought the results were not significantly different.

In the SGP region of Texas, CCs in continuous cotton systems reduced soil NO_3–N concentrations near the soil surface though total soil N was increased (Delaune et al., 2019; Lewis et al., 2018). Reductions in soil NO_3–N may have mixed effects in cropping systems. Although reductions may limit nutrient lose due to leaching and erosion, there is concern that lower soil NO_3–N may reduce subsequent crop yields due to asynchronous N release from CC residues and N demand by cash crops (Cicek, Thiessen-Martens, Bamford, and Entz, 2015). No differences were observed for soil P and K concentrations in these studies. Soil pH in the 0- to 15-cm depth was reduced by 0.5 units with a cereal rye CC, though no differences were detected in the 15- to 60-cm depths. Carbon dioxide respired during microbial decomposition of organic material can form carbonic acid, subsequently reducing soil pH (Lewis et al., 2018).

Microbial Activity

Observed increases in microorganism populations have been used as a dynamic indicator of improvement in soil properties and overall soil ecosystem services (Blanco-Canqui et al., 2015). Cover crops may enhance soil microbial activity by increasing soil carbon inputs as well as by the presence of living roots (Calderón, Nielsen, Acosta-Martínez, Vigil, and Lyon, 2016). Additionally, potentially mineralizable nitrogen (PMN) and particulate organic carbon (POC) are often referenced as they are the biologically active components of SOM and have a rapid turnover rate (< one growing season) (Drinkwater, Cambardella, Reeder, and Rice, 1996). These components are derived from the nutrients released with the turnover of microbial biomass and are very sensitive to changes in management practices such as tillage or CCs, thereby providing early indicators of the degradation or accrual of SOM.

A five-year green-manure study in the NGP region of eastern Montana revealed up to a 66% increase in PMN could be achieved with lentil green manure in place of fallow (Pikul Jr., Aase, and Cochran, 1997). In a review of CCs in dryland production systems in the semi-arid GP, R. Ghimire, et al. (2018) stated that CCs would have a greatest effect on soil chemical properties under conservation tillage systems (reduced-tillage and NT) than conventional systems. Cover crops increased POM in the 0- to 2.5-cm depth after three years in south central Nebraska (Blanco-Canqui et al., 2014) though no differences were detected at the 2.5- to 5-cm depth. These results are consistent with other studies of incorporating CCs (Blanco-Canqui et al., 2015).

Across two sites in the semi-arid CGP region of eastern Colorado and western Nebraska, Calderón et al. (2016) reported increases in fatty acid methyl ester (FAME) concentrations with CCs. These differences were most pronounced at the time of CC termination and began to diminish by the time of subsequent crop planting. The authors reported that CC mixtures did not benefit soil microbial composition and activity compared to single-species CCs and that soil water is likely the factor most influencing these properties in semi-arid regions. Results of this study suggest that single-species CCs may be adequate to benefit soil microbial communities though the effects may be transient in semi-arid dryland cropping systems.

Cover crops for weed management

Cover crops suppress weeds by reducing early-season weed densities, growth, and seed production because of direct competition from the living CC biomass or from significant residues after CC termination (Kumar, Jha, Jugulam, Yadav, and Stahlman, 2018; Kumar et al., 2020). Kochia (*Bassia scoparia* L.) is a major weed affecting cropland in the semi-arid GP. In northeastern Colorado, Anderson and Nielsen (1996) reported kochia emergence as being primarily from early April to late June. Tillage was not found to affect the kochia emergence pattern. However, the number of emerged kochia plants was increased under NT management.

Small-seeded weeds such as kochia benefit from NT, because a majority of dispersed weed seeds will stay on or near the soil surface which provides optimum germination conditions for such small seeded species (Kumar et al., 2018). Anderson and Nielsen (1996) further reported that in their semi-arid CGP location, green foxtail (*Setaria viridis* L. Beauv.), wild proso millet, and redroot pigweed (*Amaranthus retroflexus* L.) began emerging in late May and continued until August. Volunteer wheat was found emerging throughout the growing season.

In semi-arid central North Dakota, Sanderson et al (2018) reported no support that CC mixtures could suppress weeds better than monocultures even when mixtures were insured to contain equal proportions of species in the mix. The authors reported much better weed suppression with spring planted CCs over later summer plantings. Late summer seeding of CCs in semi-arid regions of the NGP has associated risks due to variable rainfall and a shortened growing season leading to little weed suppression benefit. In southwest Kansas, Petrosino, Dille, Holman, and Roozeboom (2015) determined that single-species CCs and simple mixtures that included winter triticale were able to reduce kochia density by 92% and biomass up to 99% when compared to no-till fallow. Both studies reported that the degree of weed suppression of CCs was related to the amount of biomass produced (Petrosino et al., 2015; Sanderson et al., 2018). Low biomass legume CC species often could not compete with broadleaf weeds including kochia.

In a systematic review and meta-analysis, Osipitan, Dille, Assefa, and Knezevic (2018) reported that CCs could provide early-season weed control comparable to chemical and mechanical methods of weed control. The authors went on to conclude that the decision to use CCs as multi-species mixtures versus single-species or grass versus broadleaf should be driven based upon the inherent characteristics of CCs to suppress weed growth. Based on their review and others, these characteristics include high production of biomass as well as persistence of the residue on the soil surface (Petrosino et al., 2015; Kumar et al., 2018).

Focusing upon CC management for weed suppression in the semi-arid GP region, a review from Kumar et al. (2020) discussed the potential of CC adoption in dryland cropping systems to benefit an overall integrated weed management plan. The authors concluded CCs must be managed for maximized biomass production to achieve successful weed suppression and, in that way, economic value. Although CCs may reduce subsequent grain crop yields to some degree, due to a decrease in soil water content compared to fallow, reductions in the number of herbicide applications needed in the NT fallow period may lead to economic optimization.

Objectives and Hypothesis

The objectives of these studies were to:

1. Assess the long- and short-term soil health impacts of growing CCs in the semi-arid central Great Plains

   Hypothesis: Incorporating CCs will lead to increased soil organic carbon stocks, water stable aggregates, and water infiltration both in the long- and short-term. Increasing CC species diversity will not improve soil health beyond what is achievable with simple mixtures and monocultures. Grass species will produce the greatest biomass and provide significant residue cover compared to fallow.

2. Quantify the effect of haying or grazing of CCs on soil health in NT cropping systems.

   Hypothesis: Haying and grazing of CCs will not limit potential gains in soil health compared to when CCs are left standing. The integrated crop–livestock production system of grazing CCs will not lead to sustained yield-limiting soil compaction.

3. Quantify the productivity and forage quality of CCs utilized as grazed or hayed annual forages for livestock.

   Hypothesis: Grass CC mixtures will produce excellent forage quality attributes in terms of crude protein, digestibility, and dry matter production.

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Chapter 2 - Long-term effects of cover crop management on soil properties in semi-arid dryland cropping systems

Abstract

Growing cover crops (CC) in semi-arid drylands may provide several benefits to soil health. In this study long-term CC management effects on soil properties were examined in a no-till (NT) winter wheat (*Triticum aestivum* L.)-grain sorghum (*Sorghum bicolor* Moench)-fallow (WSF) cropping system in southwest Kansas. Treatments were all spring-planted and included peas (*Pisum sativum* L.) for grain as well as one-, three-, and six-species CC mixtures compared with chemically-controlled NT fallow. Half of each CC treatment was harvested for forage. The SOC stocks within the 0- to 15-cm soil depth were greater with CCs compared to fallow when sampled in 2012 after three appearances of CCs in the initial wheat-fallow rotation. In 2018 after two cycles of the WSF rotation, SOC stocks were similar across all treatments likely because CC residue inputs declined due to a succession of drought years. However, SOC had increased in all treatments since 2012, mostly due to the significant residue contribution from grain sorghum ($r^2 = 0.35$; $P = 0.0025$). 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 (WSA) in the 0- to 5-cm soil depth was greater with standing CCs (1.11 mm) compared to peas (0.77 mm). The proportion of WSA in the >2-mm size fraction was greater and 2- to 0.25-mm size fraction was less with triticale compared to peas. Standing (3.55 mm) and hayed CCs (3.62 mm) had greater MWD of dry aggregates compared to fallow (2.75 mm). Water infiltration rates and saturated infiltrability were significantly greater with standing or hayed CCs compared to peas. Our findings suggest simple CC mixtures and CCs managed for annual forage in NT dryland systems provide similar soil health benefits as diverse CCs mixtures and CCs left standing.

Introduction

Growing cover crops (CCs) in dryland cropping systems in the semi-arid central Great Plains (CGP) has been promoted as a component of the broader movement toward regenerative agriculture and soil health (Cano et al., 2018, Rosenzweig, Carolan, and Schipanski, 2019). This includes such benefits as reduced soil erosion, enhanced nutrient cycling, as well as increased microbial activity and abundance (Blanco-Canqui, 2018; Blanco-Canqui, Holman, Schlegel, Tatarko, and Shaver, 2013; Blanco-Canqui et al., 2015; Calderón, Nielsen, Acosta-Martínez, Vigil, and Lyon., 2016). Despite these potential benefits as well as an increasing interest among producers in the CGP, CC adoption has been slow in this water-limited region (Bergtold, Ramsey, Maddy, and Williams, 2017). This is largely due to concern that CCs may deplete stored soil water compared to that obtainable with no-till (NT) chemically-controlled fallow, which the region has historically relied upon for dryland crop production (Nielsen, Unger, and Miller, 2005; Nielsen and Vigil, 2010). The CGP region is characterized by expansive semi-arid prairie, a substantial portion of which is now under cultivation for annual crop production (Hansen, Allen, Baumhardt, and Lyon, 2012). Bordered to the west by the Rocky Mountains and to the east by areas of higher rainfall, the climate of this region is best characterized by its rainfall variability (Nielsen, 2018; Robinson and Nielsen, 2015). Periodic wet cycles are contrasted by sustained droughts often not confined to a single season of the year. In addition to the variability between years, unpredictable short-term drought within a cropping season is also common (Ghimire et al., 2018; Hansen, Allen, Baumhardt, and Lyon, 2012). Although water withdrawn from the region's underlying Ogallala Aquifer has supported irrigated production, continued depletion of the saturated thickness and associated higher pumping costs have already led some producers to transition previously irrigated cropland back to dryland (Baumhardt, Staggenborg, Gowda, Colaizzi, and Howell, 2009; Cano et al., 2018; Deines et al., 2020).

Dryland crop production is prevalent in regions where precipitation accounts for only 20 to 35% of potential evapotranspiration and is made possible through increased crop residue retention by reduced tillage in order to store water in the soil during fallow periods (Robinson and Nielsen, 2015; Stewart and Peterson, 2015). The practice of fallowing has been shown to stabilize grain crop yields and to mitigate devastating crop failure, particularly in drier years (Nielsen and Vigil, 2010; Aiken, O'Brien, Olson, and Murray, 2013). However, precipitation storage efficiency during fallow is imperfect, ranging from 17 to 45%, depending primarily on tillage practice and associated residue management strategies of a given producer (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 (Bowman, Reeder, and Lober, 1990; Baumhardt, Stewart, and Sainju, 2015). This indicates room for improvement as crop producers in the CGP seek options to sustainable intensify their farming operations.

Increased adoption of CCs by dryland producers in the region may enhance residue cover and reduce the susceptibility of the soil to erosion (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, R. Ghimire, VanLeeuwen, and Mesbah, 2017). In addition, it has been documented that increased rooting activity and associated carbon inputs from CCs may improve soil aggregation and water infiltration (Chalise et al., 2018; Franzluebbers, Wright, and Stuedemann, 2000; Nouri, Lee, Yin, Tyler, and Saxton ,2019). However, many of these studies were conducted in regions that receive relatively greater annual precipitation than is common for the semi-arid CGP. Past research at this long-term study site in southwest Kansas 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 lacking regarding the long-term (>10 years) soil benefits of integrating CCs in dryland cropping systems (Blanco-Canqui et al., 2015).

Growing CCs in dryland cropping systems in the semi-arid CGP offers great potential to improve soil properties, enhance precipitation use efficiency, and diversify markets when CCs are utilized as supplemental forage. Few studies have investigated the effect of managing CCs as annual forage on soil properties in dryland crop production (Blanco-Canqui et al., 2015). Grazing and/or haying 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, Obour, and Assefa, 2020; Kumar et al., 2020). However, there is some 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, Allen, Hou, Chen, and Brown, 2013). The short-term results of Blanco-Canqui et al (2013) concluded no difference in SOC or WSA when CCs were harvested for forage, leaving 15 cm of stubble, compared to when CCs were left standing. This suggests that, with careful management, CCs could be utilized for forage with no detrimental effects on soil properties.

