Cover crops to regenerate soils and increase profitability in dryland crop production in the semi-arid central Great Plains

by

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Abstract

Replacing fallow with dual-purpose cover crops (CCs) could enhance soil health and increase cropping system profitability when CCs are grazed or hayed by providing an economic benefit to offset potential lost revenue when crop yields are reduced after CCs in dry years. However, there is concern that removing CC biomass could limit the beneficial effects of CCs for soil health and that soil compaction may occur with grazing on no-till (NT) fields, which could limit subsequent crop yields and require tillage for remediation. Flexible CC management has also been introduced as a possible strategy to take advantage of plant available water (PAW) in wet years while saving PAW for primary crops in dry years. From 2015 to 2023, a series of small-plot and on-farm experiments were conducted to determine the best management strategies for CCs to replace fallow in NT dryland cropping systems of the semi-arid central Great Plains (CGP). Studies investigated 1) grazing and haying CCs as forage, 2) interactions of CCs and tillage [NT or occasional tillage (OT)], 3) CC mixture diversity, and 4) flexible fallow-replacement based on PAW and climate outlooks. In each case, strategies were evaluated for impacts on PAW, grain and forage production, system profitability, and soil properties. Results showed that spring-planted cool-season CCs grown in place of fallow before wheat (*Triticum aestivum* L.) produced about 3100 kg biomass ha^{-1} on average. Grazing removed about 40% of the available forage while haying removed about 70%. Crop residue cover was greater with CCs (80%) compared to fallow (68%), but profile PAW at wheat planting was about 21 mm greater with fallow than with CCs. Average wheat yields were unaffected by fallow management or tillage, but fallow management effects varied across years. Net returns were in the order of grazed CCs as an alternative to confined hay feeding > hayed CCs > flex-hayed CCs > grazed CCs as an alternative to grazing rangeland > fallow > standing CCs. When planted, CCs

increased crop residue cover, particulate organic carbon, and water stable aggregates compared to fallow. Crop residue cover with NT (86%) was greater than OT (67%), but profile PAW, grain yields, net returns, and most soil properties were unaffected by tillage though the wind-erodible fraction was greater with OT compared to NT. Warm-season CCs planted immediately after wheat harvest produced about 3800 kg biomass ha^{-1} on average. Average grain sorghum (*Sorghum bicolor* Moench) yields were 11% less following standing or grazed CCs compared to fallow but yields following hayed CCs were similar to fallow. Net returns were in the order of grazed CCs (as an alternative to confined hay feeding) > hayed CCs > grazed CCs (as an alternative to grazing rangeland) fallow > standing CCs. Soil properties were unaffected by warm-season CC management compared to fallow. On-farm evaluations of CC grazing impacts in NT systems further demonstrated that CC biomass left as residue post-grazing was similar to pre-grazing and was 60% of the ungrazed CCs. Most soil properties were not different between grazed and ungrazed CCs. However, soil organic carbon and potassium concentrations were greater with grazed CCs compared to ungrazed CCs possibly due to substantial CC residue remaining following grazing coupled with manure deposition. These results suggest that dual-purpose CCs for grazing or haying can provide forage for livestock, increase crop residue cover and soil aggregate stability, maintain crop yields, and increase net returns in NT systems with limited risk of soil compaction. However, results are likely to differ based on stocking rate, category of livestock, duration of grazing, and available CC biomass for grazing or haying cutting height. Further research will be needed to determine the long-term effects of CC grazing in NT systems as well as to determine optimum rates of CC biomass removal with grazing to optimize farm income and enhance soil health in NT dryland cropping systems. Furthermore, our results suggest CC mixtures should be simple and dominated by productive grasses species to

maximize forage and residue production. If OT is necessary in a long-term NT system to correct root-limiting compaction, PAW, crop yields, net returns, and soil properties are generally unaffected compared to NT. Flexible CC management systems might still be a useful strategy in the semi-arid CGP to avoid severe wheat yield reductions following CCs in extremely dry years. However, more site-year observations will be required to better understand the impact of flex-CCs, and increased accuracy of precipitation outlook models will also be required for flex-CCs to successfully be adopted in this region.

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Chapter 1 - Introduction and literature review

Introduction

Dryland cropping systems of the semi-arid central Great Plains (CGP) rely on soil water storage during fallow periods to supplement growing season precipitation for stable grain production. However, low-intensity cropping systems that include long fallow periods have low precipitation use efficiency (Baumhardt & Jones, 2002; Nielsen & Vigil, 2010; Peterson & Westfall, 2004) and are associated with long-term soil degradation (Peterson et al., 2020; Stewart & Robinson, 1997; Unger et al., 2006b). Despite the challenges associated with intensified grain production systems in this semi-arid region, it has been proposed that growing annual forages or cover crops (CCs), in place of fallow could be superior to grain crops (Carr et al., 2020; Obour et al., 2021). Cover crops have the potential to increase precipitation use efficiency, regenerate soils, and suppress weeds (Blanco-Canqui et al., 2021a; Obour et al., 2021). Despite these benefits, the costs of establishing CCs (seed, machinery, labor, and fuel) and potential reductions in subsequent grain yields because of reduced soil water at planting, present major barriers to CC adoption in water-limited environments (Bergtold et al., 2017; Ramsey et al., 2019; Roesch-McNalley et al., 2017). Flexible CC management systems could take advantage of available soil water in wet years to produce more biomass and increase residue cover while minimizing negative effects in dry years by saving soil water for the main grain crop (Holman et al., 2021b; 2022; Obour et al., 2021). Notwithstanding, replacing fallow with grazed or hayed CCs may have the greatest potential to balance goals of environmental and economic sustainability in semi-arid dryland cropping systems (Nielsen et al., 2011; 2016; Holman et al., 2021b; 2022).

Grazing CCs could extend the livestock grazing season, delay grazing of native rangelands, and is the most efficient means of utilizing CCs in years when biomass accumulation

is relatively low (Kelly et al., 2021; Simon et al., 2021a; 2021b; Titlow et al., 2014). Additionally, in years when biomass accumulation is high, CCs could be harvested as hay or silage for future feeding (Holman et al., 2018a; 2022; Simon et al., 2021a; 2021b). Because of the significant potential for regrowth from harvested CCs, residue cover retained on the soil surface can be greater compared to fallow to maintain the soil health benefits of CCs (Kelly et al., 2021; Simon et al. 2021a). Although CC practices may be implemented differently across environments based on soil type, climate, and crop rotation, many of these benefits seem possible even in water-limited environments (Blanco-Canqui et al., 2021a; Obour et al., 2021). Less is understood about the degree to which soil health can be improved with management strategies like grazing CCs, harvesting CCs for hay, and flexible fallow replacement with CCs (Blanco-Canqui et al. 2020b, Holman et al., 2021b; 2022; Obour et al, 2021). Improved understanding of these climate-specific CC management practices for water-limited environments can increase CC adoption, regenerate soils, and increase profitability of dryland crop production the semi-arid CGP.

Dryland crop production in the semi-arid U.S. Great Plains and Canadian Prairies

Dryland agriculture refers to crop production for food, fiber, and fuel in regions where annual precipitation accounts for only 20 to 35% of potential evapotranspiration (PET) such as in the semi-arid U.S. Great Plains and Canadian Prairies (Cannell and Dregne, 1983; Stewart et al., 2006). In these environments, annual crop production with growing season precipitation alone is highly erratic but has been stabilized by the use of fallow to store water in the soil profile between grain crops (Nielsen et al., 2005; 2010; Peterson and Westfall, 2004). Typical grain production systems are based around winter or spring wheat (*Triticum aestivum* L.) with 11 to 21-month fallow periods between the harvest of one crop and the planting of another. As a water

conservation practice, fallow in the traditional wheat-fallow (WF) system has been shown to increase soil water storage between crops, stabilize wheat yields, and limit the occurrence of crop failure (Aiken et al., 2013; Nielsen & Vigil, 2018; Schlegel et al. 2017). However, fallow is an inherently inefficient practice with only 20 to 35% of all precipitation received during the fallow period effectively stored for future crop use (Baumhardt & Jones, 2002; Nielsen & Vigil, 2010; Peterson & Westfall, 2004). Precipitation storage efficiency is primarily influenced by crop residue that intercepts the impact of raindrops on the soil surface and slows runoff to increase water infiltration (Peterson et al., 1996; Nielsen et al., 2005). Additionally, crop residues mediate soil temperatures and reduce the wind velocity at the soil surface, which reduces evaporation. With the increased availability of broad-spectrum herbicides as well as advancements in planting equipment, reduced or no-tillage (NT) has widely replaced conventional tillage throughout many of the semi-arid crop production regions of the world (Unger et al., 2006a; Unger et al., 2006b).

The wide-spread adoption of NT has been successful in increasing soil water storage efficiency and crop yields as well as reducing soil erosion during fallow (Baumhardt et al., 2015; Peterson et al., 2020). In the Prairies and northern Great Plains (NGP), NT has facilitated the replacement of fallow in the WF system with pulse and oilseed crops such as field peas (Pisum sativum L.), lentils (*Lens culinaris* Medik.), chickpeas (*Cicer arietinum* L.), canola (*Brassica napus* L.), and flax (*Linum usitatissimum* L.) (Cochran et al., 2006; E. Smith et al., 2017; Sainju et al., 2020). Similarly, NT has facilitated the reduction in fallow frequency in the CGP and southern Great Plains (SGP) with the addition of a summer crop [grain sorghum (*Sorghum bicolor* Moench), corn (*Zea mays* L.), proso millet (*Panicum milliaceum* L.), or sunflower (*Helianthus annuus* L.) following wheat in the winter wheat-summer crop-fallow system (Baumhardt & Salinas-Garcia, 2006; Nielsen & Vigil, 2017; 2018; Schlegel et al., 2019). The

complete replacement of fallow and the transition to continuous cropping systems has been limited in the CGP and SCP because of greater potential evapotranspiration rates that increase the risk of crop failure with intensified grain production systems compared to the Prairies and NGP (Aiken et al., 2012; Baumhardt & Salinas-Garcia, 2006; Nielsen & Vigil, 2017; 2018). In eastern Colorado, the probability of wheat yielding <1500 kg ha^{-1} (60% of the Colorado average from 2007 to 2016) was 0.03 following fallow but 0.35 and 0.45 following field pea or proso millet, respectively (Nielsen & Vigil, 2018). In western Kansas, Holman et al. (2018a) showed that wheat following field pea or another wheat crop had 26 and 40% lower yields and 32 and 109% lower net returns compared to fallow, respectively. These results underscore the limitations of implementing productive and profitable intensified grain production systems in the semi-arid CGP.

Despite the challenges associated with intensified grain production in this semi-arid region, it has been proposed that growing annual forages or CCs, in place of fallow could be superior to grain crops (Carr et al., 2020; Obour et al., 2021). Less water is required to accumulate enough biomass for an acceptable forage harvest or CC compared to the water required to produce grain, which reduces the risk of crop failure (Stewart and Weil-Li, 2015; Stewart and Peterson, 2015). Additionally, as annual forage and CCs are usually harvested or terminated earlier in the year than grain crops, a longer period of time for soil water recharge is allowed before planting the next grain crop. In western Kansas, available soil water in the 0- to 1.8-m soil profile at wheat planting was 31 and 67% greater following winter or spring triticale (×*Triticosecale* Wittm.) forage or CCs than following another wheat crop, respectively (Holman et al., 2018a). Similarly, available soil water was 5 and 34% greater following winter or spring triticale forage or CCs than following field pea for grain. Holman et al. (2021b) showed that

precipitation utilization and storage efficiency, defined as the fraction of fallow precipitation used by fallow replacement crops or stored in the soil, with spring forage or CCs was 44% greater compared to fallow but 42% less compared to spring grain crops. Notwithstanding, available soil water at wheat planting was 29% greater following forage or CCs compared to grain crops. Given these advantages, annual forage and CCs have the potential to replace portions of the fallow periods in semi-arid dryland cropping systems for increased production and precipitation use efficiency.

Replacing fallow with cover crops for sustainable cropping system intensification

Incorporating CCs into the dryland cropping systems of the semi-arid CGP could regenerate soils, suppress weeds, and increase precipitation use efficiency (Blanco-Canqui et al., 2021a; Obour et al., 2021). Two periods in typical dryland cropping systems are available for integrating CCs including 1) fallow ahead of winter wheat planting and 2) fallow following winter wheat harvest (Simon et al., 2021a). The replacement of fallow before wheat primarily presents an opportunity for cool-season CCs that can be terminated in May or June, which allows for at least 90 days before planting wheat to allow for soil water recharge. Cool-season CCs can be planted in the fall or spring though the establishment of CCs in the fall following summer crop harvest may be challenging because of limited soil water and remaining growing season. The replacement of fallow after wheat presents an opportunity for warm-season CCs to be planted immediately after harvest and terminated by frost in October, which allows for at least 150 days before planting a summer crop the following year. Fall-planted cool-season CCs could also be integrated after wheat (Rosa et al., 2021) with the added benefit of being able to plant CCs earlier in fall (September) compared to after summer crops (November). There is greatest risk associated with fall-planted cool-season CCs following summer crop harvest and warm-

season CCs following wheat harvest compared to the other strategies discussed because soil water is often depleted at the time of grain crop harvest, late fall and winter precipitation is limited, and summer precipitation is erratic (Jenkins et al., 2019; Simon et al., 2021a; Obour et al., 2021).

Species selection and the decision to plant monocultures or diverse mixtures is a key consideration in CC management (Florence et al., 2019; Kaye et al., 2019). Past research with CCs in the semi-arid CGP showed that grass species have significantly greater potential for biomass accumulation compared to broadleaf species because of the relatively faster growth rate and greater drought tolerance of the grasses (Holman et al., 2018a; 2022; Nielsen et al., 2015a; 2015b; 2015c). In mixtures, grass species outcompete broadleaf species and are the dominant contributors to biomass accumulation of CC mixtures (Blanco-Canqui et al., 2021a; Obour et al., 2021). Diverse CC mixtures have been investigated for their potential to exhibit transgressive over-yielding, or greater biomass production with a mixture than any of the single composite species in monoculture, (Schmid et al., 2008) and provide greater ecosystem services (multifunctionality) than monoculture CCs (Finney & Kaye, 2016; Finney et al., 2017). Although CC mixtures have been observed to produce more biomass than the average of their component species in some environments, mixtures frequently failed to produce more biomass than the most productive monoculture (Florence & McGuire et al., 2020; Ruis et al., 2019; Sanderson et al.,2018). In the semi-arid CGP, diverse CC mixtures including broadleaf species produced similar or less biomass than productive grass monocultures. In eastern Colorado and western Nebraska, Nielsen et al. (2015a; 2015b; 2015c) showed that a 10-species CC mixture produced similar biomass as the most productive monoculture. Similarly, in western Kansas, Holman et al. (2018a; 2021a) showed that bi-culture triticale-legume CCs produced similar biomass as the

triticale monoculture. In a later study, they showed that biomass accumulation was in the order of triticale > triticale-oat > triticale-pea > 6-species cocktail (Holman et al., 2021b; 2022). In the second study, the 6-species cocktail produced 51% less biomass than the triticale monoculture. Biomass accumulation was more stable with a 6-species CC mixture (CV = 25%) compared to monocultures (CV ≥ 49%) in western North Dakota (Franco et al., 2021). However, despite increased stability, the most productive monoculture still produced 11% more biomass than the 6-species mixture.