To our knowledge, there is little or no information on the long-term (>10 years) effects of harvesting 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) effects of CC species diversity and the ii) effect of harvesting CCs as an annual forage on soil properties in a NT dryland cropping system. Our hypothesis was that incorporating CCs would decrease bulk density while increasing porosity, 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 monoculture of grass CCs. Furthermore, it was hypothesized that long-term haying of CCs as annual forage would not limit potential gains in soil health compared to when CCs were left standing.

Materials and Methods

Experimental layout

This study was established in 2007 at the Southwest Research-Extension Center near Garden City, KS (37°58′31″ N, 100°51′51″ W). 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 meters above sea level. Long-term (1981–2010) average annual precipitation at the study site was 489 mm (Table 2.1) with open-pan evaporation (April through September) of 1810 mm. The initial treatments reported by Blanco-Canqui et al (2013), Holman et al (2018), and Holman et al (2020) included winter- and spring-planted crops grown in place of fallow in a two-year NT winter wheat (*Triticum aestivum* L.)-fallow (WF) cropping system. In

2012, the experiment was modified to a three-year NT winter wheat-grain sorghum (*Sorghum bicolor* Moench)-fallow (WSF) cropping system to better align with the typical producer practice. Fallow replacement crops consisted of spring-planted CC monocultures and multi-species mixtures grown during the fallow period. Due to the significant water use of winter CCs compared to spring CCs (Holman et al., 2018; 2020) as well as the short time period available for fall growth following grain sorghum harvest, winter CCs were dropped from the present study. Spring CC treatment randomization within the study was kept consistent across years to determine long-term treatment effects. All phases of the WSF crop rotation were present every year to ensured that wheat, sorghum, and CCs were planted each year of the study.

The study design was a split-split-plot randomized complete block design with four replications. Crop phase was the main plot, CC treatment was the split-plot, and termination method (standing cover, hayed forage, or grain) was the split-split-plot. Each split-split-plot was 4.6 m wide and 36.6 m long. Treatments included yellow spring peas (*Pisum sativum* L.) harvested for grain, as well as three CC treatments managed as standing cover or harvested for forage: triticale (×*Triticosecale* Wittm.) alone, a three-species mixture of oat (*Avena sativa* L.) /triticale/pea, and a six-species cocktail mixture of oat/triticale/pea/buckwheat (*Fagopyrum esculentum* Moench) /turnip (*Brassica rapa* L.) /radish (*Raphanus sativus* L.). The CC treatments were compared to chemically-controlled NT fallow for a total of 8 treatments.

Crop management

Winter wheat was planted in early October and harvested in early July. Following an eleven-month fallow period, grain sorghum was planted in June and harvested in November. Spring CCs were planted between the end of February and mid-March as field conditions allowed. Cover crops were chemically terminated or harvested for forage in early June to minimize negative effects on subsequent wheat yields (Schlegel and Havlin, 1997; Holman 2018). Peas grown for grain were harvested in mid-July. Haying and termination of CCs coincided with triticale heading, which was selected as a harvest stage to optimize forge yield and quality. Wheat and peas were harvested with a stripper header (Model CX, Shelbourne Reynolds Inc., Colby, KS) and small plot combine (Model Delta, Wintersteiger Inc., Salt Lake City, UT), from a 2.4-m by 36-m area at grain maturity, which occurred approximately the first week of July. However, peas failed to produce grain in most years of the study (Holman et al., 2020). 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, Baldock, and Forbes, 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).

Soil sampling and analysis

Soil sampling took place at study initiation in fall 2007, in spring 2012 during actively growing winter wheat [as previously reported by Blanco-Canqui et al. (2013)], in fall 2018 before wheat planting, and in summer 2019 after wheat harvest. At each sampling period, ten soil cores (2.5-cm diameter) were randomly taken from the 0- to 15-cm depths for determination of bulk density as well as pH, nitrogen (NO_3 and NH_4), and SOC stocks. Briefly, the samples taken at each depth were dried at 105 °C for 48-hr, and bulk density was determined by mass of oven-dry soil divided by volume of the core. Further, soil porosity was determined using a constant particle density of 2.65 g cm^{-3}. Subsamples from each depth were air-dried and ground to pass through a 2-mm sieve and used for determining soil chemical properties. Soil pH was analyzed using a 1:1 (soil/water) ratio using deionized water and 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 removed carbonates (Nelson and Sommers, 1996). Carbon concentrations were converted to mass by multiplying concentrations by soil bulk density and the thickness of the soil layer.

Additional samples were collected from the 0- to 5-cm soil depth with a flat shovel for the determination of aggregate stability. The samples 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 water-stable aggregates (WSA) by the wet-sieving method (Nimmo and Perkins, 2002). Sand corrections were completed for each aggregate size fraction, and the data was used to compute aggregate size distribution (ASDWSA) as well as mean weight diameter (MWDWSA) of WSA. In 2019, before sieving, 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). Data was used to compute dry aggregate size distribution (ASDDA) and mean weight diameter (MWDDA) of dry aggregates as well as wind-erodible fraction (WEF). In wheat stubble in summer 2019, water infiltration rate (IR), saturated infiltrability (SI), and time-to-runoff (TTR) were measured with a Cornell Sprinkle Infiltrometer (Ogden, van Es, and Schindelbeck, 1997).

Statistical analysis

Data analysis for soil physical and chemical properties was performed using PROC GLIMMIX in SAS ver. 9.3 (SAS Institute, 2012, Cary, NC). Treatment was considered fixed with replication and their interactions considered random for the analysis of CC effects. Treatment effects were considered significant at $P \leq 0.05$. 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 sample period: 2007 to 2012 and 2012 to 2018. Regression analyses were considered significant at $P \leq 0.05$.

Results

Long-term weather patterns

Average annual precipitation from 2007 to 2012 was 446 mm or 83% of the 30-year average (489 mm) (Table 2.1). However, spring precipitation (February-May) was relatively reliable and favorable for the cool-season crops, winter wheat and CCs, in the crop rotation at the time. Average annual precipitation from 2012 to 2018 was 497 mm or 102% of the 30-year average. Although cumulative precipitation was near normal, this time 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 but too late to benefit the cool-season CCs or winter wheat in the rotation.

Soil organic carbon and crop residue input

Soil organic carbon stocks within the 0- to 15-cm depth increased with standing (20.93 Mg ha^{-1}) or hayed CCs (19.86 Mg ha^{-1}) compared to fallow (17.93 Mg ha^{-1}) in 2012 (Table 2.2). This occurred six years after study initiation and during a period when precipitation distribution was relatively favorable for cool-season CCs (Table 2.1). When left standing, CCs increased SOC compared to peas (Table 2.2). Averaged across CC mixture and monoculture treatments, SOC with hayed CCs was not different from standing CCs. Treatments did not differ in SOC in the 2018 and 2019 samplings though there was a trend of increasing SOC stocks since 2012 (19.84 Mg ha^{-1}. Averaged across treatments, SOC stocks were 21.79 and 20.01 Mg ha^{-1} in 2018 and 2019, respectively.

Regression analyses showed a positive relationship between SOC stocks in 2018 and annual crop residue inputs across the twelve years of this study (Fig. 2.1a). From 2008 to 2012, SOC stocks were unaffected by winter wheat residue (Fig. 2.1b). However, CC residue produced during this same period did positively affected SOC stocks measured in 2012 (Fig. 2.1c). Again, SOC stocks measured in 2018 were unaffected by winter wheat residue inputs from 2012 to 2018 (Fig. 2.1d). However, there was a significant positive relationship between SOC stocks measured in 2018 and grain sorghum residue input from 2012 to 2018 (Fig. 2.1e). Unlike 2008 to 2012, CC residue from 2012 to 2018 had no significant effect on SOC stocks measured in 2018 (Fig. 2.1f).

Physical and hydraulic properties

In 2018, bulk density was less with 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 2.3).

Likewise, porosity was less with fallow (44.0%) compared to standing (46.6%) and hayed CCs (46.3%). Porosity with both standing and hayed CCs were similar to with peas (47.5%). This CCs effect was clearer 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 and porosity were not influenced differently when CCs were hayed versus when they were left standing. Differences among treatments were not present in samples obtained after winter wheat harvest in summer 2019. Average bulk density and porosity were 1.39 g cm^{-3} and 47.6%, respectively (Table 2.3).

Water infiltration rate and SI measured in summer 2019 increased with standing or hayed CCs compared to peas but were both similar to fallow (Table 2.4). Interestingly, peas had significantly lower IR and SI as well as a trend toward lower TTR compared to fallow (Table 2.4). Greatest IR and SI 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 differences in IR, SI, or TTR between hayed and standing CC treatments.

Soil pH and N stocks

Soil pH in 2018 tended to be lower with standing CCs (mean of 6.99) compared to fallow (7.29) or hayed CCs (7.26), approximately 0.30 and 0.27 units less, respectively (Table 2.5). This reduction in soil pH was most pronounced with the cocktail and oat/triticale/pea CCs compared to triticale alone. Soil pH in the pea treatment was similar to all other treatments. Differences in pH between treatments were not present in 2019 after winter wheat harvest and averaged 7.45. Measured in 2018 and 2019, soil NO_3-N was not significantly different across treatments, although stocks tended to be greater with standing (28.78 kg ha^{-1}) and hayed CCs (26.62 kg ha^{-1})

compared to fallow (23.01 kg ha^{-1}) (Table 2.6). 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 4.99 and 1.77 kg ha^{-1} in 2018 and 2019, respectively (Table 2.6).

Water and Wind Erodibility

Mean weight diameter of WSA in 2018 was 44% greater with standing CCs (1.11 mm) compared to peas (0.77 mm) (Table 2.7) 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. The increase in MWDWSA with CCs compared to peas was largely due to an increase in the proportion of >2-mm aggregates (73%) and a subsequent decease in the <2-mm size fraction (20%, Fig. 2.2).

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 with 52 and 51% increases, respectively (Fig. 2.2). The proportion of aggregates in the <2-mm size fraction was less with standing or hayed CCs compared to fallow with 16 and 17% decreases, 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). This difference comes from an increase in the >2-mm size fraction (55%) and a decrease in the <2-mm size fraction (20%) with the standing triticale CC compared to peas (Fig. 2.3).

In 2019, standing CCs (3.55 mm) had greater MWDDA compared to fallow (2.75 mm). Standing CCs were similar to both peas (3.81 mm) and hayed CCs (3.62 mm) (Table 2.7).

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. Increases in MWDDA with CCs and peas compared to fallow were due to increases in the >2-mm size fractions (32%) and complimentary decreases in the <2-mm size fraction (13%) (Fig. 2.4).

Discussion

Differences observed in 2012 supported our hypothesis that CCs would increase SOC stocks compared to fallow and agreed with the results of others (Blanco-Canqui, Mikha, Presley, and Claassen, 2011; Lewis et al., 2018; Delaune, Mubvumba, Lewis, and Keeling, 2019). However, the lack of differences in SOC at the time of sampling in 2018 and 2019 with CCs compared to fallow did not support this hypothesis and suggests that increases in SOC with CCs may in fact be transient in semi-arid drylands as was speculated by Blanco-Canqui et al. (2013). This observation is 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 was greatest in the early years of this study with relatively more favorable spring precipitation that increased CC residue inputs (Fig. 2.1c). However, CC effects on SOC was diminished in the later years due to less favorable precipitation distribution that limited CC biomass production and residue retention (Fig. 2.1f). Notwithstanding, SOC stocks increased from 2012 to 2018 mostly because of cropping system intensification. In eastern Colorado, Sherrod et al. (2018) reported that 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. This observation agrees with findings in the present study where SOC stocks with CCs did not increase compared to fallow in

2018 and 2019 but had not declined after the transition from WF to WSF. The addition of grain sorghum in the cropping system had the greatest influence on SOC stocks observed between 2012 and 2018 (Fig. 2.1e). This finding suggests that rather than CCs, the intensification from a WF to WSF cropping system had the greatest contribution to the long-term maintenance of SOC at this semi-arid study site. 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 in dryland systems where producers are concerned about yield depressions following CCs in dry years.

Yield limiting compaction is a major concern for crop producers especially in long-term NT systems. Results from this study agreed with our hypothesis that CCs would reduce bulk density and increase porosity compared to fallow. This agrees with results reported by Blanco-Canqui et al. (2011) in south central Kansas and Villamil, Bollero, Darmody, Simmons, and Bullock (2006) in east central Illinois. 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, likely due to the greater biomass and root production of triticale relative to broadleaf species in semi-arid drylands (Holman et al., 2018). Differences 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 in 2019. Alternate wet-dry and freeze-thaw cycles are typical of the GP region and has been previously cited as a possible cause of diminishing effects of management on near-surface soil compaction (Baumhardt, Schwartz, MacDonald, and Tolk, 2011; Baumhardt, Johnson, Schwartz, and Brauer, 2017).