Cover crop biomass accumulation in semi-arid dryland cropping systems is highly variable from year to year in response to available soil water at planting and growing season precipitation (Blanco-Canqui et al., 2021a; Obour et al., 2021). For example, average biomass accumulation of CCs in western Kansas ranged from a low of 780 kg ha^{-1} when growing season precipitation was almost 50% less than the 30-year average to a high of 2690 kg ha^{-1} when precipitation was at or near the 30-year average (Holman et al., 2018a). Spring-planted forage triticale biomass ranged from 2967 to 6724 kg ha^{-1} across six site-years in eastern Colorado and western Nebraska (Nielsen et al., 2017). In two studies in western Kansas, Simon et al. (2021a; 2021b) showed that the biomass accumulation of spring-planted cool-season CCs averaged 2501 kg ha^{-1} and ranged from 1600 to 3218 kg ha^{-1} over six years. This variation in biomass accumulation was mostly because of differences in planting date because of excessively wet spring conditions that delayed CC planting until after the optimum date in some years. In the semi-arid CGP, when spring-planted cool-season CCs are planted later than the optimum date, they are exposed to higher temperatures and greater moisture stress that accelerates maturity and limits biomass accumulation (Simon et al., 2021a; 2021b). These authors also showed that the biomass accumulation of warm-season CCs planted immediately after wheat harvest averaged

2817 kg ha^{-1} and ranged from 1072 to 4168 kg ha^{-1} over five years with one year of crop failure. The variation in biomass accumulation was mostly because of dry summer conditions in some years that limited CC germination and reduced stand density, which suggests that stand establishment is one of the greatest challenges for CCs planted immediately after grain crop harvest in dryland cropping systems (Blanco-Canqui et al., 2021a; Obour et al., 2021).

Despite the benefits that CCs could provide in regenerating soils, suppressing weeds, and increasing precipitation use efficiency, a major limitation to their adoption in semi-arid dryland cropping systems is the water use of CCs compared to fallow and potential reductions in subsequent grain crop yields. In western Kansas, Holman et al. (2018a; 2021a) showed that in years when precipitation was above average, wheat yields were unaffected by CCs grown in place of fallow. However, in years of below average precipitation, yields were reduced by as much as 70%. In a later study, these authors showed that wheat yields were unaffected by CCs grown in place of fallow (Holman et al., 2021b; 2022). In this case, wheat yields were probably unaffected because yields were often very low (averaged 0.92 Mg ha^{-1}) throughout the study period except one year when wheat yield was very high (5.85 Mg ha^{-1}). Similarly, in eastern Colorado and western Nebraska, Nielsen et al. (2015a; 2015b; 2015c) showed that for every 20.7 kg ha^{-1} of CC biomass produced, available water at wheat planting was reduced 1 mm. These authors further showed that for every 1 mm of available water, wheat grain yield increased 12.5 kg ha^{-1}. This is to say that a CC that produced 2500 kg biomass ha^{-1} would reduce available soil water at wheat planting by 120.8 mm and wheat grain yield by 1510 kg ha^{-1}. Less is known about the effects of CCs on summer crop yields as most studies have emphasized the fallow period before winter wheat planting. However, in western Kansas, Holman et al. (2018b) showed grain sorghum yield was reduced 41% following double-crop forage sorghum compared to fallow after

wheat. Similarly, in western Nebraska, corn yield was reduced up to 20% following winter cereal CCs depending on the time of termination with earlier termination dates allowing a longer duration for soil water recharge before corn planting (Rosa et al., 2021). In a recent meta-analysis, Garba et al. (2022) showed that the costs of CCs exceeded the benefits in environments with less than 700 mm average annual precipitation and concluded that careful site-specific plans are required to successfully incorporate CCs in such environments. To overcome grain yield penalties following CCs in dry years, flexible CC management systems have been introduced as a possible strategy to take advantage of available soil water in wet years while saving soil water for the main grain crop in dry years (Felter et al., 2006; Lyon et al., 2007; Nielsen et al., 2011; Holman et al., 2021b; 2022).

Flexible cropping systems for increased water use efficiency and profitability in dryland crop production

Because of frequent reductions in grain crop yields following CCs in semi-arid dryland cropping systems, it has been suggested that flexible CC management systems based on measurements of available soil water and the climate outlook could better balance goals of enhancing soil health, maintaining or increasing grain yield, and improving precipitation use efficiency in water-limited crop production compared to CCs in a set crop rotation (Holman et al., 2021b; 2022; Obour et al., 2021). This strategy is based upon previous investigations of flexible fallow replacement, also referred to as dynamic cropping systems or opportunity cropping, in the semi-arid U.S. Great Plains and Canadian Prairies (Felter et al., 2006; Halvorson and Kresge, 1982; Liebig et al., 2007; Zentner et al., 1993). In their forum on dynamics cropping systems, Tanaka et al. (2002) referred to this concept as a long-term strategy for crop selection and sequence that could optimize productivity, profitability, and resource conservation in

dryland crop production. The key instrument used in the implementation of such systems is the Paul Brown soil moisture probe (Brown, 1959; 1960) which was developed as a quick and easy tool to use in determing the depth of moist soil for making crop management decisions. Because subsoil moisture is critical for dryland crop production, with crops often experiencing terminal drought, the depth of moist soil can be used to make decisions of crop selection, seeding rate, as well as fertilizer rate.

Nielsen et al. (2011; 2016) investigated fixed and flexible integrated grain and forage cropping systems to increase precipitation use efficiency and net returns in eastern Colorado. From 2001 to 2005 (Nielsen et al., 2011), crops were selected annually in the flexible cropping systems based on measurements of available soil water at planting, growing season precipitation outlooks of 70, 100, 130% of normal precipitation, and water use efficiency functions developed from past studies at their research site. They found that the flexible cropping system that included grain and forage crops and assumed less than or near normal growing season precipitation increased precipitation use efficiency on a value basis ($\$ ha^{-1} mm^{-1}$) by 53% compared to the fixed cropping systems that included only grain crops. Additionally, the flexible system that assumed near normal precipitation increased net returns compared to the fixed wheat-corn-fallow system, which had a negative net return, though this system was similar to the fixed WF system. From 2011 to 2015 (Nielsen et al., 2016), flexible crops were selected based on available soil water at planting and the expectation of average growing season precipitation. They found that continuous forage-based cropping systems ($\$721 ha^{-1} yr^{-1}$) and flexible cropping systems that included wheat and forages ($\$327 ha^{-1} yr^{-1}$) substantially increased average annual net income compared to fixed grain-only cropping systems ($\$41 ha^{-1} yr^{-1}$). In addition, continuous forage-based cropping systems and flexible cropping systems that included wheat

and forages had >90% probability of breaking even (total income is equal to total costs) and >75% probability of generating a net income of at least \$200 ha^{-1}. These results show the potential for dynamic cropping systems that include both grain and forage crops to increase precipitation use efficiency as well as system profitability in semi-arid dryland crop production.

The adoption of flexible CC management systems in dryland cropping systems could take advantage of available soil water in wet years to produce more biomass and increase residue cover while minimizing negative effects in dry years by saving soil water for the main grain crop. In western Kansas, Holman et al. (2021b; 2022) implemented this strategy where CCs were only planted when a minimum of 30 cm of moist soil water was measured using a Paul Brown soil moisture probe and when the National Weather Service Seasonal Climate Outlook for the year was neutral or favorable. If either of these criteria were not met, CCs were not planted and instead the plots remained fallow until wheat planting. In their study, grain yields and net returns were similar to fallow and CCs in fixed crop rotations, which was probably because of low wheat yields over the course of their study and the limitations of precipitation outlook models to accurately predict rainfall. However, the authors showed that net returns where greater when CCs were hayed to a height of 15 cm compared to unharvested CCs or field pea for grain which suggests that replacing fallow with CCs used for forage may have the greatest potential to balance cropping system goals in water-limited environments.

Integrating livestock into semi-arid dryland crop production

Despite the benefits that CCs could provide in regenerating degraded soils, suppressing weeds, and increasing precipitation use efficiency, the costs of their establishment (seed, machinery, labor, and fuel) and potential reductions in subsequent grain yields because of reduced soil water at planting present major barriers to CC adoption in semi-arid regions like the

CGP (Bergtold et al., 2017; Ramsey et al., 2019; Roesch-McNalley et al., 2017). However, most species used as CCs have excellent forage nutritive value attributes (Cicek et al., 2014; Jenkins et al., 2019; Landry et al., 2018) and could supply forage for livestock to compensate for their production costs and potentially increase system profitability (Franzluebbers & Stuedemann, 2007; Drewnoski et al., 2018; Schomberg et al., 2014). Even when subsequent crop yields are reduced after CCs, the diversification of income streams provided by integrated crop-livestock systems can facilitate increased net income and income stability (Bell et al., 2014; P. Johnson et al., 2013; Russelle et al., 2007). For example, despite 40 to 70% reductions in subsequent wheat yields in dry years, CCs increased average net returns by 26 to 240% when harvested for hay (15-cm stubble height) (Holman et al. 2018a). In the short-term, investments in fencing and watering resources can be significant barriers to integrated-livestock systems with grazing livestock, but increased net returns over time can make these systems profitable in the long-term (Drewnoski et al., 2018; Franzluebbers & Stuedemann, 2007).

Grazing CCs with beef cattle (*Bos taurus* L.), dairy cattle, or sheep (*Ovis aries* L.) could extend the livestock grazing season, delay grazing of native rangelands, and is the most efficient means of utilizing CCs in years when biomass accumulation is relatively low (Kelly et al., 2021; Simon et al., 2021a; 2021b; Titlow et al., 2014). In eastern Nebraska, Drewnoski et al. (2018) showed that grazing late-summer-planted frost-killed CCs dominated by oats (*Avena sativa* L.) resulted in average daily gains (ADG) of between 0.59 to 1.09 kg with yearling steers and heifers. In another study in northern Georgia, ADG of cow-calf pairs grazing winter rye (*Secale cereal* L.) CCs were between 0.62 to 2.26 kg and between 0.60 to 2.01 when grazing post-wheat pearl millet (*Pennisetum glaucum* L.) CCs (Franzluebbers & Stuedemann, 2007). Integrated crop-livestock systems with grazing livestock have even been reported to reduce weed biomass,

abundance, and species richness compared to traditional cropping systems (Schuster et al., 2016; 2019; MacLaren et al., 2018), which could be another significant benefit to the cropping system. Additionally, in years when biomass accumulation is high, CCs could be harvested as hay or silage for future feeding (Holman et al., 2018a; 2022; Simon et al., 2021a; 2021b). In the semi-arid CGP, stored forage from CCs could be especially valuable during drought when forage supplies become scarce. Because of the significant potential for regrowth from hayed or grazed CCs, residue cover on the soil surface can be maintained greater than fallow (Kelly et al., 2021; Simon et al. 2021a). For example, in western Kansas, CCs hayed to a height of 15-cm or grazed by yearling heifers at stocking densities of 877 to 1755 kg ha^{-1} for 4 to 7 days maintained residue cover similar to standing CCs (no forage removal), and all CCs had 32% greater residue cover than fallow (Simon et al., 2021a).

Observations discussed above suggest integrating CCs and livestock in the CGP could diversify income streams, increase system profitability, and also enhance soil health by increasing soil cover and the presence of living plant roots. However, one challenge to managing CCs as part of a livestock feeding plan is the high variability in CC biomass accumulation in dryland cropping systems (Simon et al., 2021a; 2021b). Because of this, flexibility is required when CCs are used for forage in semi-arid environments (Obour et al., 2021). For example, plans must be in place so the size of the herd that will graze CCs can be adjusted each year based on annual forage availability. Forage accumulation may be less than anticipated or conditions may change during the growing season so that livestock may need to be moved to rangeland or another forage resource earlier than expected if available forage from CCs is not enough to support grazing (Obour et al., 2021). Notwithstanding, in years when precipitation is high, forage accumulation of both CCs and rangeland will be high so that the best use of CCs may be for hay

or silage that can be stored and fed later (Holman et al., 2018a; 2022). Access to adjacent areas where cattle can be quickly and easily moved to should be a key consideration when making plans to graze CCs in order to avoid soil compaction when soils are saturated following large rain events and to accrue the greatest soil health benefits possible from CCs (Schomberg et al., 2021).

Enhancing soil health with cover crops and integrated livestock in semi-arid dryland cropping systems

No-tillage, CCs, and integrated livestock have been investigated to regenerate soils degraded after years of conventionally-tilled, low-intensity crop production in semi-arid regions (Blanco-Canqui et al., 2021a; Obour et al., 2021). Soil health benefits of adopting these practices include alleviating soil compaction, increasing water infiltration and water holding capacity, reducing wind and water erosion, sequestering soil carbon, improving soil fertility and nutrient cycling, as well as increasing soil microbial activity and abundance (Blanco-Canqui & Francis, 2016; Blanco-Canqui & Ruis, 2019; 2020; Blanco-Canqui et al., 2015). Although CC practices may be implemented differently across environments based on soil type, climate, and crop rotation, many of these benefits are possible even in water-limited environments (Blanco-Canqui et al., 2021a; Obour et al., 2021). However, the degree to which soil health can be improved with management strategies like grazing CCs, harvesting CCs for hay, and flexible fallow replacement with CCs in dryland cropping systems of the semi-arid CGP is not fully understood (Anderson et al., 2022; Blanco-Canqui et al., 2013; 2020a; 2021b; Kelly et al., 2021; Simon et al., 2021; 2022).

Alleviating soil compaction

Mitigating soil degradation by compaction is a major challenge in modern grain and forage production systems considering the continued increase in the size and weight of field equipment used for planting, harvesting, and other field operations (Batey, 2009; Hamza & Anderson, 2005). Additionally, soil compaction is associated with integrated crop-livestock practices such as grazing crop residues because of the risk of excessive hoof traffic (Baumhardt et al., 2011; 2017). In intensive crop production systems, CCs have been promoted as a strategy for alleviating soil compaction after years of heavy equipment operations, particularly brassicas with deep taproots and grasses with extensive rooting systems (Blanco-Canqui et al, 2015). This could be especially important in intensive corn silage production systems which require several heavy implements for harvest and transport (Anderson et al., 2022; Blanco-Canqui et al., 2020b). The deep taproots of some CC species such as radish (*Raphanus sativus* L.) and rapeseed (*Brassica napus* L.) can penetrate through compacted soil layers and leave behind root channels and macropores following decomposition through which water and air can flow and subsequent crops can extend roots though to access subsoil water and nutrients (Chen & Weil, 2010; Chen et al., 2014). Additionally, CCs with broad fibrous rooting systems such as oat, triticale, barley (*Hordeum vulgare* L.), rye, sudangrass (*Sorghum drummondii* (Nees ex. Steud.) Millsp. & Chase), and the millet species may also play a key role in increasing overall soil porosity (Simon et al., 2022; Villamil et al., 2006) and are best suited for dryland cropping systems (Holman et al., 2018a; 2022; Nielsen et al., 2015b; 2015c) where the growth of broadleaf CCs is limited by water availability.

While changes in soil bulk density (BD), porosity, and penetration resistance (PR) can be possible with CCs, these observations are infrequent and site-specific rather than broadly applicable. In fact, after 12 years of CC management in eastern Nebraska, no differences in soil

BD were observed with grass or legume CCs compared to no CC (Blanco-Canqui and Jasa, 2019). In this case, it was speculated that the lack of differences in BD after 12 years of CCs was partly because of 15 additional years of NT management that preceded the initiation of the experiment. Comparable results have been reported in other long-term NT systems (Chalise et al., 2018; Nouri et al., 2019; Ruis et al., 2020). This suggests that long-term NT may be more influential than CCs for managing soil compaction. Notwithstanding, Simon et al. (2022) showed a 5% decrease in BD in the 0- to 15-cm soil depth with CCs compared to fallow after 12 years of CC management in western Kansas. Cover crops had 6 to 8% greater soil BD and 6% lower porosity in the 0- to 15-cm soil depth compared to fallow after 5 and 6 years of CCs and NT management (Simon et al. 2021a). However, most interestingly, BD and porosity were not different with grazed (yearling heifers at stocking densities of 877 to 1755 kg liveweight ha^{-1} for 4 to 7 days) or hayed CCs (15-cm stubble height) compared to standing CCs (no forage removal), which is consistent with other observations (Anderson et al., 2022; Blanco-Canqui et al., 2021b; Simon et al., 2022). This suggests that grazing or haying of CCs might not cause soil compaction in NT cropping systems, which is noteworthy as grazing and haying CCs can provide economic benefits that could increase CC adoption in water-limited environments (Obour et al., 2021).