Many have reported either increased IR, SI, 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 IR, SI, and TTR compared to fallow. However, they were similar to those reported by Blanco-Canqui and Jasa (2019) in eastern Nebraska where no significant difference was observed with grass or legume CCs in a long-term NT system. Six years earlier, 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. Due to the significant water use of fall-planted winter CCs compared to spring CCs (Holman et al., 2018) and the short time period available for fall growth following grain sorghum harvest, winter CCs were dropped. In the present study, spring CCs increased IR and SI compared to peas. Results suggest that CCs may not significantly alter soil hydraulic properties in similar long-term NT cropping systems. Further, peas grown in place of fallow in this semi-arid environment contributed little surface residue and were detrimental to long-term soil hydraulic properties.

Reports of soil pH alteration with CCs are infrequent with pH either being reduced (Lewis et al., 2018; Dozier, Behnke, Davis, Nafziger, and Villamil, 2017) or more frequently unaffected (Blanco-Canqui et al., 2015). In west Texas, Lewis et al. (2018) reported decreased pH with long-term CCs in a continuous cotton 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, 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 (Table 2.5).

Cover crops in intensively managed cropping systems may influence soil nutrients by fixing atmospheric N, scavenging nutrients, as well as reducing nutrient lose due to leaching and erosion (Blanco-Canqui et al., 2015; Blanco-Canqui, 2018; Thapa, Mirsky, and Tully, 2018). Many have reported reductions in soil NO_3-N with CCs and concerns of asynchronous N mineralization from CC residues and peak N demand of subsequent crops (DeLaune et al., 2019; Lewis et al., 2018; R. Ghimire, B. Ghimire, Mesbah, Sainju, and Idowu, 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; Miller, Glunk, Holmes, and Engel., 2018; Burgess, Miller, Jones, and Bekkerman, 2014). 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 CGP (Colazo and Buschiazzo, 2010; Fultz, Moore-Kucera, Zobeck, Acosta-Martínez, and Allen, 2013). In the present study, CCs increased MWDDA and decreased WEF compared to fallow. This is significant because in this 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 (Hansen et al., 2012; Baumhardt et al., 2015). 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 most pronounced between CCs, especially triticale, and peas. Both were similar to fallow. These results suggest that CCs, especially productive grasses, may improve soil physical properties, but broadleaf monoculture crops are unlikely to provide benefits compared to grasses in this semi-arid environment 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 properties in contrast to the seemingly transient effect observed by Blanco-Canqui et al. (2013).

Most interestingly, management of CCs for annual forage 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.

Conclusions

After 12 years of growing CCs in place of fallow in the semi-arid central Great Plains, soil physical properties were enhanced with greater soil aggregation both when CCs were hayed for annual forage and when left standing. The SOC stocks in 2018 with CCs were not different compared to fallow though SOC was greater compared to 2012 mostly due to the significant residue contribution from grain sorghum in the rotation. Cover crop residue input contributed significantly to SOC stocks from 2008 to 2012 during a period of relatively greater spring precipitation that favored CC production in the first six-years of this study. Notwithstanding, findings suggest SOC gains could be sustained even during sustained 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 without long-term detrimental effects to soil health. Peas were poor yielding and often failed to produce grain. The low productivity of peas in 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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Figures

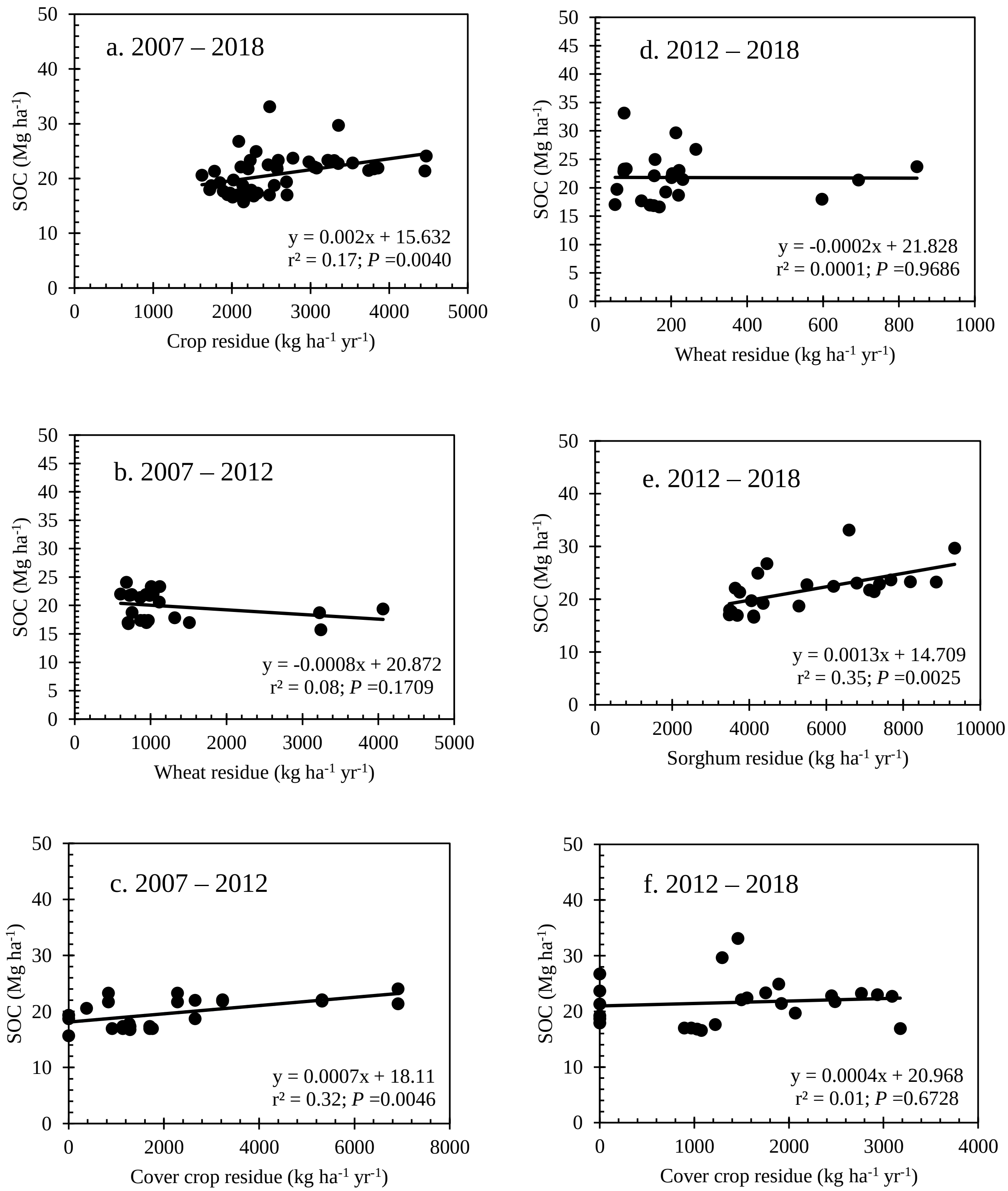

Figure 2.1. Influence of annual crop residue inputs from 2008 to 2018, 2008 to 2012, and 2012 to 2018 on soil organic carbon (SOC) stocks in the 0- to 15-cm soil depth in 2012 and 2018 at Garden City, KS.

Tables

Table 2.1. Monthly precipitation from 2007 to 2019 near Garden City, KS.

	Precipitation													
	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	30-yr avg.†
Month	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 2.2. Cover crop management effect on soil organic carbon stocks in the 0- to 15-cm soil depth in fall 2007, spring 2012, fall 2018, and summer 2019 near Garden City, KS.

		Year			
		2007	2012	2018	2019
		Soil organic carbon			
Treatment	Management	Mg ha^{-1}			
Fallow		18.00 abB†	17.93 cB	20.98 aA	19.53 abA
Pea	Grain	19.74 aA	18.46 bcA	21.56 aA	20.61 abA
Triticale	Standing	18.63 abA	20.95 aA	20.99 aA	19.88 abA
	Hayed	18.71 abA	19.15 abcA	20.50 aA	20.65 abA
Oat/Triticale/Pea	Standing	16.63 bC	20.92 abA	21.93 aA	19.02 bB
	Hayed	16.50 bC	20.21 abcAB	20.89 aA	19.17 bB
Cocktail	Standing	17.36 abB	20.92 abAB	22.98 aA	19.83 abAB
	Hayed	16.55 bB	20.21 abcAB	24.48 aA	21.40 aAB
Contrasts					
$P > F$					
Fallow vs. standing CCs		0.5870	0.0065	0.6591	0.9559
Fallow vs. hayed CCs		0.3861	0.0597	0.6627	0.3002
Pea vs. standing CCs		0.1000	0.0201	0.8539	0.2231
Pea vs. hayed CCs		0.0543	0.1619	0.8578	0.8057
Standing CCs vs. hayed CCs		0.6394	0.1273	0.9944	0.1693

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

			Bulk density	Porosity
Year	Treatment	Management	g cm^{-3}	%
2018	Fallow		1.48a[†]	44.0b
	Pea	Grain	1.39b	47.5a
	Triticale	Standing	1.39b	47.3a
		Hayed	1.40b	47.2a
	Oat/Triticale/Pea	Standing	1.44ab	45.8ab
		Hayed	1.44ab	45.7ab
	Cocktail	Standing	1.41b	46.7a
		Hayed	1.42ab	46.2ab
	Contrasts			
	P > F			
	Fallow vs. standing CCs		0.0199	0.0148
	Fallow vs. hayed CCs		0.0382	0.0283
	Pea vs. standing CCs		0.4343	0.3904
	Pea vs. hayed CCs		0.2897	0.2612
	Standing CCs vs. hayed CCs		0.6906	0.7031
2019	Fallow		1.39a	47.9a
	Pea	Grain	1.39a	47.7a
	Triticale	Standing	1.40a	47.4a
		Hayed	1.41a	46.9a
	Oat/Triticale/Pea	Standing	1.36a	48.9a
		Hayed	1.38a	47.8a
	Cocktail	Standing	1.40a	47.1a
		Hayed	1.40a	47.4a
	Contrasts			
	P > F			
	Fallow vs. standing CCs		0.9857	0.9265
	Fallow vs. hayed CCs		0.6674	0.5497
	Pea vs. standing CCs		0.9429	0.9632
	Pea vs. hayed CCs		0.7069	0.6452
	Standing CCs vs. hayed CCs		0.5272	0.4744

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

Table 2.4. Cover crop management effect on water infiltration rate (IR), saturated infiltrability (SI) and time-to-runoff (TTR) in Summer 2019 near Garden City, KS.

		IR	SI	TTR
Treatment	Management	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 > F				
Fallow vs. standing CCs		0.1705	0.1574	0.6351
Fallow vs. hayed CCs		0.0722	0.0624	0.7903
Pea vs. standing CCs		<0.0001	<0.0001	0.1389
Pea vs. hayed CCs		0.0009	0.0009	0.4961
Standing CCs vs. hayed CCs		0.4949	0.4730	0.2668

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

Table 2.5. Effect of cover crop management on soil pH in the 0- to 15-cm soil depth in fall 2007, spring 2012, fall 2018, and summer 2019 near Garden City, KS.

		Year			
		2007	2012	2018	2019
Treatment	Management	pH			
Fallow		7.40 aA†	7.30 aA	7.29 abA	7.47 aA
Pea	Grain	7.83 aA	7.50 aB	7.11 abC	7.50 aB
Triticale	Standing	7.37 aA	7.13 aA	7.08 abA	7.45 aA
	Hayed	7.37 aA	7.47 aA	7.18 abA	7.50 aA
Oat/Triticale/Pea	Standing	7.93 aA	7.43 aAB	6.98 abB	7.46 aAB
	Hayed	7.93 aA	7.37 aA	7.24 abA	7.43 aA
Cocktail	Standing	7.93 aA	7.43 aAB	6.92 bC	7.26 aB
	Hayed	7.93 aA	7.37 aA	7.36 aA	7.50 aA
Contrasts					
P > F					
Fallow vs. standing CCs		0.3483	0.9009	0.0874	0.4710
Fallow vs. hayed CCs		0.3483	0.7094	0.8400	0.8880
Pea vs. standing CCs		0.8059	0.5364	0.4793	0.3540
Pea vs. hayed CCs		0.8059	0.7094	0.3807	0.7251
Standing CCs vs. hayed CCs		1.0000	0.7253	0.0368	0.4122

†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 2.6. 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.