In an irrigated cropping system in western Nebraska, Blanco-Canqui et al. (2020b) showed a 52% increase in PR in the 0- to 10-cm soil depth where CCs were grazed with 5 cow-calf pairs ha^{-1} for 60 days or 1.2 yearling heifers ha^{-1} for 90 days compared to ungrazed CCs in one year of a 3-year study. However, PR in all treatments and years was below the threshold of 2 MPa, which is the general threshold of root-limiting compaction for typical silt loam soils. Similarly, Schomberg et al. (2021) showed a 14% increase in PR in the 0- to 30-cm soil depth

when 13 to 15 yearling heifers ha^{-1} grazed CCs for up to 10 days on a frequently saturated soil in northern Georgia. The authors showed that grazed CCs reduced the soil depth to root growth limiting compaction (2 MPa) from 15.9 cm with ungrazed CCs to 9.6 cm with grazed CCs. In northeast Missouri, Dhakal et al. (2022) showed that grazing CCs with 5 to 9 cow-calf pairs ha^{-1} for 2 to 7 days increased PR up to 20 cm below the soil surface compared to ungrazed CCs, which was associated with reduced subsequent corn yields. Notwithstanding, when the subsequent crop was soybeans, crop yields were not different between grazed and ungrazed CC treatments. However, these observations were made in irrigated and high rainfall environments that might not adequately reflect the potential effects of grazing CCs on semi-arid dryland soils. Across 10 on-farm sites in the semi-arid CGP, Kelly et al. (2021) showed that grazing CCs with cattle at stocking densities from 315 to 1221 kg LW ha^{-1} for 22 to 36 days had 18% greater soil BD in the 0- to 5-cm soil depth compared to ungrazed CCs at CC termination in mid-summer, but soil bulk densities were below the threshold of 1.6 cm^{-3} where root growth can be limited. Despite these differences in soil BD, yields of winter wheat following grazed or ungrazed CCs were not significantly difference, which confirmed that compaction from grazing was not yield-limiting. Although root-limiting compaction is a concern, the effects of compaction on water infiltration and water holding capacity are of greatest importance especially in semi-arid dryland cropping systems where water is the most limiting factor for crop production.

Increasing water infiltration and soil water storage

Because water is the most limiting factor for dryland crop production in semi-arid regions like the CGP, management strategies that reduce runoff, increase water infiltration and holding capacity, and reduce evaporation are critical for efficient precipitation use efficiency (Stewart & Peterson, 2015; Stewart & Weil-Li, 2015). Cover crops have been promoted to accomplish many

of these goals (Blanco-Canqui et al., 2015; Blanco-Canqui, 2018). By increasing residue on the soil surface, CCs can slow runoff by reducing the velocity of water flow on the soil surface to allow more time for water to effectively infiltrate the soil. Additionally, by increasing the abundance of soil macropores, CCs provide improved paths of flow through the soil to increase the rate of water infiltration and soil water storage (Blanco-Canqui et al., 2021b; DeLaune et al., 2019; Nouri et al., 2019). Increased residue cover from CCs can mediate soil temperature changes, effectively cooling the soil when ambient temperatures are high, (Blanco-Canqui et al., 2011; 2015) and also reduce wind velocities at the soil surface to reduce evaporative losses of soil water (Peterson et al., 2004; Stewart & Peterson, 2015). For this to be most effective, CCs must produce substantial biomass and persistent residues, which is more likely with grasses than broadleaf species in semi-arid dryland cropping systems (Holman et al, 2018a; 2022). Increased soil water holding capacity is often the product of increased soil organic matter (SOM) and soil porosity, which CCs could facilitate by developing root channels through the soil and depositing SOM with the decomposition of roots (Bagnall et al., 2022; Burke et al., 2021; Nouri et al., 2019; Villamil et al., 2006). However, these observations have often been limited to irrigated or high rainfall environments especially on low SOM soils with high sand content.

In western Kansas, Blanco-Canqui et al. (2013) showed that CCs reduced runoff by 64% compared to fallow. Similarly, water infiltration rate and cumulative water infiltration were 169 and 300% greater following CCs compared to no CC in south central Kansas (Blanco-Canqui et al., 2011) and eastern Nebraska (Blanco-Canqui et al., 2021b), respectively. Cumulative infiltration was possibly related to residue cover with infiltration increasing 0.54 cm for every 1% increase in residue cover. Despite these observations of increased water infiltration with CCs as well as those of others (DeLaune et al., 2019; Nouri et al., 2019), Blanco-Canqui & Jasa

(2019) and Simon et al. (2022) observed no significant difference in water infiltration with CCs compared to no CC in their long-term NT cropping systems, which suggests that CCs may not always alter water infiltration under long-term NT in all environments. In fact, Simon et al. (2022) showed that replacing fallow with field pea for grain reduced water infiltration by 75% compared to fallow because planting peas destroyed existing crop residues without contributing much additional residue. Most interestingly, these authors reported similar water infiltration with hayed CCs (15-cm stubble height) compared to unharvested CCs, which suggests that harvesting CCs for forage might not reduce water infiltration. However, contrary to these results, Blanco-Canqui et al. (2021b) showed that harvesting CCs for hay to a height of 10-cm reduced water infiltration 75% compared to unharvested CCs because residue cover was significantly reduced.

The results of Blanco-Canqui et al. (2021b) supported those of Holman et al. (2021a; 2021b) who showed that 4 to 27% less available soil water was stored at wheat planting following CCs harvested for hay (15-cm stubble height) compared to unharvested CCs. Notwithstanding, in these studies, soil water storage with CCs harvested for hay and unharvested CCs was 13 to 22% less compared to fallow, respectively. In eastern Nebraska, Anderson et al. (2022) showed no difference in water infiltration when CCs were grazed with 1.4 to 4.0 yearling steers ha^{-1} for 30 to 69 days compared to ungrazed CCs. Similar observations were made in two of three years in western Nebraska though water infiltration was reduced 80% with grazed CCs (5 cow-calf pairs ha^{-1} for 60 days or 1.2 yearling heifers ha^{-1} for 90 days) compared to ungrazed CCs in the other year (Blanco-Canqui et al., 2020b). Franzluebbers and Stuedemann (2008) showed that grazing CCs at stocking densities from 1740 to 3570 kg LW ha^{-1} for 26 to 77 days reduced water infiltration up to 68% in two of seven years, which was associated with reduced macro-porosity when CCs were grazed on saturated soil. Based on the results discussed above,

CCs frequently increase infiltration by increasing residue cover and macro-porosity but not necessarily in long-term NT cropping systems in all environments. Hayed CCs can reduce water infiltration and decrease soil water storage compared to unharvested CCs if residue cover is significantly reduced. However, water infiltration after grazed CCs is often similar to ungrazed CCs unless grazing occurs on saturated soils. In these scenarios, reduced water infiltration is the result of reduced residue cover and aggregate destruction, which could also increase risks of soil loss by wind and water erosion.

Reducing wind and water erosion

Soil loss by water and wind erosion is one of the greatest threats to the long-term resilience of crop production (Bennett & Chapline, 1928; Lowdermilk, 1953). These forces are linked to losses of SOM, crop productivity, and eventually food security (Baumhardt et al., 2015). Water erosion from croplands increases sedimentation of rivers, lakes, and reservoirs, which threatens aquatic wildlife, increases risks of flooding, and requires high-cost dredging operations for remediation (Fox et al., 2016; C. Smith et al., 2013). Additionally, water erosion delivers significant amounts of sediment-bound nutrients like phosphorus that cause eutrophication, large and potentially toxic algal blooms, loss of aquatic habitat, and degraded drinking water sources (Carpenter et al., 1998; Sharpley et al., 2019). In the CGP, the risk of water erosion is greatest in late spring and early summer when residue cover is low, summer crop canopies are not well developed, and intense rainfall events are most likely (Greb, 1983; Renard & Foster, 1983). In addition to water erosion, wind erosion can cause degradation of air quality, which threatens human and animal health alike, especially in individuals with existing respiratory problems (Lyles et al., 1983; P. Singh et al., 2012). Wind erosion also causes automotive accidents when visibility is reduced during large dust storms and can damage

machinery due to abrasion and clogging as dust accumulates. Wind erosion is also responsible for damaging crops through a phenomenon called “sand blasting” when sensitive crop seedlings are damaged by abrasions from saltating soil particles (Sterk et al., 1999). In the CGP, the risk of wind erosion is greatest in late winter and early spring when residue cover is low, winter wheat canopies are not well developed, and wind speeds are high (W. Johnson et al., 1983; Layton et al., 1993). Cover crops have the potential to reduce erosion risks in dryland cropping systems by increasing residue cover and aggregate stability as well as by physically anchoring the soil in place with active root growth (Carver et al., 2022; Nouri et al., 2019; Simon et al., 2021a; 2022).

In western Kansas, mean weight diameter (MWD) of water stable aggregates in the 0- to 15-cm soil depth was increased 50 to 110% with grass CCs compared to fallow and was positively related to crop residue inputs (Simon et al., 2021b). These authors showed that for every 1 Mg of crop residue present, MWD increased 0.3 mm. In another study, MWD of dry aggregates in the 0- to 15-cm soil depth was increased 57 to 64% with grass and legume CCs compared to no CC (Nouri et al., 2019). These authors showed that MWD in the 15- to 30-cm soil depth was 14 to 30% greater with CCs compared to no CC. However, contrary to these results above, Blanco-Canqui & Jasa (2019) showed only grass CCs, but not legumes, effectively increased MWD of aggregates in the 0- to 7.5-cm soil depth compared to no CC with no difference in MWD observed between CCs and no CC in the 7.5- to 15-cm soil depth. In western Kansas, Blanco-Canqui et al. (2013) showed that CCs reduced total sediment loss 63% and reduced phosphorus loss 42% compared to fallow. Similarly, in eastern Kansas, Carver et al. (2022) showed that CCs reduced total sediment loss 67% compared to no CC though phosphorus losses were less consistent over their 3-year study. These results and those of others (Blanco-Canqui et al., 2011; Villamil et al., 2006; Simon et al., 2022) show that CCs consistently

increased MWD and reduce sediment loss compared to no CC though these changes are most likely to be observed in the shallow soil depths and when productive CC species are selected for the climate and cropping system.

Although several authors have investigated CC effects on water erosion and water quality, less is known about the effects that CCs may have on wind erosion (Blanco-Canqui et al., 2015; 2021). In west Texas, Van Pelt and Zobeck (2004) showed that frost-terminated warm-season CCs reduced soil loss by wind erosion by 90% or more because surface residue cover was much greater than fallow. Blanco-Canqui et al. (2013) and Simon et al. (2022) showed that CCs decreased the wind-erodible fraction (WEF) of soil aggregates up to 11% compared to fallow in western Kansas. Similarly, Blanco-Canqui et al. (2021) showed that WEF decreased 49% with CCs compared to no CC, which negatively related to residue cover. For every 1% increase in residue cover, WEF decreased 0.7%. However, others have found no difference in WEF with CCs (Anderson et al., 2022), which suggests that CCs may not always decrease WEF in all environments. Most interestingly, the studies discussed above showed no difference in WEF between hayed and grazed CCs compared to standing CCs (no forage removal) which suggest that using CCs for forage could maintain the benefits of traditional CCs. Other observations of the effects of hayed or grazed CCs on water stable aggregates further support this (Franzluebbers & Stuedemann, 2008; Kelly et al., 2021; Simon et al., 2021b). However, because residue cover is critical for mitigating water and wind erosion, caution must be taken to retain adequate residue cover on the soil surface between CC termination and planting of the subsequent cash crop (Simon et al., 2021b; Van Pelt & Zobeck, 2004). Blanco-Canqui et al. (2011) showed that MWD of water stable aggregates was positively related to soil organic carbon (SOC) with a 0.27 to 0.59 mm increase in MWD for every 1 g kg^{-1} increase in SOC. This suggests that the sequestration of

SOC and accumulation of SOM could be equally as important as residue cover for reducing soil erosion.

Sequestering soil organic carbon and accumulating organic matter

The sequestration of SOC and accumulation of SOM is a major ecosystem service that could be provided by CCs (Blanco-Canqui et al., 2015; Chahal et al., 2020; McClelland et al., 2021; Poeplau & Don, 2015). Soil organic carbon makes up the carbon fraction (approximately 58%) of SOM which is the product of decomposition of plant, animal, and microbial biomass and is present in all agricultural soils (Nelson & Sommers, 1996). However, SOC must be distinguished from inorganic carbon which is the product of the carbonate mineral dissolution from calcareous parent materials and frequently exceeds SOC in calcareous soils under arid and semi-arid climates. Increased SOC and SOM is associated with increased soil fertility, aggregate stability, and water holding capacity (Bagnall et al., 2022; Blanco-Canqui et al., 2015), and increased attention has been placed on agricultural soils as major sinks for carbon dioxide which is a prominent greenhouse gas associated with global climate change (Chahal et al., 2020; McClelland et al., 2021; Poeplau & Don, 2015). As countries, municipalities, and businesses continue to set carbon neutrality goals and policies, the role that agricultural soils could play in reducing carbon dioxide in the atmosphere has become incredibly significant. In a global meta-analysis, Poeplau and Don (2015) showed that CCs sequestered 0.32 Mg SOC ha^{-1} yr^{-1} in the upper 22-cm soil depth. Similarly, McClelland et al. (2021) showed that CCs sequestered 12% or 1.11 Mg ha^{-1} more SOC compared to no CC under temperate climates. However, SOC sequestration with CCs depends on biomass accumulation, which is water-limited in semi-arid drylands. Despite these limitations, a review of the ecosystem services of CCs in arid and semi-arid cropping systems showed that CCs accumulated 0.43 Mg SOC ha^{-1} yr^{-1} in the 0- to 30-cm

soil depth (Blanco-Canqui et al., 2021a), which suggests that significant SOC sequestration can be possible even when production is water-limited.

In southern Illinois, Olson et al. (2014) showed that CCs under NT management increased SOC stock 21% and 12% in the 0- to 15-cm and 15- to 75-cm soil depths, respectively, and resulted in a 1.21 Mg ha^{-1} yr^{-1} increase in SOC in the 0- to 75-cm depth over 12 years. This was especially noteworthy as it showed that CCs could increase SOC to a substantial depth and supports the argument that assessments of SOC sequestration across management systems should consider deep soil depths (Blanco-Canqui et al., 2021c). Despite this, many studies have shown that SOC sequestration with CCs in NT cropping systems might actually be limited to the shallow soil layers (Blanco-Canqui et al., 2011; 2013) and most others reported SOC stock for only a single depth (Hubbard et al., 2013; Kelly et al., 2021; Simon et al., 2021a, 2022). Several studies have shown 10 to 36% increases in SOC with CCs compared to no CC in the upper 7.5- or 15-cm soil depths (Blanco-Canqui et al., 2011; 2013; Chahal et al., 2020; Hubbard et al., 2013; Simon et al., 2021a; Stavi et al., 2012), though others have shown no difference even after long-term CC management (Acuña & Villamil, 2014; Dozier et al., 2017; Kaspar et al., 2006; Kelly et al., 2021; Rosa et al., 2021; Simon et al., 2022; V. Thapa et al., 2021). This is probably due to limited CC biomass accumulation in many temperate environments because of cool temperatures and limited precipitation during the CC growing season as well as the short periods available for CC growth especially in continuous summer crop systems such as the corn-soybean (*Glycine max* L.) rotation (Ruis et al., 2019; 2020). Notwithstanding, even when differences in total SOC are not observed between CCs and no CC treatments, particulate organic carbon (POC) and permanganate oxidizable carbon (POXC) can indicate trends of increasing or decreasing SOC under short-term management (Kelly et al., 2021; Faé et al., 2009;

Franzluebbers & Stuedemann, 2008; 2014; Ladoni et al., 2016). In western Kansas, despite no differences in SOC with CCs compared to fallow after long-term CC management, a transition from a WF rotation to wheat-grain sorghum-fallow (WSF) increased SOC after 6 years (Simon et al., 2022) which highlights the importance of cropping system diversity and intensification for SOC sequestration (Sherrod et al., 2018; Schmer et al., 2020).