		Year			
		2018		2019	
		NO_3-N	NH_4-N	NO_3-N	NH_4-N
Treatment	Management	kg ha^{-1}			
Fallow		33.83a[†]	3.94b	12.18c	0.16a
Pea	Grain	44.57a	5.57ab	14.70abc	1.90a
Triticale	Standing	33.48a	4.67ab	13.51abc	1.14a
	Hayed	35.94a	4.67ab	12.99bc	3.12a
Oat/Triticale/Pea	Standing	45.59a	5.45ab	13.82abc	1.71a
	Hayed	37.36a	6.11a	16.09abc	1.27a
Cocktail	Standing	49.53a	4.98ab	16.74a	3.39a
	Hayed	42.33a	4.52ab	15.02abc	1.45a
Contrasts					
P > F					
Fallow vs. standing CCs		0.2624	0.1545	0.0915	0.2076
Fallow vs. hayed CCs		0.5521	0.1325	0.0905	0.2395
Pea vs. standing CCs		0.8295	0.4709	0.9940	0.9028
Pea vs. hayed CCs		0.4495	0.5269	0.9986	0.9733
Standing CCs vs. hayed CCs		0.4427	0.8981	0.9935	0.9002

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

Table 2.7. Impact of cover crop management 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.

		Year			
		2018	2019		
		MWDWSA	MWDWSA	MWDDA	WEF
Treatment	Management	——	mm	——	%
Fallow		0.84ab†	2.09ab	2.75d	50.79a
Pea	Grain	0.77b	1.78b	3.81abc	43.03bc
Triticale	Standing	1.21a	2.57a	3.95a	42.56c
	Hayed	1.13ab	2.11ab	3.28c	47.87ab
Oat/Triticale/Pea	Standing	1.08ab	2.43ab	3.29c	46.72abc
	Hayed	1.03ab	2.12ab	3.88ab	43.17bc
Cocktail	Standing	1.04ab	1.82ab	3.42bc	46.67abc
	Hayed	1.04ab	1.89ab	3.69abc	42.01c
Contrasts					
P > F					
Fallow vs. standing CCs		0.1022	0.5441	0.0004	0.0083
Fallow vs. hayed CCs		0.1741	0.8825	0.0001	0.0020
Pea vs. standing CCs		0.0393	0.1129	0.2445	0.2604
Pea vs. hayed CCs		0.0728	0.3975	0.3828	0.5145
Standing CCs vs. hayed CCs		0.6845	0.2879	0.6780	0.5005

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

Table 2.8. 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.

Year	Treatment	Management	2- to 8-mm	0.25- to 2-mm	<0.25-mm
			%		
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 > F				
	Fallow vs. standing CCs		0.0708	0.0149	0.6459
	Fallow vs. hayed CCs		0.0752	0.0442	0.9941
	Pea vs. standing CCs		0.0277	0.0582	0.4790
	Pea vs. hayed CCs		0.0296	0.1458	0.2431
	Standing CCs vs. hayed CCs		0.9667	0.5116	0.5097
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 > F				
	Fallow vs. standing CCs		0.4100	0.1243	0.3738
	Fallow vs. hayed CCs		0.8839	0.4203	0.4538
	Pea vs. standing CCs		0.0642	0.0161	0.5650
	Pea vs. hayed CCs		0.2331	0.0883	0.6641
	Standing CCs vs. hayed CCs		0.3379	0.2939	0.8412

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

Table 2.9. Effect of cover crop management on the size distribution (%) of dry aggregates in the 0- to 5-cm soil depth in summer 2019 near Garden City, KS.

Treatment	Management	6.3- to 19-mm	2- to 6.3-mm	0.84- to 2-mm	0.42- to 0.84-mm	<0.42.mm
		%				
Fallow		12.78c[†]	15.63d	20.80a	19.16a	31.63a
Pea	Grain	21.00a	17.82abc	18.15bc	15.42bcd	27.60b
Triticale	Standing	22.07a	18.77ab	16.59cd	14.01cd	28.55ab
	Hayed	16.88bc	17.52bcd	17.72bcd	15.88bc	31.99a
Oat/Triticale/Pea	Standing	16.87bc	16.94bcd	19.47ab	17.48ab	29.25ab
	Hayed	21.23a	19.60a	16.00d	13.60d	29.56ab
Cocktail	Standing	18.11ab	16.72cd	18.50bc	17.42ab	29.25ab
	Hayed	19.66ab	18.56abc	19.77ab	16.14ab	25.87b
Contrasts						
P > F						
Fallow vs. standing CCs		0.0004	0.0237	0.0034	0.0023	0.0966
Fallow vs. hayed CCs		0.0002	0.0004	0.0009	<0.001	0.1131
Pea vs. standing CCs		0.2433	0.6724	0.9673	0.3379	0.3654
Pea vs. hayed CCs		0.3053	0.3556	0.7104	0.8151	0.3253
Standing CCs vs. hayed CCs		0.8396	0.0590	0.5601	0.0938	0.9110

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

Chapter 3 - Dual-purpose cover crops in the semi-arid central Great Plains: Forage productivity, nutritive value, and effects on soil properties

Abstract

Intensification of dryland cropping systems with cover crops (CCs) in the semi-arid central Great Plains could enhance soil health and diversify production when used for forage. This study was conducted to determine forage accumulation and nutritive value of CCs and effects of dual-purpose CCs on soil properties in a no-till (NT) winter wheat (*Triticum aestivum* L.)–grain sorghum (*Sorghum bicolor* Moench)–fallow (WSF) cropping system. Oat (*Avena sativa* L.)/triticale (×*Triticosecale* Wittm.) CCs were grown in place of fallow and hayed to a height of 15 cm, grazed by yearling heifers, or left standing. All phases of the WSF rotation were present every year. Forage accumulation varied across years and averaged 3546 kg ha^{-1} for standing CCs. Hayed and grazed CCs removed 73 and 26% of available forage. Greater forage nutritive value was observed with grazed CCs because of earlier forage harvest compared to hayed CCs. Bulk density was not different with haying or grazing compared to standing CCs after two cycles of CCs in the WSF rotation. In 2019, soil organic carbon (SOC) stocks were similar among CC treatments (27.31 Mg ha^{-1}). Stocks with standing and hayed CCs were greater than fallow (24.79 Mg ha^{-1}) which was similar to grazed CCs. However, in 2020, SOC was less with hayed CCs (21.80 Mg ha^{-1}) compared to the grazed or standing treatments (24.27 Mg ha^{-1}) and all were similar to fallow. Mean weight diameter of water stable aggregates was greater with standing and grazed CCs (2.89 mm) compared to fallow (1.67 mm) in both years and was greater with hayed CCs in one year. Findings suggest that CCs can replace fallow to produce high-

quality forage while improving soil health. However, residue management is critical when CC productivity is low such that grazing CCs is more desirable than haying to improve soil properties.

Introduction

Due to water limitations, wheat (*Triticum aestivum* L.)-fallow (WF) has been the historically dominant dryland cropping system throughout the semi-arid Great Plains where one wheat crop was grown every other year followed by a full year of fallow between crops (Nielsen and Vigil, 2005; Peterson et al., 1998). This practice of fallowing has been shown to stabilize grain crop yields and mitigate, though not necessarily prevent, crop failure during extended periods of drought (Nielsen and Vigil, 2010; Aiken, O'Brien, Olson, and Murray, 2013). However, with the wide adoption of no-till (NT), more intensive crop rotations developed throughout the region including the complete replacement of fallow in the WF system with pulse, oilseed, and cover crops (CCs) in the northern Great Plains (NGP) (Engel, Miller, McConkey, and Wallander, 2017; Miller, Glunk, Holmes, and Engel, 2018; Miller et al., 2015). Similarly, reduced fallow frequency with wheat-summer crop [corn (*Zea mays* L.), grain sorghum (*Sorghum bicolor* Moench), proso millet (*Panicum milliaceum* L.) or sunflower (*Helianthus annuus* L.)]-fallow has replaced WF in the central (CGP) and southern regions (SGP) (Schlegel, Assefa, Haag, Thompson, and Stone, 2017; Nielsen and Vigil, 2018). Cover crops offer opportunities for dryland crop producers in the Great Plains to enhance soil health, produce forage for livestock, and support integrated weed management (Kumar et al., 2020; Rosenzweig, Carolan, and Schipanski, 2019; Petrosino, Dille, Holman, and Roozeboom, 2015). However, CC adoption and the general transition to continuous cropping systems has been slower in both the central and southern portions of the region largely due to increased potential evapotranspiration rates that lead to much greater risk associated with intensified production relative to the north (Hansen, Allen, Baumhardt, and Lyon, 2012; Robinson and Nielsen, 2015).

Potential benefits of CCs for soil health in agricultural systems include greater soil organic carbon (SOC) sequestration, reduced wind and water erosion, increased microbial activity and abundance, enhanced nutrient cycling, as well as alleviation of soil compaction (Blanco-Canqui et al., 2015; Calderón, Nielsen, Acosta-Martínez, Vigil, and Lyon, 2016; Ghimire et al., 2018). Utilizing CCs as a forage resource for grazing and/or haying may provide an opportunity for dryland producers to balance the long-term sustainability and short-term profitability of their operations, especially when the water use of CCs limits subsequent grain yields in drier years (Holman et al., 2018; Kumar et al., 2020; Sanderson, Johnson, and Hendrickson, 2018). Such systems may meet many of the core principles outlined in the movements for soil health (USDA-NRCS, 2013), and more recently, regenerative agriculture (Cano et al., 2018, Rosenzweig et al., 2019) including i) minimized soil disturbance, ii) maximized soil coverage and iii) living plant roots, as well as iv) livestock integration. These practices are useful in mitigating wind and water erosion which is of critical importance in semi-arid dryland crop production where residue levels may be low during fallow periods, leaving the soil exposed to the high winds and short duration, intense, rainfall events that are typical of the region (Baumhardt, Stewart, and Sainju, 2015; Hansen et al., 2012).

Previous research demonstrated improved soil health with CCs in regions that receive relatively greater annual precipitation than is common for the semi-arid CGP (Blanco-Canqui et al., 2015), and, in southwest Kansas, replacing fallow with CCs in a WF system increased SOC content, reduced wind-erodible fraction, and increased water stable aggregates (WSA) (Blanco-Canqui, Holman, Schlegel, Tatarko, and Shaver, 2013). These results suggest that although rainfall is limited and evaporative demand is high in this semi-arid region, CCs may provide similar benefits to soil health as those observed in more humid environments. Although many proponents of CC adoption have asserted the superiority of hyper-diverse multi-species CCs to optimize soil health, weed suppression, and water use efficiency, there is little data to support such recommendations (Chapagain, Lee, and Raizada, 2020; Florence, Higley, Drijber, Francis, and Lindquist, 2019; Florence and McGuire, 2020) especially in semi-arid drylands (Nielsen et al., 2015a; 2015b). Rather, CC species must be selected based on specific goals and the inherent properties of given species such as greater biomass productivity and persistence of residue (Baraibar, Hunter, Schipanski, Hamilton, and Mortensen, 2017; MacLaren, Swanepoel, Bennett, Wright, and Dehnen-Schmutz, 2019; Osipitan, Dille, Assefa, and Knezevic, 2018).

Most plant species utilized as CCs have excellent forage nutritive value attributes in terms of crude protein (CP), digestibility, and dry matter (DM) production (Jenkins, Creech, Hergert, and Berger, 2019; Nielsen, Lyon, and Miceli-Garcia, 2017; Obour and Holman, 2016). However, CCs used for forage should be closely managed with an ultimate goal of leaving >30% residue, or about 1120 kg ha^{-1}, to meet soil health objectives (Kelly et al., 2021). Time of grazing initiation, duration, as well as stocking density are key considerations to prevent soil degradation when CCs are used for forage (Blanco-Canqui et al., 2016; Rakkar et al., 2018). Due to significant regrowth potential, especially of grass species, hayed or grazed CCs may be allowed to regrow to provide substantial residue cover relative to fallow. With this in mind, opportunity certainly exists for the dual-purpose use of CCs in dryland cropping systems to provide forage as well as residue cover to reduce erosion and build soil health (Blanco-Canqui et al., 2013; Holman et al., 2018; Holman, Obour, and Assefa, 2020). Such cropping systems take advantage of available soil moisture, extend the grazing season, and delay grazing of native perennial grasslands (Sanderson et al., 2018; Titlow, Luebbe, Lyon, Klopfenstein, and Jenkins, 2014).

Still, concerns remain that forage utilization of CCs and any subsequent reduction in surface residue might negate the beneficial effects of using CCs for soil health by limiting potential SOC gains and possibly increasing soil compaction and degrading structure when cattle graze CCs, especially in NT cropping systems (Bergtold, Ramsey, Maddy, and Williams, 2017; Li, Allen, Hou, Chen, and Brown, 2013). Previous studies have reported on the influence of crop residue grazing and haying on soil properties (Baumhardt, Johnson, Schwartz, and Brauer, 2017; Blanco-Canqui et al., 2016; Rakkar et al., 2018). However, at this time, there is limited information regarding the influence of CC grazing and haying (Blanco-Canqui et al., 2013; Blanco-Canqui et al., 2020; Franzluebbers and Stuedemann, 2008a; 2008b). In southwest Kansas, Blanco-Canqui et al. (2013) reported no difference in SOC concentration, bulk density, or aggregation when CCs were hayed for annual forage, leaving 15 cm of stubble, compared to when CCs were left standing. These results suggest that harvesting CCs for forage, being careful to retain adequate residue, may be implemented without limiting potential benefits to soil health. Further, it is plausible that potential near-surface soil compaction due to CC grazing could be eliminated with the alternate wet-dry and freeze-thaw events that occur annually in the CGP (Baumhardt, Schwartz, MacDonald, and Tolk, 2011; Baumhardt et al., 2017; Entz et al, 2002).

The objectives of this study were to i) determine the forage productivity and nutritive value of CCs as well as to ii) evaluate the effect of dual-purpose CCs, managed for annual forage, on soil health in a NT dryland cropping system. Our hypothesis was that CCs would have excellent forage productivity (>3000 kg ha^{-1}) with greater nutritive value for the grazed CCs relative to when CCs were hayed due to differences in the time of forage harvest. Further, it was hypothesized that soil properties with hayed or grazed CCs would be similar to when CCs were left standing, and CCs would improve soil properties compared to fallow.

Materials and Methods

This study was established in 2015 at the Kansas State University HB Ranch near Brownell, KS (38°38′23″ N, 99°44′45″ W) to investigate CC management in place of fallow in a NT winter wheat-grain sorghum-fallow (WSF) crop rotation. The soil at the study site was mapped as a Harney silt loam (Fine, smectitic, mesic Typic Argiustolls) formed from loess material at an elevation of 736 meters above sea level. Long-term average (30 yr. avg.) annual precipitation at the study site was 566 mm. The study design was a split-plot randomized complete block with four replications. Crop phase was the main plot and split-plots were oat (*Avena sativa* L.)/triticale (×*Triticosecale* Wittm.) CCs grown during the fallow phase of the WSF rotation. Oats and triticale were selected based on their past performance in the region, producing substantial biomass consistently (Holman et al., 2018; Holman, Schlegel, Obour, and Assefa, 2020; Obour, Holman, and Schlegel, 2019; 2020). Cover crops were managed as standing cover, hayed to a height of 15 cm, or grazed with yearling heifers and were compared with chemically-controlled NT fallow for a total of 4 treatments. Split-plots were 18.3 m wide and 30.5 m long. All crop phases of this WSF rotation were present at this site every year of the study.

Crop management

At this site, winter wheat was planted each year in early October and harvested the following year in early July. After an eleven-month fallow period, grain sorghum was planted in June and harvested in November. A detailed description of cover crop management is provided in Table 3.1. Generally, cover crops were planted by a target date of mid-March as field conditions allowed at a seeding rate of 36 and 43 kg ha^{-1} for oats and triticale, respectively. Cover crops were hayed, grazed, and chemically terminated by mid-June in an effort to minimize negative effects on subsequent winter wheat yields (Schlegel and Havlin, 1997; Holman et al., 2018) though this varied across years as field conditions allowed. Mechanical forage harvest and subsequent chemical termination of CCs generally coincided with oat/triticale heading corresponding to Zadoks growth stages 51 to 59 (Zadoks, Chang, and Konzak, 1974). This was selected as a harvest stage to optimize forge accumulation and nutritive value (Landry, Janovicek, Lee, and Deen, 2018). Hayed CCs were harvested at a 15-cm cutting height using a small plot forage harvester (Carter Manufacturing Company, Brookston, IN). Additionally, grazed CCs were stocked with yearling heifers (*Bos taurus* L.) at densities averaging 1463 kg liveweight (LW) ha^{-1} for four to seven days (Table 3.1) to utilize approximately 30 to 40% of the available forage in fenced paddocks across the four replications of this study. This approach required stocking densities be adjusted and grazing be delayed relative to what can be obtained by producers in the region (30 grazing days at 608 kg LW ha^{-1}; Kelly et al., 2021) to balance forage accumulation and removal on the 2.2 ha available for grazing in the study area. The 30 to 40% forage utilization was selected to leave adequate CC residue to meet soil health goals. In practice, producers could grazed a little more (~50 to 60%) with anticipation of CC regrowth to provide enough residue by CC termination.

Forage dry matter and nutritive value assessment

Prior to grazing, available forage mass was determined for the grazing treatment by hand-clipping, to the ground level, two areas of 0.50 m^2 per plot (Table 3.1). Fresh sample weights were recorded and dried at approximately 50°C for a minimum of 48 hours in a forced-air oven for DM determination. Following grazing, this treatment was resampled as previously described, and standing CC treatments were sampled similarly prior to chemical termination. For the hayed treatment, samples were harvested with a small plot forage harvester from a strip of 0.9 m × 30.5

m in the middle of each plot. Whole plot weights were recorded, subsamples collected and weighed, and then oven-dried to determined DM yield. Whole plots were harvested following the cutting of a sample strip. Pre-grazing and hayed CC DM samples were ground to pass through a 1-mm screen using a Wiley Mill (Thomas Scientific, Swedesboro, NJ) and subsamples were sent to a commercial lab (Ward Laboratories, Inc., Kearney, NE) to determine nutritive value of the grazed and hayed CC treatments. Ground samples were analyzed for forage nutritive value parameters including CP, acid detergent fiber (ADF), neutral detergent fiber (NDF), total digestible nutrients (TDN), and in-vitro dry matter digestibility (IVDMD) using a Foss 6500 near infrared spectroscopy system (Foss Analytical Systems, Hillerød, Denmark). Greater values for CP, TDN, and IVDMD indicate greater available energy and digestibility of the forage, and lower values for ADF and NDF indicate greater dry matter intake and digestibility (Horrocks and Vallentine, 1999).

Soil sampling, analysis, residue assessment

Soil samples were collected at the initiation of this study in 2015 and again in the fall of 2019 and 2020 following the termination of CCs but before subsequent winter wheat planting. Sampling in each year took place in different whole plots that represented the same phase of the crop rotation to determine the effect on soil properties as influenced by previous crop history. Plots where CCs were produced in 2016 and 2019 were sampled for soil properties in fall 2019, and plots where CCs were produced in 2017 and 2020 were sampled in fall 2020. Samples were used for the determination of soil chemical and physical properties. Ten soil cores (2.5-cm diameter) were randomly taken from the 0- to 15-cm depths for determination of bulk density and porosity as well as SOC stocks. Briefly, samples were dried at 105°C for 48-hr, and bulk density was determined as mass of oven-dry soil divided by volume of the core. Soil porosity was determined using a constant particle density of 2.65 g cm^{-3}. Subsamples were air-dried and ground to pass through a 2-mm sieve and used for determining SOC. A portion of each sample was ground with a mortar and pestle to pass through a 0.25-mm sieve, and SOC concentrations were determined by dry combustion using a CN analyzer after pretreating samples with 10% (v/v) HCl to removed carbonates (Nelson and Sommers, 1996). Carbon mass was calculated by multiplying SOC concentrations by soil bulk density and the thickness of the soil layer.

Additional samples were collected from the 0- to 5-cm soil depth with a flat shovel for the determination of WSA. Partially air-dried samples were gently passed between sieves with 8.0- to 4.75-mm mesh and then allowed to fully air-dry. Two sub-samples from each plot 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 (MWD) and aggregate size distribution (ASD).

In 2020, in order to further document the forage harvesting effect on the cropping system, soil surface residue cover was determined by the line-transect method (USDA-NRCS, 2002). A 3.05-m long rod with marks at every 0.305 m interval was randomly placed at four separate points diagonally across crop rows, and marks directly above crop residue were counted. The percentage of residue cover was calculated by dividing the total number of residue cover points by 10 and multiplying by 100. The four sub-measurements were averaged to obtain one value for each plot.

Statistical analysis

Analysis of CC forage accumulation and nutritive value as well as soil physical and chemical properties was performed using PROC GLIMMIX in SAS ver. 9.3 (SAS Institute, 2012, Cary, NC). Treatment and year were considered fixed, and replication was considered random for the analysis of CC effects. The LSMEANS procedure was used for mean comparisons, and treatment effects were considered significant at $P \leq 0.05$. Linear regression analyses were performed using PROC REG in SAS to characterize the relationship between cover crop residue inputs in each cropping system and accrued SOC stocks, bulk density, and water stable aggregates observed in 2019 and in 2020. For residue inputs, standing CC and post-grazing CC biomass were used directly to estimate residue amounts for the standing and grazed CC treatments. However, for the hayed treatment, residue retained was estimated by multiplying the standing CC biomass within each replication in each year by the average residue retention ratio with haying (one minus the hayed CC yield divided by the standing CC biomass) for that year.

Results

Precipitation and temperature

Annual precipitation was greater than the 30-year average in three of six years studied and near or below average in the other three (Table 3.2). Rainfall was 12, 37, and 39% above average in 2016, 2018, and 2019, respectively. However, rainfall was near average in 2017 and was 21 and 7% below average in 2015 and 2020, respectively. Very high precipitation in 2019 was mostly due to an extremely wet August when >300 mm was received in a single month. Annual temperatures were near the 30-year average for the entire study period (Table 3.2). Still, as is typical of the semi-arid climate, monthly precipitation and temperature varied substantially across years.

Forage accumulation and forage quality

Standing and hayed CC forage accumulation varied substantially over the six-year study period, averaging 3546 and 2577 kg ha^{-1}, respectively (Table 3.3). This indicates that approximately 70% of the available forage was removed with the hayed treatment compared to the standing CC biomass. Average forage mass at the end of grazing was 2086 kg ha^{-1} and was 74 and 59% of the pre-grazing available forage mass (2838 kg ha^{-1}) and the standing CC, respectively. Interestingly, in 2019, forage mass at the end of grazing (2214 kg ha^{-1}) was greater than at the start (1806 kg ha^{-1}). Forage accumulation was greatest in 2015, 2017, and 2018, and somewhat lower yields were observed in 2016. The lowest yields occurred in 2019 and 2020. Low yields in 2019 were mostly due to excessively cool and wet conditions (Table 3.2) in the spring that delayed CC planting (Table 3.1). In 2020, although CCs were planted on time, abnormally dry conditions that extended into the month of June limited CC growth early in the growing season.

Cover crop CP, TDN, and IVDMD, were greatest in 2015 and lower in all subsequent years (Table 3.4). Hayed and grazed CCs averaged 10.5 and 12.6% CP, 58.7 and 63.6% TDN, as well as 71.7 and 76.8% IVDMD. Grazed CCs had greater CP than the hayed treatment in three of the six years of this study: 2015, 2017, and 2020. In the other three years, CP concentrations were similar for these two annual forage treatments. Although, on average, both hayed and grazed CCs had CP concentrations >10%, this was not observed every year of the study, and in 2016, 2019, and 2020, hayed CCs had CP concentrations <10%. Similarly, grazed CCs had CP concentrations <10% in 2016 and 2018. In four of the six years, TDN and IVDMD were greater for grazed CCs than the hayed treatment and were not different in the other two years. Grazed CCs averaged >60% TDN and were <60% in only one of the six years of this study. However, hayed CCs averaged <60% and were >60% in three of the six years: 2015, 2017, and 2018. Both hayed and grazed CCs averaged >70% IVDMD with grazed CCs having <70% in only two of the six years. Hayed CCs had <70% IVDMD in four of the six years with a low of 66.9% in 2016.

Acid and neutral detergent fiber were generally greater with hayed CCs compared to the grazed treatment (Table 3.4). Hayed and grazed CCs averaged 38.4 and 34.1% ADF as well as 62.9 and 56.8% NDF, respectively. Hayed CCs had greater ADF concentrations in 2015, 2017, 2019 and 2020 and were not different from the grazed treatment in the remaining two years. Similarly, NDF was greatest for the hayed treatment in all years except for 2016 when the two annual forage treatments were not different. Acid detergent fiber concentrations were <35% for the grazed treatment in four of the six years of this study, and NDF was <60% in all years except for 2016. Still, the hayed treatment was observed to have >35% ADF in all six years of the study and >60% NDF in most years except for 2015.