As mentioned above, SOC makes up the carbon fraction (58%) of SOM, which is an important agent of most soil physical, chemical, and biological processes (Bagnall et al., 2022; Reeves, 1997) though it is often depleted in modern dryland agricultural soils of arid and semi-arid regions (Peterson et al., 2020; Stewart & Robinson, 1997; Unger et al., 2006b). The depletion of SOM in semi-arid dryland cropping systems has occurred because of mineralization that exceeds accumulation in rotations that include fallow as well as current and historic soil erosion that removed topsoil once rich in SOM. In central Illinois, Villamil et al. (2006) showed a 10% increase in SOM stock in the 0- to 30-cm soil depth with CCs compared to no CC that was greater with vetch and rye-vetch CCs than rye alone. This might have been because the transformation of rye residues to SOM was limited without adequate nitrogen supplied by vetch. However, Blanco-Canqui et al. (2019) in eastern Nebraska showed that SOM increased 11% with only grass CCs, but not legumes, compared to no CC. After 12 years of CC management, differences in SOM were only observed in the 0- to 7.5-cm soil depth but not at deeper depths, which was probably because of many years of NT management both before and throughout the duration of the study. Similar observations were made in a short-term study of CCs in an irrigated cropping system (Blanco-Canqui et al., 2021c) though most short-term studies show no significant differences in SOM with or without CCs (Blanco-Canqui et al., 2020b; Dozier et al., 2017; Rosa et al., 2021). Measures of particulate organic matter (POM) have suggested trends of

increasing SOM with CCs in short-term studies when no significant differences were observed in total SOM or SOC (Anderson et al., 2022; Ruis et al., 2020), which suggests that CCs have the potential to accumulate SOM after long-term management.

In their study, Anderson et al. (2022) showed no difference in SOM or POM when CCs were grazed (1.4 to 4.0 yearling steers for 30 to 69 days) compared to ungrazed CCs, which agrees with the results of most other studies of grazing CCs (Blanco-Canqui et al., 2020b; Franzluebbers & Stuedemann, 2008; 2014; Kelly et al., 2021; Simon et al., 2021b). This suggests that grazing CCs is an effective strategy that maintains the SOC sequestration and SOM accumulation benefits of ungrazed CCs. Similarly, Blanco-Canqui et al. (2013) and Simon et al. (2022) showed no difference in SOC stock between CCs harvested for hay compared to unharvested CCs. However, Simon et al. (2021b) showed that the effects of hayed CCs (15-cm stubble height) on SOC stock compared to standing CCs (no forage removal) and fallow might not be as consistent as with grazed CCs. In one year of their study, SOC stock in the 0- to 15-cm soil depth were similar with hayed CCs compared to standing CCs and both CCs increased SOC stock 11% compared to fallow. However, in the second year on different experiment plots, SOC stock was 9% less with hayed CCs compared to standing CCs, and SOCs stock with both CCs were similar to fallow. These results agree with those of Blanco-Canqui et al. (2021b) who showed that SOM was 10% less in both the 0- to 10- and 10- to 20-cm soil depths when CCs were harvested for hay (10-cm stubble height) compared to unharvested CCs. In this study, hayed CCs were similar to no CC in either soil depth. This suggests that hayed CCs may not always maintain the SOC and SOM accumulation benefits of unharvested CCs and highlights the importance of raising the cutting height of the harvester for hayed CCs compared to traditional hay crops to ensure adequate residue, and residue associated carbon, is retained to maintain soil

health benefits. Increased SOC and SOM with CCs is associated with increased nutrient retention, availability, and cycling which can reduce requirements for applied fertilizers to meet crop nutrient demand and maintain or increase yield potential (Reeves, 1997; Stewart & Robinson, 1997).

Improving soil fertility and nutrient cycling

Loss of soil fertility with depleted SOM is widely associated with long-term continuous crop production especially in semi-arid environments where the annual supply of plant, animal, and microbial biomass for decomposition is water-limited (Reeves, 1997; Stewart & Robinson, 1997). The increased use of synthetic fertilizers has been beneficial for increasing grain production (Stewart & Lal, 2017) despite depleted SOM but has also been damaging because of nutrient loss to the environment, especially nitrogen and phosphorus (Carpenter et al., 1998; Sharpley et al., 2019). Nutrient loss from leaching, surface runoff, and water erosion from agricultural fields has been the primary contributor to eutrophication, large and potentially toxic algal blooms, loss of aquatic habitat, and degraded drinking water sources though nutrient loss. Additionally, wind-blown soil particles can also be a major cause of nutrient loading in environments effected by wind erosion (Godlinski et al., 2008; Sharratt et al., 2019). Aside from environmental harm, nutrient loss from agricultural fields limits nutrient use efficiency in crop production and adds substantially to the costs of production as greater fertilizer application rate are required to meet crop demand (Stewart & Lal, 2017; Sharpley et al., 2019). Cover crops primarily contribute to improving soil fertility and nutrient cycling by reducing nutrient loss by leaching, runoff, and erosion and sequestering those nutrients for later release for subsequent crop use as CC residues decompose (Blanco-Canqui et al., 2015; R. Thapa et al., 2018). Additionally, in the case of legume species, biologically-fixed nitrogen can be contributed to

complement or replace synthetic fertilizer applications (Mahama et al., 2016a; 2016b; 2020) though significant nitrogen fixation requires substantial biomass accumulation which is often limited in drought-prone semi-arid dryland cropping systems (Holman et al., 2018a; 2022).

Reduced nitrogen leaching is primarily associated with species that develop deep fibrous root systems like rye, triticale, as well as millet and sorghum species (Crandell et al., 2005; Hirsh et al., 2021; Kaye et al., 2019). Additionally, these grasses produce substantial above-ground biomass that can reduce nitrogen and phosphorus losses in runoff water and eroded sediment (Blanco-Canqui et al., 2013; Carver et al., 2022). However, nutrient release from CC residues can be slow because of the high carbon to nitrogen ratio of the grass residue that slows decomposition (Ghimire et al., 2021; Rosa et al., 2021). Synchronization of CC residue decomposition and peak nutrient demand of subsequent crops can be accomplished with strategic termination timing and methods, though decomposition rates can be difficult to predict. To overcome dyssynchronous nutrient release, non-leguminous broadleaf species like buckwheat (*Fagopyrum esculentum* Moench), radish, rapeseed, and sunflower can be incorporated to lower the carbon to nitrogen ratio of the CC residue to increase the pace of decomposition (Hirsh et al., 2021; Kaye et al., 2019; Nevins et al., 2020). In the above scenarios, nutrients are captured and retained in the field, but only legumes are capable of nitrogen fixation (Blesh & Drinkwater, 2013; Drinkwater et al., 1998). Through a symbiotic relationship with species-specific rhizobia bacteria, legumes form root nodules that encapsulate and supply carbon to bacteria in exchange for bacterial fixation of atmospheric nitrogen gas to ammonia (Weaver & Graham, 1994). Leguminous species like pea, lentil, clover (*Trifolium spp*.), cowpea (*Vigna unguiculate* L. Walp.), soybean, and sunn hemp (*Crotalaria juncea* L.) can be important sources of nitrogen for subsequent crops to complement or potentially replace synthetic nitrogen fertilizers (Blanco-

Canqui et al., 2012; Burgess et al., 2014; Hubbard et al., 2013; MacMillan et al., 2022; Northup & Roa, 2015; 2016).

In their review, R. Thapa et al. (2018) showed that CCs reduced nitrate losses to freshwater systems by 56% on average compared to no CC with greatest reductions when the CC growing season was long and CC biomass production was high. Winter cereal CCs like rye reduced soil profile nitrate concentrations by 56 to 67% and reduced nitrate leaching to buried anion exchange resins by 90% compared to no CC in the U.S. mid-Atlantic states of Maryland (Hirsh et al., 2021) and Pennsylvania (Kaye et al., 2019) which suggests winter cereal CCs have a substantial capacity to reduce nutrient leaching. In Kansas, Blanco-Canqui et al. (2013) and Carver et al. (2022) showed that triticale and wheat CCs significantly reduced sediment losses though reductions in nitrogen and phosphorus losses in runoff were less consistent. In one of four years, total phosphorus loss was reduced with CCs compared to no CC though loss was increased with CCs in another year and similar to no CC in the other two years (Carver et al., 2022). In fact, dissolved reactive phosphorus increased 63% with CCs compared to no CC in three of four years. Notwithstanding, sediment loss was reduced 68% with CCs compared to no CC, which suggests CCs can effectively reduce nutrient loss by runoff and erosion. Warm-season legume CCs planted after wheat harvest supplied 27 to 64 kg N ha^{-1} for subsequent corn and grain sorghum crops in eastern Kansas (Mahama et al., 2016a; 2016b). In this study, pigeonpea (*Cajanus cajan* (L.) Millsp.) supplied the greatest fertilizer nitrogen replacement followed by cowpea. By replacing synthetic nitrogen fertilizers with warm-season legume CCs, nitrous oxide emissions per unit grain yield were reduced 48% to 56% (Mahama et al., 2020). In west Texas, cool-season legumes CCs fixed 46 to 74 kg N ha^{-1} in their biomass with the greatest production from pea and vetch (MacMillan et al., 2022). However, in the semi-arid CGP and SGP, the

biomass accumulation of most legume species is severely limited compared to grasses because of less tolerance of drought and heat tolerance as well as the great sensitivity of some species to iron deficiency chlorosis that can severely limit the rate of biological nitrogen fixation in the calcareous soils of the region (Holman et al., 2018a; 2022; Schlegel & Havlin, 1997; Schlegel et al., 2019).

Although several have investigated the effects of CCs on nutrient dynamics compared to no CC, less is known about the effects that grazed CCs or harvesting CCs for hay might have compared to traditional CCs. Most studies have found no difference in soil nutrient concentrations when CCs are hayed or grazed compared to standing CCs (Blanco-Canqui et al., 2020b; Franzluebbers & Stuedemann, 2014; 2015; Kelly et al., 2021; Simon et al., 2022). However, Blanco-Canqui et al. (2021) showed that CCs harvested for hay (10-cm stubble height) reduced soil nitrate 37% in the 0- to 10-cm soil depth compared to no CC which was similar to unharvested CCs possibly because harvesting removed nitrate from the system in the CC biomass while CC residues left by the unharvested CCs released nitrate back into the soil. Because much of the nutrients in forages grazed by ruminant livestock can be recycled in the manure, grazing CCs might be a strategy to effectively cycle nutrients within a cropping system (Ryschawy et al., 2017; Sanderson et al., 2013.). Grazed CCs on croplands could help close nutrient cycles that currently export nutrients from the soil in harvested grain and forage to centers of confined animal feeding where manure must be disposed of locally (Kronberg et al., 2021). Instead, manure management is simplified, and nutrients are recycled in the crop field with less risk for losses to the environment. However, grazing crop residues has been shown to increase nutrient loss in eroded sediments (Baumhardt et al., 2017; Blanco-Canqui et al., 2016a; 2016b) due to surface compaction that reduces water infiltration and increases runoff. This issue

could be avoided when grazing CCs by removing livestock temporarily before and/or following large rain events and returning them when soil has had time to dry. Because of potential soil compaction concerns, access to adjacent areas where cattle can be quickly and easily moved to must be considered when making plans to graze CCs (Schomberg et al., 2021). Another indicator of nutrient cycling in the soil is microbially-derived enzyme activity which could be increased with the incorporation of CCs that stimulate microbial activity and abundance.

Increasing soil microbial activity, diversity, and abundance

Soil microbial activity, diversity, and abundance have considerable influence over many soil processes including carbon and nutrient cycling as well as soil aggregation (Drinkwater et al., 1996; Coleman & Wall, 2015). Cover crops have been shown to enhance soil microbial properties across several environments and cropping systems (Kim et al., 2020; Muhammad et al., 2021) with the greatest effects of CCs on microbial biomass and abundance when the CC growing season was long enough to produce substantial CC biomass. Microbial abundance was increased 26 to 38% with CCs compared to no CC in central Missouri (Rankoth et al., 2019). Cover crops increased bacterial, fungal, and actinomycetes biomass 60 to 150% compared to no CC though the relative abundance ratios of all microbial communities were unaffected by CCs. Anderson et al. (2021) showed comparable results though differences with CCs compared to no CC were restricted to the upper 5-cm soil depth. In eastern South Dakota, long-term CC management (20 years) increased microbial biomass 124% compared to no CC though differences were less frequently observed after only short-term management (3 or 6 years) (Feng et al., 2021). However, both long and short-term CC management was shown to increase the activities of β-glucosidase, urease, acid and alkaline phosphatase, and arylsulfatase, which are soil enzymes associated with carbon, nitrogen, phosphorus, and sulfur cycling. Despite this, in

another eastern South Dakota study, J. Singh & Kumar (2021) showed no effect of CCs on microbial abundance or diversity though soil respiration tended to increase with CCs compared to no CC which suggests that CC may have increased microbial activity. Notwithstanding, these authors reported a significant increase in microbial abundance in their extended four-year crop rotation that included spring and winter cereals compared to a two-year rotation of corn and soybean alone. Earthworms are also important parts of the soil ecosystem that play a critical role in maintaining soil porosity, water infiltration, aggregate stability, and nutrient cycling by burrowing, ingesting soil and plant residues, and depositing their castings (Shipitalo and Korucu, 2017). Cover crops have also been shown to substantially increase earthworm abundance in a few studies (Blanco-Canqui et al., 2011; Korucu et al., 2018). These results suggest that CCs have the potential to increase microbial abundance, diversity, and activity, especially near the soil surface, though this depends on adequate biomass accumulation by CCs as well as the duration of time that CCs have been incorporated in the cropping system.

As cover crop biomass production is most limited by water in semi-arid dryland cropping systems, changes in soil microbial properties may be less likely. However, in their review of CC effects on soil ecosystem services in arid and semi-arid cropping stems, Blanco-Canqui et al. (2021) showed that CCs increased microbial biomass 54 to 85% in 80% of comparisons, which suggests soil microbial properties can be improved even in water limited environments. In eastern New Mexico, oats or a 6-species CC mixture increased microbial abundance 31 and 41% compared to fallow, respectively (V. Thapa et al., 2021). Additionally, arbuscular mycorrhizal fungi increased 84% and the ratio of fungi to bacteria increased 13% with an oat CC compared to fallow. Combined alkaline phosphatase and β-glucosaminidase activity was increased 44% with a 6-species CC mixture compared to fallow in one year but unaffected by CCs in the second year

(V. Thapa et al., 2021). Similarly, Calderón et al. (2016) showed that CCs increased microbial biomass 92% compared to fallow when measured at CC termination in eastern Colorado and western Nebraska. The abundance of all microbial communities was increased with CCs in their study with the greatest effect on arbuscular mycorrhizal and saprophytic fungi. However, no differences across treatments were observed at subsequent wheat planting or harvest, which suggests that the effects of CCs on soil microbial processes may be short-lived in semi-arid cropping systems or require longer time spans to develop a lasting influence. B-glucosidase, β-glucosaminidase, and phosphodiesterase activities were unaffected by CCs compared to fallow (Calderón et al., 2016). In another short-term study in western Nebraska, CCs had no effect on soil respiration compared to fallow (Rosa et al., 2021). These results suggest that CCs might increase soil microbial abundance, diversity, and activity in semi-arid dryland cropping systems, but these properties may require long-term CC adoption for lasting change to be observed.