Soil organic carbon stocks and residue cover

The SOC stocks measured in the 0- to 15-cm soil depth in 2019 with standing and hayed CCs (mean of 27.54 Mg ha^{-1}) were greater compared to fallow (24.79 Mg ha^{-1}), and grazed CCs (26.87 Mg ha^{-1}) were similar to all other treatments (Table 3.5). No significant differences between fallow and the CC treatments were observed in 2020. However, SOC was significantly less with hayed CCs (21.80 Mg ha^{-1}) compared to the standing or grazed treatments (mean value of 24.27 Mg ha^{-1}). In 2019, a net increase in SOC since study initiation in 2015 was observed for all treatments with greatest increases for the standing and hayed CCs (mean of 3.91 Mg ha^{-1}). Similarly, SOC increases were observed for the standing and grazed CCs again in 2020 (mean of 1.34 Mg ha^{-1}) though they were less compared to 2019. However, in 2020, there was a net decrease in SOC stocks with hayed CCs (-1.13 Mg ha^{-1}) and only a marginal change in the fallow treatment (0.29 Mg ha^{-1}) compared to initial levels in 2015. Measured in August 2020, soil surface residue cover was greater with all CC treatments (mean of 87%) compared to the fallow (66%) (Fig. 3.1). Residue cover was similar for all CC management scenarios and was 91% with the standing, 84% with the hayed, and 86% with the grazed treatments. Results from regression analysis between CC residue inputs and accrued soil organic carbon stocks were not significant (Fig. 3.2a).

Bulk density and porosity

Significantly greater bulk density and lower porosity in the 0- to 15-cm soil depth were observed with standing CCs (means of 1.29 g cm^{-3} and 51.3%) compared to fallow (means of 1.21 g cm^{-3} and 54.4%) in both 2019 and 2020 (Table 3.6). This was a significant, though not substantial, difference between these two treatments. Interestingly, bulk density and porosity with hayed CCs (means of 1.27 g cm^{-3} and 52.2%) were similar to all other treatments in both years. The grazed treatment was similar to all other treatments in 2019 (1.22 gcm^{-3} and 54.0%) and were similar to standing CCs but different from fallow in 2020 (1.32 g cm^{-3} and 50.2%). Across treatments and years, average bulk density was 1.26 g cm^{-3} and porosity was 52.5% in the 0- to 15-cm soil depth. Results from regression analysis between CC residue inputs and bulk density in 2019 and 2020 were not significant (Fig. 3.2b).

Water stable aggregates

In 2019, MWD was greater with all CC treatments (mean value of 2.68 mm) compared to the fallow treatment (1.35 mm) (Fig. 3.3a). Mean weight diameter was similar among CC management strategies and was 2.53 mm with the standing, 2.66 mm with the hayed, and 2.84 mm with the grazed treatments. This increase in WSA with CCs was further observed in the ASD (Fig. 3.4a) with all CC management scenarios having a greater proportion of aggregates (mean of 48.9%) in the 8- to 2-mm size fraction compared to fallow (19.3%). Differences among CC treatments were observed only once in the 2- to 0.25-mm size fraction where standing CCs had a significantly greater proportion of aggregates (34.0%) compared to the grazed treatment (22.6%). Both standing and grazed CCs were similar to the hayed treatment. No differences among treatments were observed for the <0.25-mm size fraction.

Similar to 2019, MWD measured in 2020 was greater for the standing (2.99 mm) and grazed CCs (3.18 mm) compared to fallow (1.98 mm) (Fig. 3.3b). However, MWD with hayed CCs (2.57 mm) was not significantly different from the fallow treatment. No significant differences in the ASD were observed among standing, hayed, and grazed CCs in 2020 though there was a trend of hayed CCs having a somewhat lower proportion of 8- to 2-mm sized aggregates (47.1%) compared to the standing and grazed treatments (mean of 58.2%) (Fig. 3.4b). Standing and grazed CCs had a significantly greater proportion of aggregates in the 8- to 2-mm size fraction compared to fallow (33.5%). Further, these treatments had a lower proportion of aggregates in the 2- to 0.25-mm size fraction (mean of 22.8%) compared to fallow (37.8%). Again, no differences were observed among treatments for the <0.25-mm size fraction. Results from regression analysis between CC residue inputs and MWD in 2019 and 2020 were significant ($r^2 = 0.3956$; $P = 0.001$) and positive with an intercept of 2.05 and a slope of 0.0003, suggesting that with 1000 kg CC residue input ha^{-1}, MWD increased approximately 0.3 mm (Fig. 3.2c).

Discussion

Results of forage production supported our hypothesis that CCs would have substantial production potential with forage accumulation >3000 kg ha^{-1} in this CGP environment. Forage accumulation observed in the present study was similar to that reported by others for cool-season annual forages at similar stages of maturity in the central and northern GP. In western Kansas, Obour et al. reported forage accumulation of 3266 kg ha^{-1} for oats (2019) and 5010 kg ha^{-1} for triticale (2020) harvested at heading. In southwestern North Dakota, Carr et al. (2004) reported 2910 and 3840 kg ha^{-1} DM yield for barley and oat, respectively, at mid-milk to early dough growth stages. Similarly, in central North Dakota, Sanderson et al. (2018) reported an average spring triticale DM yield of 3165 kg ha^{-1} at a less mature stage (stem elongation). In the central North Dakota study, DM yield ranged from a high of 4208 to a low of 2112 kg ha^{-1}. This variation in forage productivity was also observed in the present study. As is typical of dryland cropping systems in this semi-arid region (Nielsen and Vigil, 2010), forage accumulation varied substantially from year to year in this study mostly due to differences in temperature as well as rainfall amount and distribution (Table 3.2). Similar variation was also observed by Holman et al. (2018) in southwest Kansas where spring triticale CC forage accumulation ranged from a high of 3024 to a low of 1575 kg ha^{-1}. Holman et al. (2020b) further reported variation in spring triticale forage accumulation (ranging from 190 to 5910 kg ha^{-1}) across seven site-years in southwest Kansas.

Results of CC forage removal through cattle consumption reported from studies in northern Georgia by Franzluebbers and Stuedemann (2007) and Schomberg et al. (2014) as well as in west central Nebraska by Blanco-Canqui et al. (2020) were similar to those observed with mechanical forage harvest and were greater than was observed with the grazing strategy implemented in the present study. This is mostly due to differences in forage removal goals between the Georgia and Nebraska studies (>90% removal) and the present (30 to 40% removal). Although greater forage removal may provide greater economic return when grazing CCs, this increased biomass removal may come at the expense of soil health (Bergtold et al., 2017; Li et al., 2013). In order to balance resource utilization and soil conservation goals, lower forage removal and greater residue retention levels (at least 30% or 1120 kg ha^{-1}) are recommended. Across 10 on-farm sites in the semi-arid CGP, Kelly et al. (2021) obtained 30 grazing days with spring CCs with an average stocking density of 608.2 kg LW ha^{-1}. In this study, the authors further reported greater residue cover with both grazed and standing CCs compared to fallow with 78% for the standing CC, 72% for the grazed CC, and 64% for fallow. This was also observed in the present study with no difference in residue cover between standing and grazed CCs though both were greater than fallow. Although CC regrowth was observed in the form of greater CC biomass post-grazing versus pre-grazing in 2019, this was not the case in the other five years. Further on-farm research looking at CC grazing on producer fields will be necessary to better understand the regrowth potential of CCs in the semi-arid CGP.

Results of forage nutritive value supported our hypothesis. Forage nutritive value parameters measured pre-grazing were >10% CP, <35% ADF, <60% NDF, >60% TDN, and >70% IVDMD on average. However, this was not the case for the hayed treatment, which averaged > 35% ADF, >60% NDF, and <60% TDN but maintained >10% and >70% average CP and IVDMD, respectively. On average, grazed CCs had greater forage nutritive value compared to the hayed treatment mostly due to differences in maturity at forage harvest, and in those years when forage nutritive value was not greater with grazed CCs these annual forage treatments were similar. As was observed with DM production, forage nutritive value parameters varied significantly over the years mostly due to differences in temperature as well as rainfall amount and distribution (Table 3.2) which led to variable planting and harvest dates from year-to-year (Table 3.1). In this semi-arid environment, early planting dates gave spring-planted cool-season CCs the opportunity to both take advantage of early spring precipitation as well as to develop as much vegetative growth as possible when temperatures were relatively cooler (Kelly et al., 2021). In this study, it was observed that warmer summer temperatures stimulated rapid maturation of CCs at which point vegetative growth ceased and forage nutritive value declined as has been observed by others (Miller et al., 2018; Titlow et al., 2014).

These results for forage nutritive value were similar to those observed by others at similar stages of maturity in the semi-arid NGP region of North Dakota and Montana (Carr et al., 2004; Miller et al., 2018; Sanderson et al., 2018). In these studies, CP of oat/pea (*Pisum sativum* L.), barley/pea, and triticale annual forages were 10.1, 12.7, and 11.1%, respectively. In western Kansas, Obour et al. reported 11.4% CP with oats (2019) and 13.7% with triticale (2020). These were similar to the grazed treatment in the present study but were greater than when CCs were hayed. Additionally, in southwest Kansas, triticale, pea, and triticale/pea CCs harvested at the triticale heading stage had 15.7, 20.2, and 17.9% CP, respectively (Holman, Assefa, and Obour, 2020). These were all greater than was observed for the oat/triticale mixture in the present. Further, in western Nebraska, Titlow et al. (2014) observed an average 10.0% CP concentration with a grazed oat/pea/turnip (*Brassica rapa* L.) CC. These authors observed decreasing CP later in the growing season when oats reached grain development stages. This was most similar to the hayed treatment in the present study and lower than was observed for grazed CCs due to the later maturity of the hayed CC at the time of harvest. The authors further observed 36.6% ADF, 50.9% NDF, and 66.1% IVDMD in their CGP environment. This result of ADF was similar to the average of ADF for both the hayed and grazed CCs in the present study though their values of NDF and IVDMD were lower than was observed for either of the present forage treatments. This may be due to difference in species composition of their annual forage mixture of oat/pea/turnip compared to the present mixture of oat/triticale. Obour et al. (2019) reported 37.2% ADF, 59.9% NDF, and 77.0% IVDMD with oats in western Kansas. These authors further reported 37.1% ADF, 62.9% NDF, and 72.8% IVDMD with triticale (2020). As may be expected, these valves were similar to those reported with the oat/triticale CC mixture harvested at the same maturity in the present study. In southwest Kansas, Holman et al. (2020) reported 37.7% ADF, 61.3% NDF, and 60.5% TDN with triticale CCs harvested at heading. These were similar to those observed for the hayed CCs in the present study. These authors reported lower ADF and NDF as well as greater TDN when peas were mixed with triticale which were similar to the values reported with the grazed CCs in the present due to the earlier maturity at the time of harvest. Results of NDF were similar to those observed with oat and triticale CCs in southwest (Carr et al., 2004) and central North Dakota (Sanderson et al., 2018) though, in the southwest North Dakota study, TDN was less than those observed for either hayed or grazed CCs in the present. This difference in TDN concentration is likely due to the relative difference in maturity at the time of harvest in their study, mid-milk to early dough stages, compared the present, early to late heading.

Results of SOC stocks in the 0- to- 15-cm soil depth in 2019 partially supported our hypothesis that CC treatments would have greater SOC stocks compared to fallow. This was observed with the standing and hayed treatments though the grazed CCs were similar to fallow. However, results in 2020 did not support our hypothesis when all CC treatments were similar to fallow, and, in fact, the hayed CCs were less than the standing and grazed treatments. This was also observed with the change in SOC compared to study initiation in 2015. In 2019, all treatments had substantial increases in SOC, but this was not the case in 2020 when the hayed treatment had reduced SOC stocks. Interestingly, this was observed despite greater percent soil residue cover observed with all CC treatments relative to fallow and was probably due to greater hayed forage removal in 2020 relative to 2019. This suggests that CCs may not always increase SOC compared to fallow in similar NT dryland cropping systems and that mechanical removal of CC biomass could be detrimental to SOC stocks compared to when CCs are grazed or left standing.

Increases in SOC with CCs were observed by some (Blanco-Canqui, Mikha, Presley, and Claassen, 2011; Lewis et al., 2018; Delaune, Mubvumba, Lewis, and Keeling, 2019) though this has not been the case for all (Blanco-Canqui and Jasa, 2019; Chalise et al., 2018 R. Ghimire, B. Ghimire, Mesbah, Sainju, and Idowu, 2019). Only a few have reported on the influence of CC biomass removal on soil properties, and Blanco-Canqui et al (2013), in southwest Kansas, reported that soil properties were similar with standing and mechanically harvested CCs. These results agree with those in the present study in 2019 though not in 2020. In northern Georgia, Franzluebbers and Stuedemann (2014) observed no differences in SOC stocks when CCs were grazed compared to when CCs were left standing. Similar results were reported for soil organic matter from a CC grazing study in west central Nebraska (Blanco-Canqui et al., 2020). These results were supported by those from the present study where standing and grazed treatments were similar in both 2019 and 2020. Results from the present study and the observations of others indicate that hayed CCs may be a viable option for producers to balance profitability and soil health though this may carry some risk of SOC degradation compared to standing or grazed CCs especially in years when CC forage accumulation is relatively low. In contrast, results suggest that SOC may be accrued or maintained with grazed CCs similarly to when CCs are left standing.