The few studies that have investigated the effects of grazing CCs on soil microbial properties have found no differences between grazed CCs and ungrazed CCs (Anderson et al., 2021; Franzluebbers & Stuedemann, 2008; 2015; Sekaran et al., 2021). Franzluebbers et al. (2008; 2015) showed inconsistent effects of grazing CCs (from 1740 to 3570 kg LW ha^{-1} for 26 to 77 days) on soil microbial biomass carbon compared to ungrazed CC across tillage systems. Grazing CCs tended to increase soil microbial biomass carbon compared to ungrazed CCs under NT though the opposite was true under conventional tillage. Soil respiration was not different between grazed and ungrazed CCs. Soil microbial abundance in the 0- to 5-cm soil depth was similar between grazed (1.4 to 4.0 yearling steers for 30 to 69 days) and ungrazed CCs and both were 19% greater compared to no CC (Anderson et al., 2021). This was primarily because of increases in bacteria as well as arbuscular mycorrhizal and saprophytic fungi abundance though

micro-eukaryote abundance was unaffected by either CCs compared to no CC. Less is known about the effects of harvesting CCs for hay on soil microbial properties (Blanco-Canqui et al., 2020a) though investigations of corn silage harvest compared to grain harvest suggest that microbial abundance and activity could be reduced if soil temperature is increased and water content is decreased because of limited residue cover (Anderson et al., 2021; Ruis et al., 2019). Although microbial properties were not measured in their study, Blanco-Canqui et al. (2021) showed that soil temperature in the 0- to 10-cm soil depth was similar between CC harvested for hay (10-cm stubble height) and unharvested CCs though volumetric water content was 26% less, -which suggests that microbial properties may have been negatively affected by harvesting CCs for hay. These results suggest that grazing CCs maintains soil microbial properties similar to ungrazed CCs, but hayed CCs may not benefit microbial properties. This further highlights the importance of raising the cutting height of the harvester for hayed CCs compared to traditional hay crops to ensure adequate residue cover is maintained.

Objectives and hypothesis

The objectives of this dissertation research are to:

1. Determine the effects of dual-purpose CCs and tillage practice on crop yields, net returns, and soil properties in a dryland winter wheat-grain sorghum-fallow cropping system.

   Hypothesis 1: Replacing fallow with CCs, whether standing, hayed, or grazed, will decrease winter wheat yield compared to fallow.

   Hypothesis 2: Net returns will be greatest when CCs are grazed or hayed compared to standing CCs and fallow because of the increased value of CCs as forage resource.

Hypothesis 2: Occasional tillage will increase winter wheat yields and net returns compared to NT if compaction develops when CCs are grazed.

Hypothesis 3: Replacing fallow with CCs, whether standing, hayed, or grazed, will increase SOC, and MWD of wet and dry aggregates while decreasing BD and wind erodible fraction compared to fallow.

Hypothesis 4: Occasional tillage will reduce BD compared to NT if compaction develops when CCs are grazed, but negatively affect SOC, MWD of wet and dry aggregates, and wind erodible fraction compared to NT.

2. Assess post-wheat summer CC management effects on productivity, profitability, and soil properties in the semi-arid CGP.

   Hypothesis 1: Grain sorghum yields will be reduced following CCs compared to fallow because of reduced soil water and available nitrogen at grain sorghum planting though there should be no difference between CC management strategies (standing, hayed, or grazed).

   Hypothesis 2: Winter wheat yields two years after summer CCs will be unaffected by CCs or CC management strategy.

   Hypothesis 3: Net returns will be greater when CCs are grazed or hayed compared to standing CCs and fallow because of the increased value of CCs as a forage resource.

   Hypothesis 2: Regardless of management strategy, post-wheat CCs will increase SOC, and MWD of wet and dry aggregates while decreasing BD and wind erodible fraction compared to fallow.

3. Determine the effects of flexible fallow replacement with CCs on crop yields, net returns, and soil properties in a NT dryland winter wheat-grain sorghum-fallow cropping system.

   Hypothesis 1: Flexible fallow replacement with hayed CCs in wet years will maintain average winter wheat yields similar to fallow by avoiding wheat yield reductions following CCs in dry years. Net returns will be greater with flex-hayed CCs and hayed CCs compared to standing CCs and fallow because of the increased values of CCs for hay.

   Hypothesis 2: The effects of flexible fallow replacement with hayed CCs on soil properties will be similar to hayed and standing CCs in fixed rotations. All CCs will increase SOC and MWD of wet and dry aggregates while decreasing BD and wind erodible fraction compared to fallow.

4. Quantify CC grazing effects on soil properties in NT dryland cropping systems on farmer fields in western and central Kansas.

   Hypothesis: Grazing CCs will maintain similar SOC, BD, PR, MWD of wet and dry aggregates, and wind erodible fraction compared to ungrazed CCs. Integration of CCs will increase SOC and MWD of wet and dry aggregates while decreasing BD, PR, and wind erodible fraction.

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Chapter 2 - Dual-purpose cover crops maintained productivity but increased net returns and soil aggregate stability in dryland cropping systems

Abstract

Replacing fallow with dual-purpose cover crops (CCs) for grazing or haying could enhance soil health and increase cropping system profitability. However, there is concern that removing CC biomass could reduce the beneficial soil health effects of CCs for soil health and that root-limiting soil compaction may occur with grazing and haying no-till (NT) fields, which could reduce subsequent grain crop yields and require tillage for remediation. The objectives of this study were to determine dual-purpose CC management and occasional tillage (OT) effects on plant available water (PAW), crop yields, net return, and soil properties in a NT winter wheat (*Triticum aestivum* L.)–grain sorghum (*Sorghum bicolor* Moench)–fallow (WSF) cropping system. This study was conducted from 2015 to 2023 near Brownell, KS with spring oat (*Avena sativa* L.)/triticale (×*Triticosecale* Wittm.) CCs grown in place of fallow and either hayed, grazed, or left standing. Half of each plot was tilled with a sweep plow once every three years ahead of wheat planting, while the other half remained NT in a split-split-plot randomized complete block with four replications. Results showed that CC biomass production averaged 3100 kg ha^{-1} over the 8-year study. Grazing removed 40% of the available forage while haying removed 70%. Crop residue cover at wheat planting was greater with CCs (80%) compared to fallow (68%) and greater with NT (86%) compared to OT (67%). Profile PAW at wheat planting was about 21 mm greater with fallow than with CCs but not different between NT and OT. Wheat and sorghum yields were unaffected by fallow management or tillage treatments, but

fallow management effects on wheat yields varied across years. The CC treatments decreased wheat yields up to 39% compared to fallow in four years and increased yields up to 23% in one year. Net returns were in the order of grazing CCs (as an alternative to confined hay feeding) > hayed CCs > grazed CCs (as an alternative to grazing rangeland) > fallow > standing CCs and were unaffected by tillage. However, the advantage of haying over grazing (as an alternative to grazing rangeland) depended on CC biomass production. Fallow management had no effect on soil bulk density, which was slightly less with OT compared to NT. Bulk-soil and particulate-organic carbon were unaffected by fallow management or tillage. However, the mean weight diameter of water stable aggregates was 37% greater with CCs compared to fallow but unaffected by tillage. Wind-erodible fraction was unaffected by fallow management but was increased with OT compared to NT in one of two years. These results suggest that dual-purpose CCs for grazing or haying can provide forage for livestock, increase crop residue cover and soil aggregate stability, maintain crop yields, and increase net returns in NT systems with limited risk of soil compaction. If OT is necessary in a long-term NT system to correct root-limiting compaction or to control herbicide-resistant weeds, PAW, crop yields, net returns, and soil properties were generally unaffected compared to NT.

Introduction

In semi-arid environments like the central Great Plains (CGP), annual grain crop production with growing season precipitation alone is highly erratic but can be stabilized with 11 to 14 month long fallow periods to store water in the soil profile between crops (Nielsen et al., 2005; Nielsen & Vigil, 2010; Peterson & Westfall, 2004). As a water conservation practice, fallow in the traditional dryland winter wheat (*Triticum aestivum* L.)-fallow (WF) system was shown to increase soil water storage between crops, stabilize wheat yields, and limit the

occurrence of crop failure (Aiken et al., 2013; Holman et al., 2018; Nielsen & Vigil, 2018; Schlegel et al. 2017). However, fallow is an inherently inefficient practice with only 20 to 35% of precipitation received during the fallow period effectively stored for future crop use (Baumhardt & Jones, 2002; Holman et al., 2021a; Nielsen & Vigil, 2010; Peterson & Westfall, 2004). The wide-spread adoption of no-tillage (NT) has been successful in increasing soil water storage efficiency and dryland crop yields (Baumhardt et al., 2015; Peterson et al., 2020). This has facilitated the reduction in fallow frequency in the semi-arid CGP with the addition of summer crops [grain sorghum (*Sorghum bicolor* Moench), corn (*Zea mays* L.), proso millet (*Panicum milliaceum* L.), or sunflower (*Helianthus annuus* L.)] following wheat in the winter wheat-summer crop-fallow system (Baumhardt & Salinas-Garcia, 2006; Schlegel et al., 2019).

Notwithstanding, complete replacement of fallow and the transition to continuous cropping systems has been limited in the CGP compared to the northern Great Plains and Canadian Prairies because of higher potential evapotranspiration rates that increase the risk of crop failure with dryland production systems (Aiken et al., 2013; Nielsen & Vigil, 2017; 2018). Despite the challenges associated with intensified grain production in this semi-arid region, it has been proposed that growing annual forages or CCs, in place of fallow could be superior to alternative short-season grain crops (Carr et al., 2020; Holman et al., 2021b; 2023; Obour et al., 2021a). Less water is required to accumulate enough biomass for an acceptable forage harvest or CC compared to the water required to produce grain, which reduces the risk of crop failure (Holman et al., 2020; 2021; Stewart and Weil-Li, 2015; Stewart and Peterson, 2015). Additionally, annual forage and CCs are usually harvested or terminated earlier in the year than grain crops, providing a longer period for soil water recharge before planting the next crop.

Incorporating CCs into the dryland cropping systems of the semi-arid CGP could enhance soil health, suppress herbicide-resistant weeds, and increase precipitation use efficiency (Blanco-Canqui et al., 2021a; Obour et al., 2021a). Cover crops have been promoted as a strategy for alleviating soil compaction after years of heavy equipment operations (Blanco-Canqui et al, 2015; Blanco-Canqui, 2018). Additionally, by increasing the abundance of soil macropores, CCs could provide improved paths of flow through the soil to increase the rate of water infiltration and soil water storage (Blanco-Canqui et al., 2021b; DeLaune et al., 2019; Nouri et al., 2019). Reduced water infiltration is often the result of reductions in residue cover as well as distribution of soil aggregates, which could also increase the risk of soil loss by wind and water erosion. Cover crops have the potential to reduce erosion risk in dryland cropping systems by increasing residue cover and aggregate stability as well as by physically anchoring the soil in place with active root growth (Carver et al., 2022; Nouri et al., 2019; Simon et al., 2021; 2022). The sequestration of soil organic carbon (SOC) and accumulation of soil organic matter (SOM) is a major ecosystem service of growing CCs (Blanco-Canqui et al., 2015; Chahal et al., 2020; McClelland et al., 2021; Poeplau & Don, 2015). Soil aggregation is positively associated with SOC and SOM (Bagnall et al., 2022; Blanco-Canqui et al., 2011; 2015), which suggests that their sequestration and accumulation could be equally as important as residue cover for reducing soil erosion. Although CC strategies may be implemented differently across environments based on soil type, climate, and crop rotation, many of these benefits could be possible even in water-limited environments (Blanco-Canqui et al., 2021a; Obour et al., 2021a).

Despite the benefits that CCs could provide, the costs of their establishment (seed, machinery, labor, and fuel) and potential reductions in subsequent grain yields because of reduced soil water at planting present major barriers to CC adoption in semi-arid regions like the

CGP (Bergtold et al., 2017; Ramsey et al., 2019; Roesch-McNalley et al., 2017). In a recent meta-analysis, Garba et al. (2022) showed that the costs of CCs exceeded the benefits in environments with less than 700 mm average annual precipitation and concluded that careful site-specific plans are required for successful adoption of CCs in such environments. Holman et al. (2018; 2021a) showed that in years when precipitation was above average, wheat yields were unaffected by CCs grown in place of fallow in western Kansas with 425 mm average annual precipitation. However, in years of below average precipitation, yields were reduced by as much as 70%. In a later study, these authors showed that under certain conditions wheat yields in semi-arid regions were unaffected by CCs grown in place of fallow (Holman et al., 2021b; 2022). In this case, wheat yields were unaffected when yields were very low (averaged 0.92 Mg ha^{-1}) throughout the study period except one year when wheat yield was very high (5.85 Mg ha^{-1}). Both scenarios of extremely dry and wet in-season moisture availability masked any differences in soil water availability following a CC compared to fallow. However, the authors showed that net returns were greater when CCs were harvested for hay compared to unharvested CCs (Holman et al., 2018; 2021b). These result suggests that replacing fallow with dual-purpose CCs used for forage may have the greatest potential to balance cropping system goals in water-limited environments.

Most species used as CCs have excellent forage nutritive value attributes (Jenkins et al., 2019; Landry et al., 2018; Obour et al., 2022; Simon et al., 2021; Titlow et al., 2014) and could supply high-quality forage for livestock to compensate for their production costs and potentially increase system profitability (Franzluebbers & Stuedemann, 2007; Drewnoski et al., 2018; Schomberg et al., 2014). Even when subsequent crop yields are reduced, the diversification of income streams provided by dual-purpose CCs could facilitate increased net profit and income

stability (Bell et al., 2014; P. Johnson et al., 2013; Russelle et al., 2007). Grazing CCs could extend the livestock grazing season, delay grazing of native rangelands, and is the most efficient means of utilizing dual-purpose CCs in years when biomass accumulation is relatively low (Kelly et al., 2021; Simon et al., 2021; Titlow et al., 2014). Notwithstanding, in years when precipitation is high, forage accumulation of both CCs and rangeland will be high so that the best use of dual-purpose CCs may be for hay or silage that can be stored and fed later (Holman et al., 2018; 2022; Jenkins et al., 2019; Obour et al., 2022; Simon et al., 2021). However, the impact of management strategies like grazing CCs or harvesting CCs for hay on soil health in NT dryland cropping systems of the semi-arid CGP is not fully understood (Blanco-Canqui et al., 2013; Kelly et al., 2021; Simon et al., 2021; 2022).

One primary concern with grazing CCs in NT systems is the risk of excessive soil compaction from animal hoof traffic that could suppress subsequent crop yields and require some form of tillage for remediation (Blanco-Canqui et al., 2021b; Franzluebbers & Stuedemann, 2008; Schomberg et al., 2021). If root-limiting soil compaction were to develop, one possible solution could be occasional tillage (OT) to strategically ameliorate soil compaction if it occurs, after which the cropping system would return to NT (Obour et al., 2021b; Schlegel et al., 2020; Vandeveer et al., 2023). In a winter wheat–grain sorghum–fallow rotation, OT was implemented with a single tillage event every three years either in summer before wheat planting or summer following wheat harvest (Schlegel et al. 2020; Vandeveer et al., 2023). However, OT may not be a sustainable solution if tillage in long-term NT systems can significantly degrade soils in such a way that all improvements in soil properties gained from long-term NT management can be lost following the implementation of a single tillage event (Grandy & Robertson, 2006). In addition to compaction concerns, removing CC biomass through grazing or

haying could limit the beneficial effects of CCs for soil health (Franzluebbers & Stuedemann, 2008; 2014; 2015). Past research suggests that only mild increases in soil bulk density (BD) or penetration resistance could be expected with CC grazing (Blanco-Canqui et al., 2021b; Franzluebbers & Stuedemann, 2008; Kelly et al., 2020; Schomberg et al., 2021). In fact, grazed or hayed CCs could increase SOC, water stable aggregates, dry aggregate stability, and water infiltration compared to no CC (Blanco-Canqui et al., 2013; Kelly et al., 2020; Simon et al., 2021; 2022). Currently there is insufficient information available, especially regarding impacts of long-term (>5-yr) CC grazing, in the literature. The objectives of this current research were to determine the effects of dual-purpose CC management and OT on plant available water (PAW), grain crop yields, net returns, as well as soil chemical and physical properties in a NT dryland winter wheat–grain sorghum–fallow cropping system.