Results of bulk density and porosity partially supported our hypothesis. Rather than reducing bulk density and increasing porosity, there was a trend of standing CCs having the opposite effect relative to the fallow treatment in the 0- to 15-cm soil depth. Interestingly, hayed and grazed CCs were found to be similar to both standing CCs and fallow in both years. Although bulk density was relatively greater with standing CCs, this was still below the critical bulk density of 1.60 g cm^{-3} for silt loam soils at which root growth may be restricted (Nyéki, Milics, Kovács, and Neményi, 2017). While some have reported decreased bulk density with CCs (Blanco-Canqui et al., 2011; Villamil, Bollero, Darmody, Simmons, and Bullock, 2006), this has not been the case for all (Blanco-Canqui and Jasa, 2019; Lewis et al., 2018; Nouri, Lee, Yin, Tyler, and Saxton, 2019). In southwest Kansas, Blanco-Canqui et al. (2013) reported no difference in bulk density with CCs compared to fallow in a NT dryland cropping system. The authors further reported that bulk density was not different when CCs were hayed as annual forage compared to standing CCs, which agrees with those observed in the present study where bulk density with hayed CCs was similar to the standing treatment. Results of bulk density with the grazed treatment relative to standing CCs were similar to those observed by Franzluebbers and Stuedemann (2008b) who reported no difference in bulk density after 2 and 4.5 years with cattle grazing CCs in their NT cropping system in northern Georgia. These results suggest that grazing and haying of CCs may not affect bulk density and porosity compared to when CCs are left standing.

Results of WSA mostly agreed with our hypothesis. Although, in 2019, all CC management strategies increased aggregate size compared to fallow, this was not the case in 2020 when hayed CCs were similar to fallow. Surface residue tended to increase aggregate stability in the present study (Fig. 3.2), and the greater removal of CC biomass for hay in 2020 result in a somewhat lower MWD compared to the standing and grazed treatments. In dryland systems, season-long cover is critical to protect the soil against erosion and SOC depletion. Increased MWD with CCs in NT cropping systems has been reported by others including: Blanco-Canqui et al. (2011) in Kansas, Blanco-Canqui and Jasa (2019) in Nebraska, as well as Nouri et al. (2019) in Tennessee. However, few have reported on the influence of annual forage management. Although results of hayed versus standing CCs and fallow in 2019 agreed with those of Blanco-Canqui et al. (2013), the results in 2020 did not, probably due to greater level of forage removal and loss of SOC. This suggests that soil aggregation may not always be increased with hayed CCs compared to fallow and underscores the need for careful management that maintains adequate CC residue to meet both forage production and soil conservation goals. Future research should aim to investigate to the effects of different levels of CC biomass removal on soil properties to more precisely determine sustainable rates of forage removal. Results of grazed versus standing CCs in the present study partially agreed with those of Franzluebbers and

Stuedemann (2008b) in Georgia who saw mixed results where grazed CCs were typically not different from standing CCs in a NT production system though MWD and macroaggregates (>0.25-mm) were occasionally lower. Additionally, results partially agreed with those of Blanco-Canqui et al. (2020) who observed no difference in MWD when CC were grazed compared to when they were left standing. These authors reported no difference between CCs and the no CC treatments possibly due to the inherently coarse soil texture at their study site. In the present study, differences between grazed and standing CCs were observed only in the 2- to 0.25-mm aggregate size fraction in 2019 when standing CCs had a greater proportion of aggregates in this size fraction compared to the grazed treatment. The results from this study and those of the Georgia and Nebraska studies suggest that soil aggregation when CCs are utilized for grazing may not be affected differently compared to when CCs remain standing.

Conclusions

Dual-purpose CCs grown in place of chemically-controlled NT fallow produced >3000 kg DM ha^{-1} in this semi-arid CGP environment. Forage nutritive value was greater when CCs were grazed than when hayed due to difference in maturity at forage harvest. However, both forage accumulation and nutritive value varied substantially across the six years of this study. Results indicate the greatest forage accumulation occurred when CCs were planted as early as possible to take advantage of spring precipitation and cool temperatures for vegetative growth. Bulk density and porosity were not different when CCs were hayed or grazed as an annual forage resource compared to when CCs remained standing and often were not different from fallow. Soil organic carbon stocks were either greater or similar with CCs compared to fallow and were dependent upon adequate CC residue inputs. Water stable aggregates were consistently greater with standing and grazed CCs compared to fallow in both years, but hayed CCs were greater than fallow in only one of the two years. These findings suggest that CCs may be grown in place of fallow to produce desirable forage of good quality for livestock especially when grazed or hayed early. Further, dual-purpose management strategies may provide benefits to soil health similar to those obtained when CCs are left standing. However, careful management is critical to maintain adequate residue. Grazing CCs would be more desirable than mechanical forage harvest to maintain soil properties when forage productivity is low.

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Figures

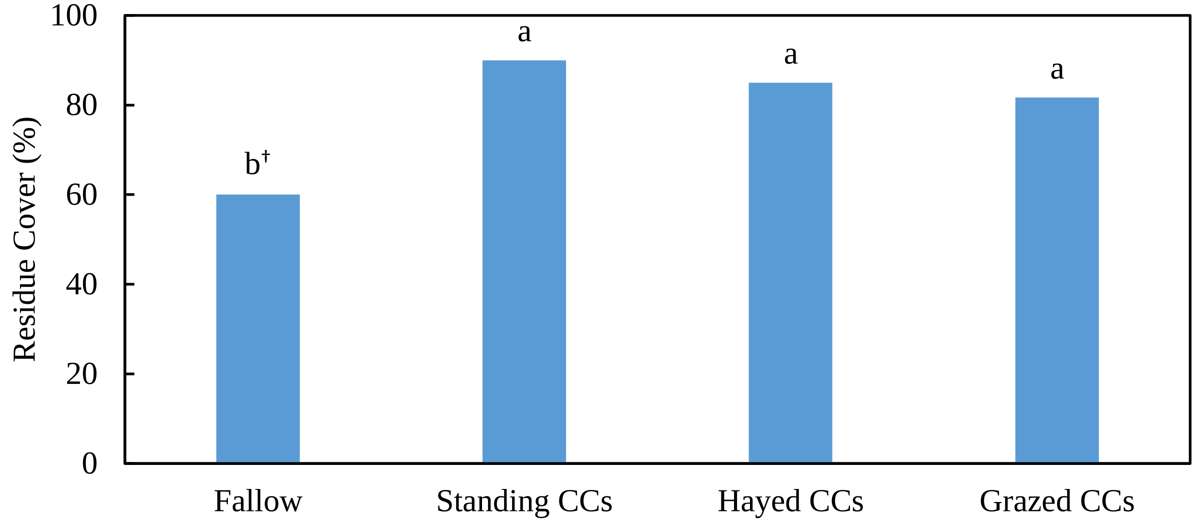

Figure 3.1. Soil surface residue cover measured in August 2020 after cover crop termination and before winter wheat planting near Brownell, KS.

†Means with the same letter are not significantly different (α =0.05) among cover crop treatments.

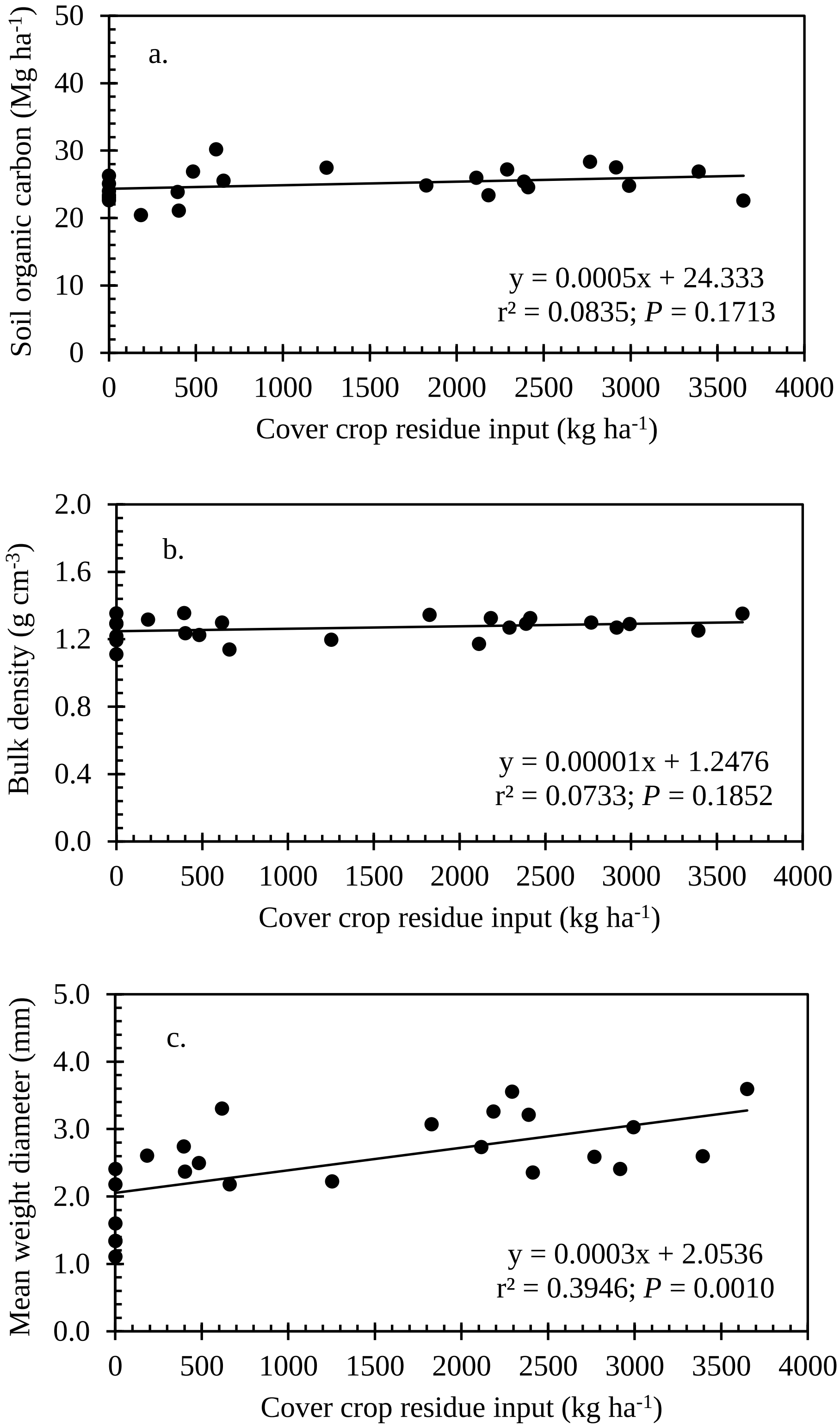

Figure 3.2. Linear regression analysis of cover crop residue inputs and measured soil organic carbon stocks (a.), bulk density (b.), and mean weight diameter (c.) of water stable aggregates in the 0- to 15-cm soil depth in 2019 and 2020 near Brownell, KS.