Materials and methods

Site and study description

This study was conducted from 2015 to 2023 at the Kansas State University Hearting Beason Ranch (38˚38′23″ N, 99˚44′45″ W) near Brownell, KS to investigate best management strategies for CCs to replace fallow in the traditional dryland cropping systems of the semi-arid CGP. The soil at the study site was Harney silt loam (fine, smectitic, mesic Typic Argiustolls), a soil series of large extent formed from loess on uplands in west-central Kansas (National Cooperative Soil Survey, 2023). Long-term average (30 yr) annual precipitation at the study site was 566 mm (Table 2.1). The study design was a split-plot randomized complete block with four replications. Crop phase was the main plot, and split-plots fallow and spring oat (*Avena sativa* L.)−triticale (× *Triticosecale* Wittm.) mixed CCs there were either grazed, hayed, or left standing for a total of four treatments. Split-plots were 18.2 m wide and 30.5 m long. In 2018, the study

was modified into a split-split-plot design by dividing each split-plot into NT and OT to evaluate possible interactions between CC management and tillage for a total of eight treatments. The split-split-plots were 9.1 m wide and 30.5 m long. All crop phases (wheat, sorghum, or fallow) of this WSF rotation were present each year, which allowed wheat, sorghum, and CC/tillage treatments to be implemented in every year of the study.

Management

Each year, winter wheat was planted at 67 kg ha^{-1} the 1st week of October using a NT drill (Model 3P1006NT, Great Plains Manufacturing, Salina, KS) with 19 cm row spacing. Each plot received 20 kg ha^{-1} P_2O_5 as monoammonium phosphate (11–52–0) with the seed at planting. At spring green up, (~approximately by 25 March), an additional application of 84 kg nitrogen (N) ha^{-1} as urea (46–0–0) was broadcasted on each plot. Postemergence winter annual weed control in wheat was accomplished with metsulfuron methyl at 5.3 g ai ha^{-1} in or dicamba at 140 g ae ha^{-1} across years. Wheat was harvested in early July (Fig. 2.1) using a Massey Ferguson 8XP small plot combine harvester (Massey Ferguson, Duluth, GA, USA). Typically, one herbicide application of glyphosate at 1,260 g ae ha^{-1} tank-mixed with 2,4-D at 560 g ae ha^{-1} was made following wheat harvest to control weeds through the late summer and another application of glyphosate at 1,260 g ae ha^{-1} and atrazine at 1,160 g ai ha^{-1} was made the following spring to control weeds before planting grain sorghum. Following an 11-month fallow period, sorghum was planted at 77,000 seeds ha^{-1} the 1st week of June using the same NT drill as used for wheat except with 38.1 cm row spacing. Nitrogen and P_2O_5 were applied at sorghum planting at similar rates as previously described for wheat. Grain sorghum was harvested in mid-October to 1st week in November (Fig. 2.1) using the same small plot combine harvester as used for wheat.

Cover crops were planted in mid-March as field conditions allowed using the same NT drill as used for wheat and sorghum with 19 cm row spacing at a seeding rate of 36 and 43 kg ha^{-1} for oat and triticale, respectively, in the fallow period between grain sorghum harvest and the planting of the next winter wheat crop in the rotation (Fig. 2.1). Typically, four herbicide applications were made through the late spring and summer to control weeds through the fallow period before planting winter wheat again. Generally, dicamba at 280 g ae ha^{-1} alone or with 1,260 g ae ha^{-1} of glyphosate was applied in March, followed by 840 g ae ha^{-1} paraquat and 0.032 g ae ha^{-1} carfentrazone in May. Two more sequential burndown applications of glyphosate at 1,260 g ae ha^{-1} with 560 g ae ha^{-1} of 2,4-D were made in July and September to control weeds prior to winter wheat planting in October. Two herbicide applications were eliminated when CCs replaced a portion of the fallow period. Cover crops were hayed, grazed, and chemically terminated by mid- to late June in an effort to minimize negative effects on subsequent winter wheat yields (Holman et al., 2018; 2021b).

Cover crops were grazed with yearling heifers (*Bos taurus*) at densities from 877 to 1,755 kg liveweight ha^{-1} for 4–7 d to remove approximately 50% of the available forage based on visual assessment in fenced paddocks across the four replications of this study. Grazing generally coincided with oat/triticale heading (Zadoks growth stages 51–59; Zadoks et al., 1974), which was selected to optimize forage mass and nutritive value (Landry et al., 2018). On or within one week following the last day of grazing, hayed CCs were harvested at a 15-cm cutting height using a small plot forage harvester (Carter Manufacturing Company, Inc., Brookston, IN). Cover crops were then chemically terminated within one week following hay harvest with glyphosate and 2,4-D in 2015 and with paraquat and carfentrazone following 2016 to control herbicide-resistant kochia [*Bassia scoparia* (L.) A.J. Scott]. Beginning in 2018, split-plots were divided

into split-split-plots of NT and OT. Implemental of OT was accomplished by tilling once in July or August (Fig.2.1) following CC termination prior to winter wheat planting to a depth of 7.5 cm using a sweep plow equipped with 1.5 m blades and treader (Premier Tillage Inc., Quinter, KS, USA), which is a non-inversion, conservation tillage implement commonly used in the semi-arid CGP. Using this strategy, OT plots were tilled only once every three years in the fallow phase of the winter wheat–grain sorghum–fallow rotation. Occasional tillage typically eliminated one herbicide application.

Cover crop biomass

Each year before grazing was initiated, available CC biomass was determined for the grazing treatment by hand clipping, to the ground level, two areas of 0.50 m^2 per plot. Samples were dried at approximately 50˚C for a minimum of 48 h in a forced-air oven and weighed to determine dry matter content. After grazing, each plot was resampled as previously described to determine CC residue remaining. Standing CC treatments were sampled similarly immediately prior to chemical termination. Hayed treatments were harvested with a small plot forage harvester from a strip of 0.9 m by 30.5 m in the middle of each plot. Whole plot fresh weights were recorded, subsamples collected and weighed, and then oven-dried to determine CC hay yield. Cover crop biomass removed with haying was subtracted from the standing CC biomass to estimate CC residue remaining. Following the cutting of a sample strip, the remaining plot area in the hayed plots were harvested with the same equipment, and forage was removed from the plots.

Plant available soil water

Plant available water at winter wheat planting in the soil profile (0-120 cm) and surface (0-15 cm) was determined gravimetrically each year in September. Two soil cores were taken

from each plot with a hydraulic probe (Giddings Machine Company, Windsor, CO) and samples were portioned into 15 cm increments to the 30 cm soil depth and into 30 cm increment thereafter to the 120 cm soil depth. Samples were weighed fresh and then dried at 105 °C for at least 48 h or until constant weight to estimate BD by mass of oven dry soil divided by volume of the core. The gravimetric water content (GWC) was computed as the difference between wet soil weight and weight after drying at 105 °C, divided by dry weight of the sample. Data for the two cores were averaged for a single soil water content measurement, which was converted to volumetric water content using measured BD at each sampling depth. The equivalent depth of plant available soil water was then calculated as measured volumetric soil water content minus soil water content at permanent wilting point (−1.5 MPa matric potential) multiplied by the length of the soil core.

Grain crop yields

Both winter wheat and grain sorghum yields were determined by harvesting an area 1.5 m wide by 30.5 m long from the center of each plot. Winter wheat was harvested in July and grain sorghum was harvested in October each year of the study (Fig. 2.1). Grain moisture content was determined using a DICKEY-john grain moisture tester (DICKEY-john Inc., Auburn, IL, USA), and yield of both wheat and grain sorghum was adjusted to 13.5% moisture content. Exceptional drought conditions resulted in a failed grain sorghum crop in 2022 (<75 and <50% of normal preceding fallow and growing season precipitation, respectively) and failed winter wheat (<50% of normal preceding fallow and growing season precipitation) and grain sorghum crops (<50 and <75% of normal preceding fallow and growing season precipitation, respectively) in 2023 (Table 2.1).

Economic analysis

Net returns were calculated for the fallow/CC and subsequent wheat phase of the WSF cropping system as total fallow/CC and wheat revenue minus total fallow/CC and wheat costs for each treatment and year (Table A.1). Estimates of current field operations and input costs used 5-yr average custom rate values published by Kansas State University Land Use Survey Program and the Kansas Department of Agriculture (AgManager, 2021). Winter wheat grain and CC hay prices were determined from the USDA Economic Research Services market reports (USDA ERS, 2021) for Kansas and calculated as \$0.21 kg^{-1} for winter wheat and \$0.15 kg^{-1} for CC hay, which was estimated from published values for good brome and alfalfa hay. Cover crop grazing lease rates were calculated by two strategies to represent scenarios where the alternative to grazing CCs is grazing native rangeland (\$73 AUM^{-1}) or where the alternative to grazing CCs is confined feeding of hay (\$146 AUM^{-1}). For the first scenario, the lease rate was calculated using the return on investment (ROI) method described by Hofstrand & Edwards (2015) using a land value of \$3,778 ha^{-1} and 2.0% ROI for Trego County, Kansas (Reid, 2024). Lease rates were converted from US\$ ha^{-1} to US\$ animal unit month $(AUM)^{-1}$ by multiplying values by 4.9 ha divided by 6 months and then multiplying by 1.2 animal unit equivalents (Ohlenbusch & Watson, 1994). For the second scenario, the lease rate was calculated using the previously mentioned hay price of \$0.15 kg^{-1} and a yardage (i.e., non-feed cost per head for every day that an animal is fed harvested feed in some form of confinement) cost of \$0.50 $head^{-1}$ day^{-1}. Lease rates were calculated as US\$ AUM^{-1} by multiplying the hay price by 871.91 kg AUM^{-1} plus \$0.50 $head^{-1}$ day^{-1} multiplied by 30 days. Total variable costs were calculated as the sum of the expenses for fertilizer product and application costs, herbicide products and application, tillage operations, seed, planting, grain harvesting, as well as forage swathing, baling, and stacking

bales at field edge. All costs and revenue were calculated on a ha^{-1} basis in US$ (Table A.1). Net returns determined across the eight years of this study were used to calculate cumulative exceedance probabilities of net returns (probability of obtaining a minimum net return) for Fallow Management treatments to determine probabilities of at least breaking even (income = expenses) and obtaining income of at least \$200 ha^{-1} similar to analyses conducted by Nielsen et al. (2016). Sensitivity analyses were performed to determine the variability in net returns and trade-offs across a range of CC biomass yields (0 to 5000 kg biomass ha^{-1}) and subsequent winter wheat yields (0 to 5000 kg grain ha^{-1}).

Residue cover and soil properties

Crop residue cover measurements and soil samples were collected from each split-split-plot in fall 2021 and 2022 following the termination of CCs and implementation of tillage but before winter wheat planting. These sampling times represented three cycles of CCs in the WSF rotation with plots sampled in 2021 following CCs grown in 2021, 2018, and 2015 and plots sampled in 2022 following CCs grown in 2022, 2019, and 2016. The line-transect method was used to determine surface residue cover (USDA-NRCS, 2002). Briefly, a 3.05-m long wooden rod with marks at every 0.305-m interval was randomly placed at two 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 two sub-measurements were averaged to obtain one value for each plot.

For the determination of BD, two intact soil cores (5-cm diameter) were randomly taken from the 0-5 and 5-15 cm depths within each plot. The two samples from each depth were dried separately at 105° C for 48 hr, and BD was determined as mass of oven dry soil divided by volume of the core. Additionally, 10 soil cores (2.5-cm diameter) were randomly collected

within each plot, divided into the 0-5 and 5-15 cm depths, and composited by depth. Samples were air-dried, crushed, and sieved to pass through a 2 mm stainless steel screen. A portion of the 2 mm sieved 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 LECO TruSpec CN analyzer (LECO Corporation, St. Joseph, MI) after pretreating samples with 10% (v/v) HCl to remove carbonates (Nelson & Sommers, 1996). Carbon mass was calculated by multiplying SOC concentrations by soil BD and the thickness of the soil layer. Particulate organic carbon (POC, >53 μm) was determined by the procedure outlined by Cambardella & Elliott (1992). Briefly, the POC fraction was isolated by dispersing soil in 5 g L^{-1} hexametaphosphate and passing the dispersed soil samples through a 53 μm sieve. Samples were dried in a forced-air oven and POC content was determined by dry combustion (Nelson & Sommers, 1996). Particulate organic carbon mass was calculated as previously described.

Lastly, 5 intact soils samples were collected from the 0-5 and 5-15 cm soil depths in each plot with a flat shovel for the determination of water stable aggregates and dry aggregate stability. Soil aggregates were allowed to air-dry and were then gently passed through a 19 mm sieve. From there, two approximately 50 g subsamples of 8-4.75 mm diameter dry aggregates were obtained for each replicated treatment and used to estimate mean weight diameter (MWD) of water stable aggregates by the wet-sieving method (Nimmo & Perkins, 2002). The remaining aggregate sample of approximately 3000 g was used to estimate wind-erodible fraction (WEF; <0.84 mm) by the dry-sieving method (Chepil, 1962). For the wet sieving method, an approximate 50 g sample was placed on top of a stack of nested sieves of 2-, 1-, and 0.25-mm sized openings in a water column (Nimmo & Perkins, 2002). The samples were allowed to wet by capillarity for 5 minutes, after which the stacks of sieves were vertically oscillated a distance

of 3.7 cm at 30 oscillations minute^{-1} for 5 minutes. The amount of soil retained on each sieve was transferred into glass beakers, dried at 105° C, and weighed to determine the proportion of water stable aggregates within each size fraction. Each dry sample was then corrected for coarse sand by mixing the oven-dried aggregates with 30 ml of 0.5% sodium hexametaphosphate to disperse soil particles and allowing them to soak for a minimum of four hours. Samples were then swirled on an orbital shaker for an additional four hours. Each dispersed sample was then passed back through individual sieves with the same size openings. The recovered sand was oven-dried and weighed to correct for coarse soil particles. Sand-corrected values were used to compute MWD (Nimmo & Perkins, 2002). For the dry-sieving method, an approximately 3000 g air-dried sample was placed on top of a stock of nested sieves of 6.3-, 2-, 0.84-, and 0.42-mm sized openings (Chepil, 1962). Samples were shaken for 5 min using a portable orbital sieve shaker (W.S. Tyler Model RX-812, Mentor, OH). The soil particles remaining on each sieve were weighed and the data was used to compute WEF (Chepil, 1962).

Statistical analysis

Analyses of CC biomass, crop residue cover, grain yields, net returns, as well as soil chemical and physical properties were performed using the PROC GLIMMIX procedure in SAS ver. 9.4 (SAS Institute, 2012). For CC biomass, Fallow Management (M), Year (Y), and their interactions were modeled as fixed effects, while replication and its interaction with fixed effects were considered random in the model. For crop residue cover, plant available water, grain yields, net returns, BD, SOC, POC, MWD, and WEF, Fallow Management, Tillage (T), Year, and their interactions were modeled as fixed effects, while replication and its interaction with fixed effects were considered random in the model. Interactions and treatment effects were considered significant at $\alpha = 0.05$. Correlation analysis among crop residue cover, BD, SOC, POC, GWC,

MWD, and WEF was conducted using the PROC CORR procedure in SAS. Correlations were considered significant at $\alpha = 0.05$.

Results

Precipitation patterns over the study period

Typical of the semi-arid climate of the CGP, precipitation during the study period (2015-2023, Table 2.1) varied year-to-year and provided a broad range of water availability conditions for quantifying cropping system productivity. The average precipitation received during the CC, wheat, and sorghum growing seasons was 242, 359, and 331 mm, respectively, which was near the 30-yr average for each period. However, precipitation ranged substantially from lows of 165, 209, and 150 mm to highs of 354, 461, and 601 mm for the CCs, wheat, and sorghum growing seasons, respectively. Similar variance was observed during the fallow periods that preceded each crop (Table 2.1). On average, precipitation received during the fallow periods preceding CC or sorghum were 55 and 519 mm, respectively, which was near the 30-year average. Precipitation received during the fallow period preceding wheat if following sorghum was 547 mm or approximately 2.3-fold the precipitation received during the shortened fallow period if following CCs (239 mm).

Cover crop biomass

The two-way interaction of Fallow Management and Year was significant for CC biomass (Table 2.2) with CC biomass retained following grazing, haying, and termination varying substantially over the study period (Fig. 2.2). Cover crop biomass retained following haying was less than the standing CC in all but one year when hayed CCs retained similar biomass as standing CCs. Grazed CCs retained less biomass than standing CCs in six years and was similar to standing CC in two years (Fig. 2.2). Cover crop biomass retained following

grazing was greater than hayed CCs in three years and similar to hayed CCs in five years. The main effects of Fallow Management and Year were both significant for CC biomass (Table 2.2). On average, standing CCs produced 3104 kg biomass ha^{-1}, and haying and grazing retained 33 and 62% of the standing CC biomass, respectively. Cover crop biomass retained as residue was >2000 kg ha^{-1} in four years and <2000 kg ha^{-1} in the other four years (Table 2.2).

Plant available water and grain crop yields

The three-way interaction of M × T × Y was not significant for either profile (0-120 mm) or surface (0-15 cm) PAW at winter wheat planting nor were the two-way interactions of M × T or T × Y (Table 2.2). Similarly, the two-way interaction of M × Y was not significant for profile PAW. However, there was a significant effect of M × Y for surface PAW. In five of eight years, PAW at the surface was not significantly different between Fallow Management treatments (Fig. 2.3). However, CCs decreased surface PAW 47 to 89% compared to fallow in 2016 and 2017. In one year, grazed and hayed CCs had 11% less surface PAW than standing CCs, though CC treatments were all similar to fallow (Fig. 2.3). The main effects of Fallow Management and Year but not Tillage were significant for both profile and surface PAW (Table 2.2). On average, profile PAW was not different between standing, hayed, and grazed CC treatments but all decreased PAW by 19% compared to fallow. Similarly, hayed and grazed CCs decreased average surface PAW 18% compared to fallow though standing CCs were similar to fallow.

The three-way interaction of M × T × Y as well as the two-way interactions of M × T and T × Y were not significant for winter wheat yields (Table 2.3). However, there was a significant interaction of M × Y. Winter wheat yields were not different across Fallow Management treatments in two years though CC treatments decreased yields 15 to 39% compared to fallow in four years and increased yields 23% compared to fallow in one year with one year of crop failure

for all Fallow Management treatments due to exceptional drought when preceding fallow and growing season precipitation were <50% of normal (Fig. 2.4; Table 2.1). The main effect of Year but not Fallow Management or Tillage was significant for winter wheat yields (Table 2.3). Winter wheat yields varied over the study period with four years greater than 3000 kg ha^{-1}, three years less than 3000 kg ha^{-1} and one year of crop failure as previously mentioned. The three-way interaction of M × T × Y as well as the two-way interactions of M ×T, M × Y, and T × Y were not significant for grain sorghum yields (Table 2.3). Similar to winter wheat yields, grain sorghum yields were unaffected by Fallow Management or Tillage but varied over the 8-yr study. Sorghum yields were greater than 5000 kg ha^{-1} in three years, two years less than 5000 kg ha^{-1}, and two years of crop failure due to exceptional drought when preceding fallow and growing season precipitation were <75 or <50% of normal.

Net returns

The three-way interaction of M × T × Y as well as the two-way interactions of M × T and T × Y had no significant on cropping system net returns (Table 2.3). However, the two-way interaction of M × Y had an effect on net returns. Generally, net returns were greatest with grazed or hayed CCs and least with fallow or standing CCs (Fig. 2.5). Net returns from grazed CCs as an alternative to confined hay feeding were greater than fallow in five of eight years and greater than standing CCs in seven years. However, net returns from grazed CCs as an alternative to grazing rangeland were greater than fallow in three of eight years and greater than standing CCs in five years (Fig. 2.5). Net returns from hayed CCs were greater than fallow or standing CCs in four of eight years and greater than grazed CCs as an alternative to grazing rangeland in one year. Standing CCs provided net returns that were less than fallow in two years and greater than fallow in one year (Fig. 2.5). The main effects of Fallow Management and Year

but not Tillage were significant for cropping system net returns (Table 2.3). On average, net returns across Fallow Management treatments were in the order of grazed CCs as an alternative to confined hay feeding > hayed CCs > grazed CCs as an alternative to grazing rangeland > fallow > standing CCs. Cumulative exceedance probability analysis indicated that the probability of obtaining break-even net returns was similar among treatments but the probabilities of obtaining net returns above break-even were always greater for grazed and hayed CCs compared to fallow or standing CCs (Fig. 2.6). For example, the probability of obtaining net returns equal to or greater than \$200 ha^{-1} was 84, 83, 83, 73, and 55% for grazed CCs as an alternative to confined hay feeding, hayed CCs, grazed CCs as an alternative to grazing rangeland, fallow, and standing CCs, respectively. Sensitivity analyses further showed the variability and trade-offs in potential net returns from grazed or hayed CCs depending on CC biomass yield and subsequent winter wheat yields (Table 2.4). Analyses show that when wheat yield was 2500 kg ha^{-1} and CC biomass was 2000 kg ha^{-1}, there was a \$69.82 ha^{-1} advantage of haying over grazing as an alternative to grazing rangeland. However, when CC biomass was 4000 kg ha^{-1} that was a \$139.63 ha^{-1} advantage of haying over grazing as an alternative to grazing rangeland (Table 2.4).

Residue cover and soil properties

The three-way interaction of M × T × Y as well as the two-way interactions of M × T, M × Y, and T × Y had no significant effect on crop residue cover at winter wheat planting (Table 2.5). However, the main effects of M × T × Y were all significant. On average, crop residue cover was not different between standing, hayed, or grazed CC treatments, but all CC treatments were about 12.3% greater than fallow, and NT had 18.8% more crop residue cover than OT. Averaged across treatments, crop residue cover was 10% greater in 2021 than in 2022 (Table 2.5). Soil organic carbon concentrations were unaffected by main effects or interactions of

Fallow Management, Tillage, or Year. However, there was a significant effect of Year on SOC stock in the 0-5 or 5-15 cm soil depths (Table 2.5, 2.6). Soil organic carbon stock was significantly greater in both depths in 2022 than in 2021. Similarly, POC concentrations were unaffected by main effects or interactions of Fallow Management, Tillage, or Year. Year was the only factor to significantly affect POC in the 0-5 cm soil depth (Table 2.5). Particulate organic carbon in the 0-5 cm soil depth was greater in 2022 than in 2021, but POC in the 5-15 cm soil depth was unaffected by main effects or interactions of Fallow Management, Tillage, or Year (Table 2.6).

The three-way interaction effect of M × T × Y as well as the two-way interactions of M × T, M × Y, and T × Y were not significant for BD in either the 0-5 or 5-15 cm soil depths (Table 2.5, 2.6). However, the main effect of Tillage and Year but not Fallow Management was significant for BD in the 0-5 cm soil depth. On average, OT had a 5% lower BD than NT, and BD was greater in 2022 than in 2021. Similarly, the main effect of Year but not Fallow Management or Tillage was significant for BD in the 5-15 cm soil depth. Like the 0-5 cm soil depth, BD in the 5-15 cm soil depth was greater in 2022 than 2021. Fallow Management was the only factor to significantly affect MWD in either the 0-5 or 5-15 cm soil depths (Table 2.5, 2.6). On average, MWD of water stable aggregates was not different between standing, hayed, and grazed CC treatments in either soil depth. However, all CC treatments increased MWD by 26 and 51% compared to fallow in the 0-5 and 5-15 cm soil depths, respectively. The three-way interaction of M × T × Y as well as the two-way interactions of M × T and M × Y were not significant for WEF in either the 0-5 or 5-15 cm soil depths (Table 2.5, 2.6). The two-way interaction of T × Y was significant for WEF in the 0-5 cm soil depth but not in the 5-15 cm soil depth. In 2021, WEF was not different across tillage treatments, but in 2022, WEF was 17%

greater with OT than NT (Fig. 2.7). The main effects of Fallow Management and Tillage were not significant for either the 0-5 or 5-15 cm soil depths (Table 2.5, 2.6). However, the main effect of Year was significant for the 0-5 cm soil depth but not the 5-15 cm soil depth. The WEF was greater in 2022 than in 2021.

Relationships between soil chemical and physical properties

First, there were significant positive correlations between CC biomass and crop residue cover as well as MWD of water stable aggregates (Table 2.7). Bulk density had significant negative correlations with SOC, POC, MWD, and WEF and a significant positive correlation with GWC. There were also significant positive correlations between SOC and POC as well as WEF and a significant negative correlation between SOC and GWC (Table 2.7). Particulate organic carbon had a significant positive correlation with WEF and a significant negative correlation with GWC. Lastly, there was a significant negative interaction between GWC and WEF.

Discussion

Dual-purpose CCs could supply high-quality forage for livestock to compensate for their production costs and potentially increase system profitability (Franzluebbers & Stuedemann, 2007; Drewnoski et al., 2018; Holman et al., 2018; Schomberg et al., 2014). However, there is concern that removing CC biomass through grazing or haying could limit the beneficial effects of CCs for soil health (Franzluebbers & Stuedemann, 2008; 2014; 2015). In the present study, CC biomass remaining after either haying or grazing was usually less than but occasionally similar to the standing CC. On average, CC biomass remaining after grazing and haying was 62 and 33% of the standing CC, respectively. However, all CC treatments increased crop residue cover at subsequent wheat planting compared to fallow. In fact, despite reductions in residue

amount, grazing or haying CCs maintained percent crop residue cover similar to standing CCs. This was likely achieved because CCs in this study were managed as dual-purpose for forage production and enhancing soil health, which was different from other studies that placed greater priority on forage production and therefore had substantially higher rates of biomass removal (Blanco-Canqui et al., 2021a; 2021b). Also of important note is that CC root mass, although not quantified in this study, likely provided additional biomass returned to the system in all CC treatments compared to fallow. Crop residue cover at subsequent wheat planting was reduced from 86.1% with NT to 67.3% with OT, which is an expected outcome of tillage operations (Hansen et al., 2012; Triplett & Dick, 2008). However, substantial crop residue cover (>50%) was maintain in this system as the tillage tool used here was a sweep plow, which is a non-inversion, conservation tillage implement commonly used in the semi-arid CGP. An inversion-type tillage tool such as a moldboard plow or disk would be expected to reduce crop residue cover significantly more than what is expected with a sweep plow (Kettler et al., 2000; Quincke et al., 2007).

Cover crop biomass accumulation was highly variable over the study period and suggests that, while CCs could be a suitable short-term feed source for livestock, they are unlikely to be a reliable long-term feed source in the semi-arid CGP. In the present study, CCs produced as much as 5483 kg ha^{-1} but as little as 1607 kg ha^{-1}. This could pose another potential barrier to dual-purpose CC adoption, as producers will be required to have alternate plans for feeding livestock when CCs yields are insufficient. Holman et al. (2023) proposed harvesting and storing excess CC production either as hay or silage in wet years and grazing CC in dry years as a means to stabilize forage demand in highly variable moisture limited environments. Notwithstanding, the greatest barrier to CC adoption in the semi-arid CGP is the risk of limiting subsequent grain yield

potential because of reduced soil water at planting (Bergtold et al., 2017; Ramsey et al., 2019; Roesch-McNalley et al., 2017). In the present study, CCs (standing, hayed, or grazed) decreased profile PAW at subsequent wheat planting by 19% compared to fallow on average, which was similar to previous findings in the semi-arid CGP (Holman et al., 2018; 2021b; Nielsen et al., 2016). Interestingly, despite reduced profile PAW, average wheat yields were not significantly different between Fallow Management treatments, which was similar to other observations in the region (Holman et al., 2021b; 2022). In their case, wheat yields were unaffected because productivity was often very low (averaged 920 kg ha^{-1}) except one year when wheat yield was very high (5850 kg ha^{-1}).

In an earlier study, Holman et al. (2018) showed that in years when precipitation was above average, wheat yields were unaffected by CCs grown in place of fallow. However, in years of below average precipitation, yields were reduced by as much as 70%. They concluded winter wheat yield potential in the range of 1500 to 3500 kg ha^{-1} would likely to be reduced when growing a CC in dry years and proposed flex-fallow as a management solution. In the present study, wheat yields were relatively more stable year-to-year and ranged from a low of 2455 kg ha^{-1} to a high of 3832 kg ha^{-1}. Another key difference is that in one year, CC management strategies increased subsequent wheat yields compared to fallow, which was never observed by Holman et al. (2018; 2021b) or Nielsen et al. (2016). Notwithstanding, one year of complete wheat crop failure and two years of complete sorghum crop failure were also observed in the present study due to exceptional drought. Similar to Holman et al. (2021b), no difference was observed between fallow treatment in these years. On average, the grain yields of sorghum grown two years after CCs replaced fallow in the WSF rotation in the present study were

unaffected by fallow management, which agrees with the observations of Holman et al. (2021b) and Nielsen et al. (2017).

A primary concern with grazing CCs in NT systems is the risk of root-limiting soil compaction that could suppress subsequent crop yields and require some form of tillage for remediation (Blanco-Canqui et al., 2021b; Obour et al., 2021a; Schomberg et al., 2021). In the present study, average profile and surface PAW as well as wheat and sorghum yields were not different between grazed and standing CC treatments and were also unaffected by tillage system, which suggest that OT was not required to remediate yield-limiting soil compaction. However, grazing was of very short duration and seldom on wet soil during this study period. Research results on soil physical and chemical properties from season-long grazing over multiple years is needed to better determine effects of this practice. Similarly, Schlegel et al. (2020) reported no significant difference in PAW or wheat and sorghum yields with a single tillage pass with a sweep plow in a long-term NT WSF rotation. Occasional tillage was found to increase PAW compared to NT in a similar environment which might have been due to soil surface compaction and little residue cover (Holman et al. 2021c). Nevertheless, the benefit of strategic tillage to help manage herbicide-resistant weeds may still make OT a desirable practice for some when weed competition decreases yields in long-term NT systems as was observed by Obour et al. (2021b).

Even when subsequent crop yields are reduced after CCs, the diversification of income streams provided by integrated crop-livestock systems can facilitate increased net profit and profit stability (Bell et al., 2014; P. Johnson et al., 2013; Russelle et al., 2007). Despite either reduced or similar subsequent wheat yields following CCs compared to fallow, Holman et al. (2018; 2021b) showed that net returns were greater when CCs were harvested for hay compared

to unharvested CCs, which suggests that replacing fallow with dual-purpose CCs used for forage may have the greatest potential to balance cropping system goals in water-limited environments. In the present study, net returns were in the order of grazed CCs as an alternative to confined hay feeding hayed CCs > grazed CCs as an alternative to grazing rangeland > fallow > standing CCs, and this trend was consistent across years. However, sensitivity analyses revealed that the advantage of haying over grazing (as an alternative to grazing rangeland) depended on CC biomass production with a greater advantage of haying when CC biomass was high and less of an advantage when CC biomass was low. In the study by Holman et al. (2018; 2021b) as well as the present study, CCs reduced the number of herbicide applications and associated expenses required to control weeds during the fallow period but generally increased total costs of production compared to fallow, especially when the cost of hay harvest is considered. In their study, Holman et al. (2021b) showed that the costs of production differed across CC species or mixtures and highlighted the importance of considering seed costs when selecting CC species or mixtures. In the present study, oats and triticale were selected based on their past performance in the region, consistently producing substantial biomass, as well as for their relatively low cost of seed (Holman et al., 2018; Holman et al., 2021b; Obour et al., 2019, 2020). Increasing costs of seed with more diverse CC mixtures may limit net returns directly because of their seed cost as well as indirectly if income from grazing or haying was limited by lower biomass production. Occasional tillage had similar average net returns as NT, which agreed with the results reported by Vandeveer et al. (2023) and supports their conclusion that if OT is necessary in a long-term NT system, for example to correct root-limiting compaction or to control herbicide-resistant weeds, crop yields and net returns were not significantly affected compared to NT.