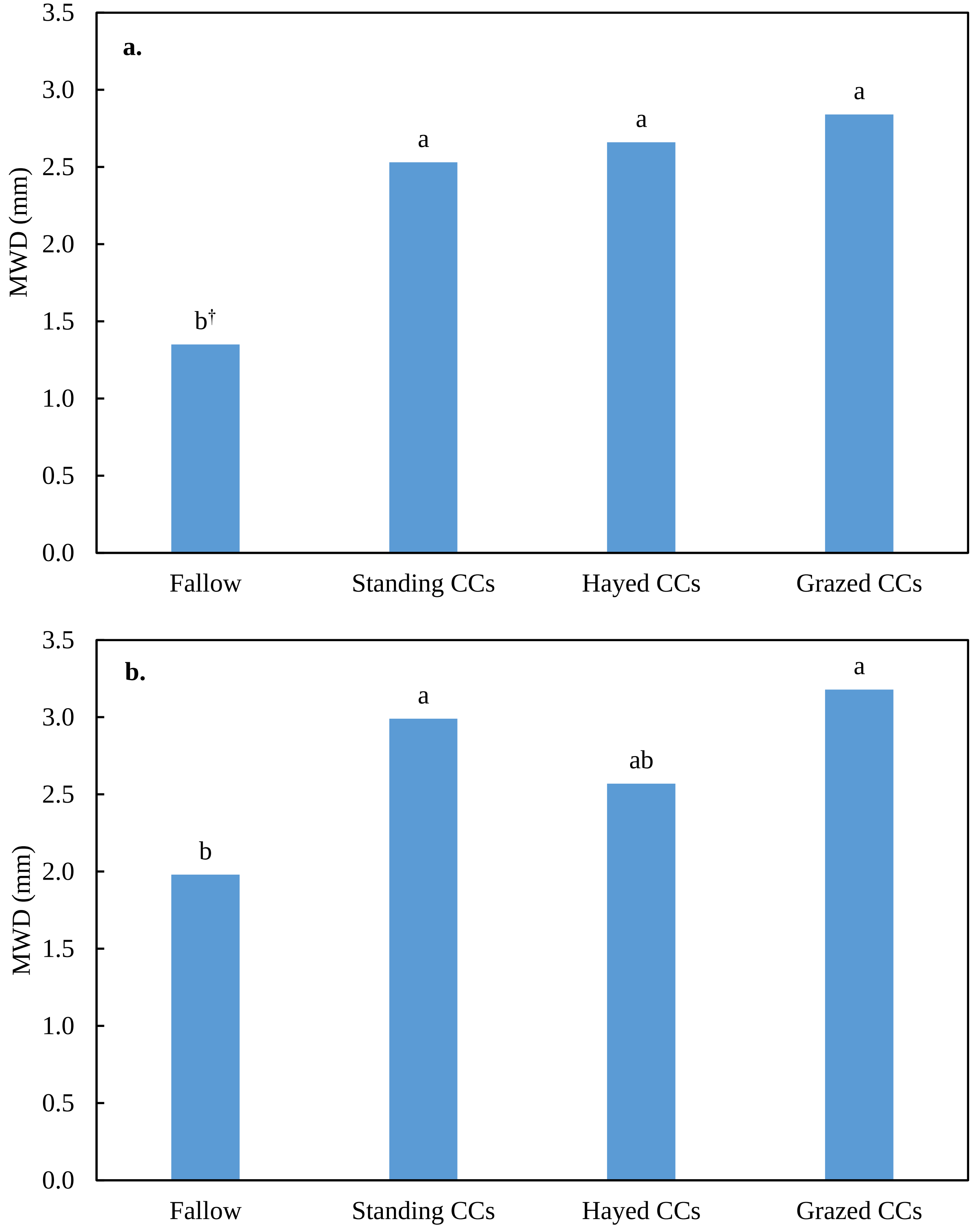

Figure 3.3. Cover crop management effect on mean weight diameter (MWD, mm) from the 0- to 5-cm soil depth in 2019 (a.) and 2020 (b.) near Brownell, KS.

†Means with the same letter are not significantly different (α =0.05) among cover crop treatments.

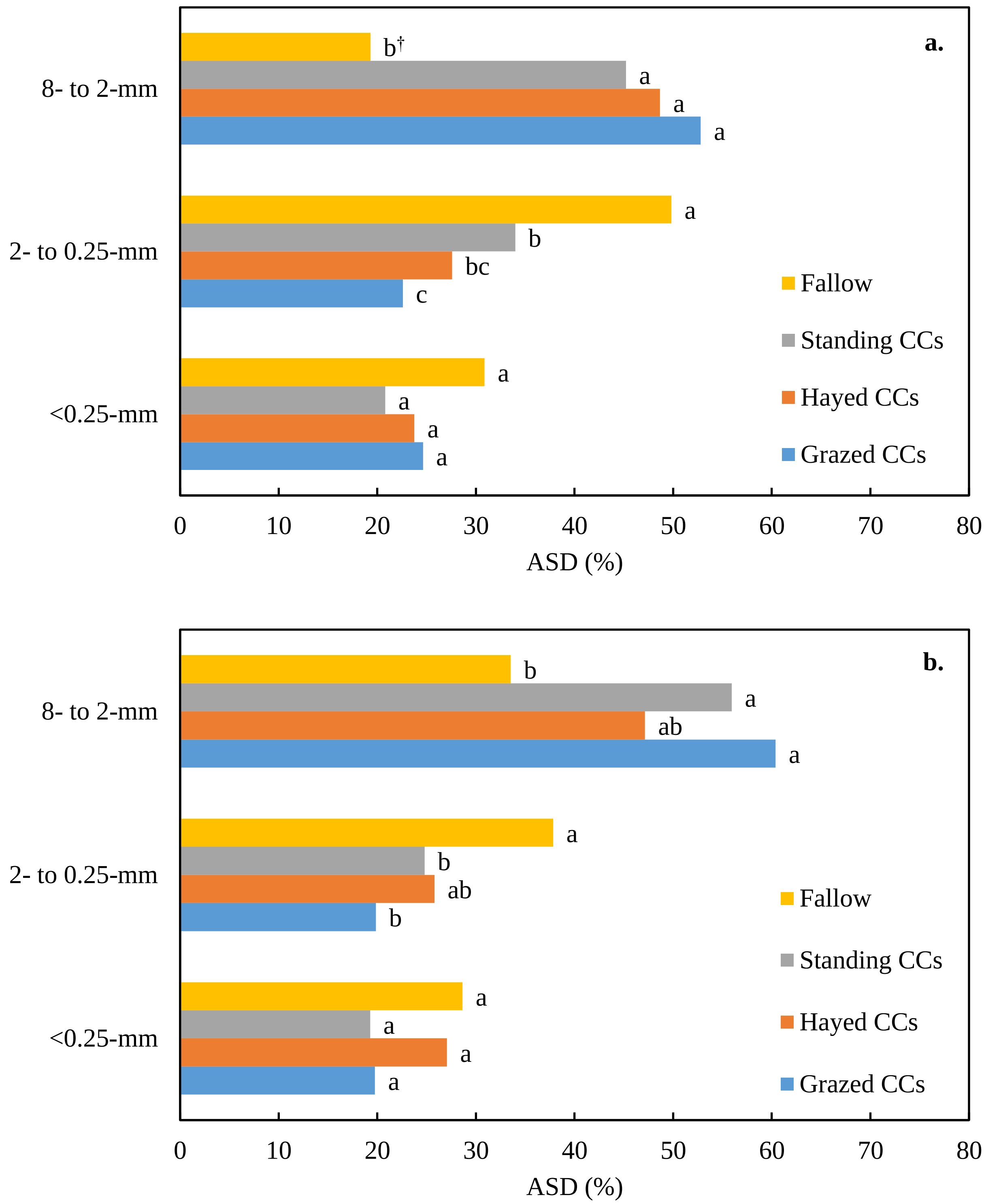

Figure 3.4. Effect of cover crop management strategies on aggregate size distribution (ASD, %) from the 0- to 5-cm soil depth in 2019 (a.) and 2020 (b.) near Brownell, KS.
†Bar sections of the same color contained the same letter are significantly different (α =0.05) among cover crop treatments.

Tables

Table 3.1. Cover crop planting dates, biomass harvest dates, grazing dates, stocking densities, termination dates, and herbicides used from 2015 to 2020 near Brownell, KS.

	Year					
Activity	2015	2016	2017	2018	2019	2020
Planting Date†	3/15	3/17	3/1	3/15	4/17	3/13
Pre-grazing biomass collection date	5/19	6/13	5/24	6/18	6/13	6/29
Grazing dates	5/19 to 5/23	6/14 to 6/21	5/30 to 6/3	6/19, 6/25 to 6/27‡	6/17 to 6/20	6/29 to 7/3
Stocking density (kg ha^{-1})	1755	1755	1755	1755	877	877
Post-grazing biomass collection date	5/27	6/21	6/7	6/27	6/20	7/3
Mechanical forage harvest date	6/5	6/21	6/7	6/18	6/13	7/1
Termination date	6/9	6/23	6/9	6/28	6/26	7/6
Herbicides used for termination	††Glyphosate and 2,4-D	——— Paraquat and carfentrazone ———				

†Seeding rate of 36 and 43 kg ha^{-1} for oats and triticale, respectively.

‡Cattle were removed after the one day due to wet conditions, and were returned when conditions improved.

††Glyphosate (N-[phosphonomethyl] glycine), 2,4-D (2,4-dichlorophenoxy-acetic acid), paraquat (N,N′-dimethyl-4,4′-bipyridinium dichloride), and carfentrazone (carfentrazone-ethyl).

Table 3.2. Monthly precipitation and mean temperature from 2015 to 2020 near Brownell, KS.

	Year						
	2015	2016	2017	2018	2019	2020	30-yr avg.
	Precipitation						
Month	mm						
January	17	9	29	1	13	25	12
February	4	5	2	1	8	40	22
March	1	11	33	8	18	11	26
April	21	176	135	17	23	12	62
May	153	69	100	92	197	81	95
June	16	80	40	94	40	61	83
July	102	79	39	199	24	178	64
August	10	118	82	142	317	62	69
September	10	33	47	87	40	24	43
October	43	16	51	78	38	2	45
November	38	29	2	12	10	24	19
December	29	10	0	43	59	8	26
Annual	445	635	559	775	789	527	566
	Temperature						
	°C						
January	0	0	0	-1	-1	1	-1
February	-1	4	5	0	-4	2	1
March	8	9	8	7	3	7	7
April	13	7	12	8	12	11	11
May	16	16	16	21	15	16	17
June	25	25	24	25	22	25	24
July	26	27	27	25	26	26	26
August	25	24	23	24	25	24	24
September	24	21	22	20	24	19	22
October	15	16	13	11	10	11	13
November	7	9	7	3	5	8	6
December	2	-2	-1	1	2	2	0
Annual	13	13	13	12	12	13	13

Table 3.3. Forage accumulation of cover crops from 2015 to 2020 near Brownell, KS.

	Year						
	2015	2016	2017	2018	2019	2020	6-yr avg.
	Forage accumulation						
Treatment	——— kg ha^{-1} ———						
Standing CCs	5483a†	3262a	4099a	3670a	2622a	2138a	3546a
Hayed CCs	3908b	3033a	3215ab	3127b	779d	1398b	2577b
Pre-Grazing CCs	2607c	2779a	3933ab	3769a	1806c	2133a	2838b
Post-Grazing CCs	2102c	1691b	2507b	2520c	2214b	1482b	2086c

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

Table 3.4. Forage nutritive value of hayed and grazed cover crops (CCs) from 2015 to 2020 near Brownell, KS.

Treatment	2015	2016	2017	2018	2019	2020	6-yr avg.
	Crude protein						
	%						
Hayed CCs	16.4b†	8.4a	10.1b	10.1a	9.8a	8.0b	10.5b
Grazed CCs	21.8a	8.8a	13.3a	9.6a	10.8a	11.4a	12.6a
	Acid detergent fiber						
	%						
Hayed CCs	36.9a	39.0a	36.9a	36.3a	40.1a	41.4a	38.4a
Grazed CCs	30.5b	40.7a	32.0b	36.5a	31.4b	33.6b	34.1b
	Neutral detergent fiber						
	%						
Hayed CCs	58.3a	65.4a	67.7a	62.2a	61.5a	68.4a	62.9a
Grazed CCs	49.2b	67.7a	57.6b	54.0b	52.7b	59.5b	56.8b
	Total digestible nutrients						
	%						
Hayed CCs	60.4b	58.1a	60.4b	61.1a	56.8b	55.4b	58.7b
Grazed CCs	67.8a	56.1a	66.0a	61.0a	66.7a	64.3a	63.6a
	In vitro dry matter digestibility						
	%						
Hayed CCs	80.6b	66.9a	68.3b	68.0a	77.4b	69.0b	71.7b
Grazed CCs	89.0a	65.1a	77.7a	68.3a	82.9a	77.5a	76.8a

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

Table 3.5. Cover crop management effect on soil organic carbon (SOC) from the 0- to 15-cm soil depth in 2019 and 2020 and change (ΔSOC) from study initiation in 2015 near Brownell, KS.

Year	Treatment	SOC	ΔSOC
		—— Mg ha^{-1} ——	
2019	Fallow	24.79 b†	1.17b
	Standing CCs	27.59a	3.96a
	Hayed CCs	27.48a	3.85a
	Grazed CCs	26.87ab	3.25ab
2020	Fallow	23.22ab	0.29ab
	Standing CCs	23.99a	1.06a
	Hayed CCs	21.80b	-1.13b
	Grazed CCs	24.54a	1.61a

†Means with the same letter within the same column are not significantly different (α =0.05) among cover crop treatments within each year.

Table 3.6. Bulk density and porosity from the 0- to 15-cm soil depth in 2019 and 2020 near Brownell, KS.

Year	Treatment	Bulk density	Porosity
		$g\ cm^{-3}$	%
2019	Fallow	1.17b[†]	55.7a
	Standing CCs	1.26a	52.4b
	Hayed CCs	1.23ab	53.5ab
	Grazed CCs	1.22ab	54.0ab
2020	Fallow	1.24b	53.1a
	Standing CCs	1.32a	50.1b
	Hayed CCs	1.30ab	50.9ab
	Grazed CCs	1.32a	50.2b

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