A primary concern with the adoption of dual-purpose CCs is that removing CC biomass through grazing or haying could limit the beneficial effects of CCs for soil health (Franzluebbers & Stuedemann, 2008; 2014; 2015). Grazing CCs in NT systems has been of particular concern because of the risk of excessive soil compaction from animal hoof traffic that could suppress subsequent crop yields and require some form of tillage for remediation (Blanco-Canqui et al., 2021b; Franzluebbers & Stuedemann, 2008; Schomberg et al., 2021). In the present study, grazed and hayed CCs had no significant effect on SOC, POC, BD, or WEF compared to standing CCs or fallow, which agrees with previous studies that concluded CC grazing or haying had no effect on soil properties compared to standing CCs (Blanco-Canqui et al., 2013; 2020; 2021b; Kelly et al., 2021; Simon et al., 2021; 2022). However, in the present study, grazing only occurred for a short period and compaction was not measured near watering areas or in cattle paths that develop over long periods of grazing. All CCs increased MWD of water stable aggregates compared to fallow in the 0-5 cm and 5-15 cm soil depth, which agrees with the findings of Kelly et al. (2021) and Simon et al. (2021). This suggests that, while CCs may not have immediate or consistent effects on all soil properties in semi-arid dryland cropping systems, MWD of water stable aggregates appear to be robust indicator of soil health response to CCs. Although root-limiting compaction was not observed because of grazing CCs in the present study, OT could be a possible solution to strategically ameliorate soil compaction when and where it occurs before returning to NT (Obour et al., 2021b; Schlegel et al., 2020; Vandeveer et al., 2023). In the present study, OT had no effect on SOC, POC, or MWD of water stable aggregates compared to NT, which agrees with the observations of Obour et al. (2021b) who investigated strategic tillage of long-term NT systems using a sweep plow similar to the present study. However, OT did decrease BD and increase WEF in the 0-5 cm soil depth compared to

NT though no differences were observed in the 5-15 cm soil depth. In their study, Obour et al. (2021b) also showed a decrease in BD with strategic tillage on long-term NT soils near the soil surface but did not report effects on WEF. Our results showed that if OT is necessary to correct root-limiting compaction or to control herbicide-resistant weeds, soil properties are generally not affected compared to NT, but OT could increase WEF compared to NT. Therefore, tillage operations should be implemented strategically to avoid the time of year when risk of wind erosion is greatest, which would be the late winter and early spring in the CGP when crop residue cover is frequently low and wind speeds are high (W. Johnson et al., 1983; Layton et al., 1993).

Conclusion

Results from this eight-year study showed that CC biomass production averaged about 3100 kg ha^{-1}. Grazing and haying CCs removed about 40% and 70% of the available forage, respectively, but maintained crop residue cover similar to standing CCs and greater than fallow. Profile PAW at wheat planting was less with CCs compared to fallow. However, wheat and sorghum yields were unaffected by Fallow Management on average though Fallow Management effects on wheat yields varied across years. Nevertheless, net returns were in the order of grazing CCs (as an alternative to confined hay feeding) > hayed CCs > grazed CCs (as an alternative to grazing rangeland) > fallow > standing CCs, though the advantage of haying over grazing (as an alternative to grazing rangeland) depended on CC biomass production. Fallow Management had no effect on BD, SOC, POC, or WEF, but MWD of water stable aggregates was 37% greater with CCs compared to fallow. Additional biomass in the form of root mass contributed by CC might have been part of the reason for improved MWD following CCs compared to fallow. Crop residue cover was reduced with OT compared to NT, but Tillage had no significant effect on

PAW, crop yield, or net returns. Bulk density was slightly lower and WEF was greater with OT compared to NT near the soil surface in one year, but SOC, POC, and MWD were unaffected by Tillage. These results suggest that dual-purpose CCs for grazing or haying can provide forage for livestock, increase crop residue cover and soil aggregate stability, maintain grain crop yields, and increase net returns in NT systems with limited risk of root-limiting soil compaction. Combining the two, haying in wet years and grazing in dry years, could be a means to balance forage availability and forage demand across years. If OT is necessary in a long-term NT system, for example to correct root-limiting compaction or to control herbicide-resistant weeds, PAW, crop yields, net returns, and soil properties are generally unaffected compared to NT.

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Figures

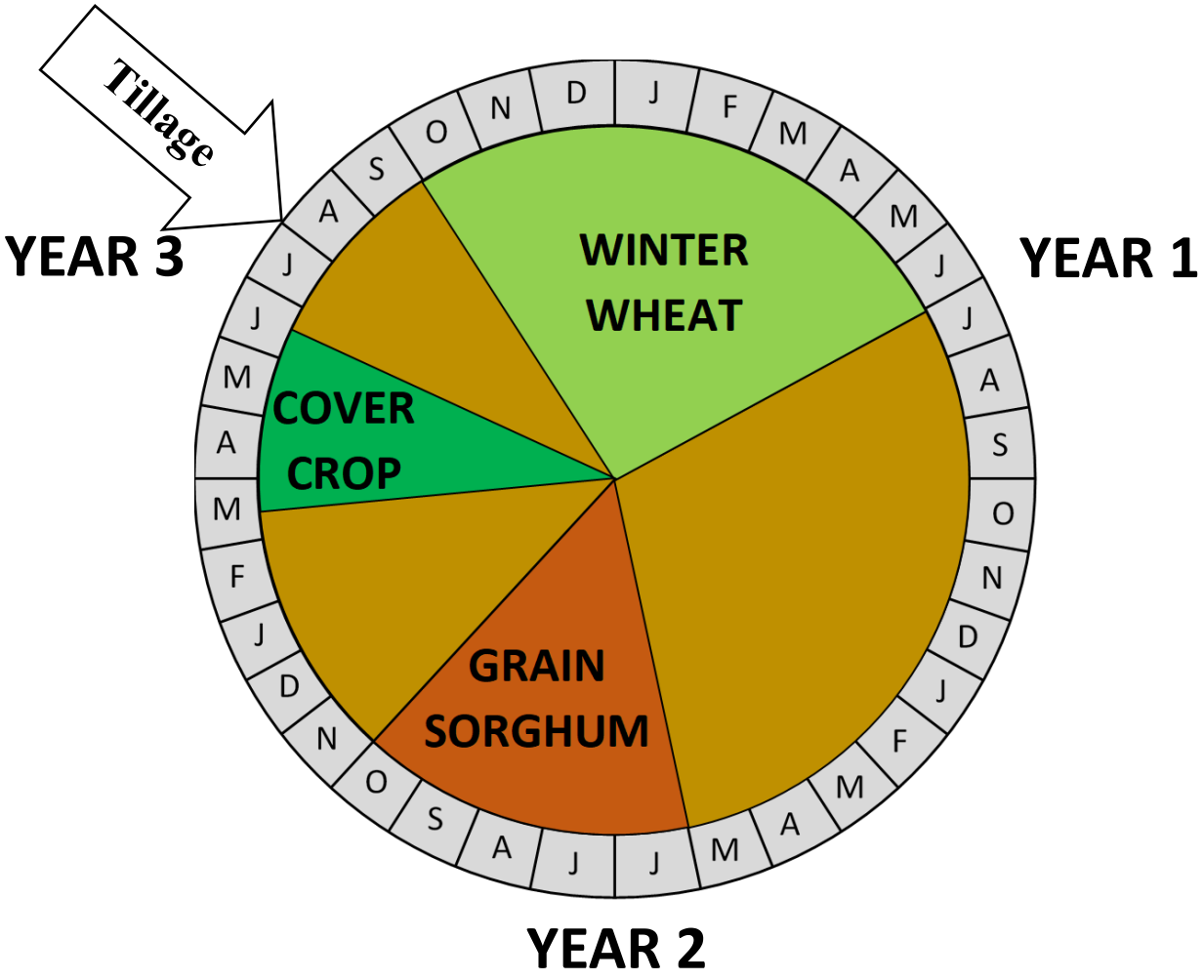

Figure 2.1. A pictorial representation of the winter wheat–grain sorghum–fallow cropping system with cover crops, which could be standing, hayed, or grazed, grown in place of traditional fallow as well as an arrow indicating the time of occasional tillage in summer before winter wheat planting in the long-term cover crop management study at the Kansas State University Hearting-Beason Ranch near Brownell, KS.

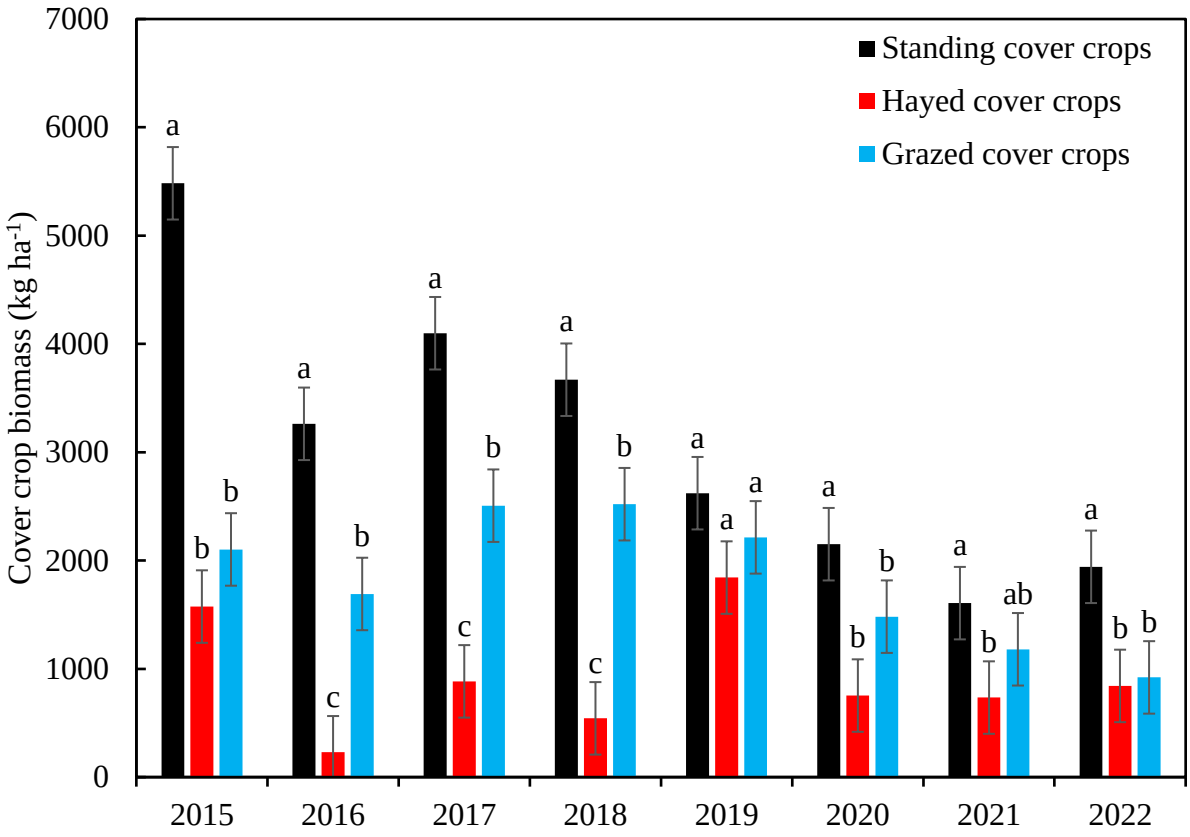

Figure 2.2. Cover crop biomass remaining as residue following cover crop grazing, haying, and termination from 2015 to 2022 near Brownell, KS. Means followed by the same lower-case letter are not significantly different ($\alpha = 0.05$) among cover crop management treatments and bars indicate one standard error of the mean.

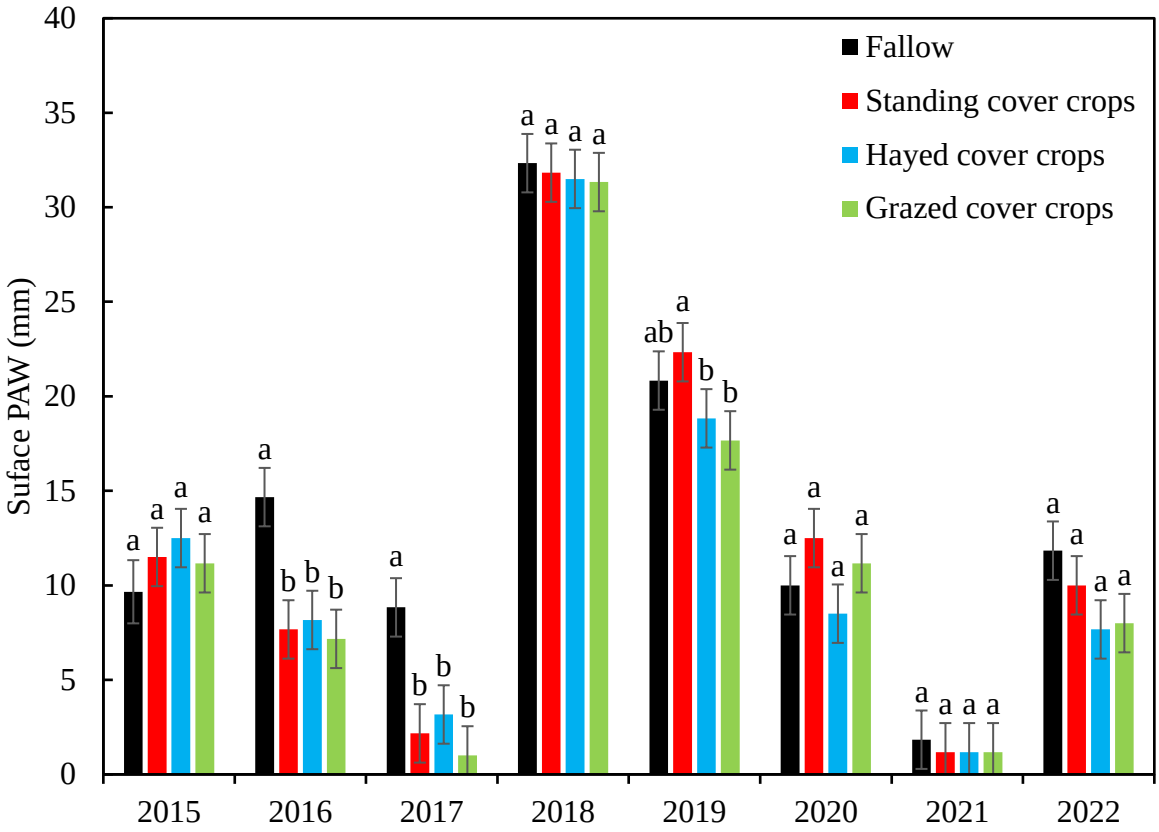

Figure 2.3. Fallow management and tillage effects on surface (0-15 cm) plant available water (PAW) at winter wheat planting from 2015 to 2022 near Brownell, KS. Means followed by the same lower-case letter are not significantly different ($\alpha = 0.05$) among cover crop management treatments and bars indicate one standard error of the mean.

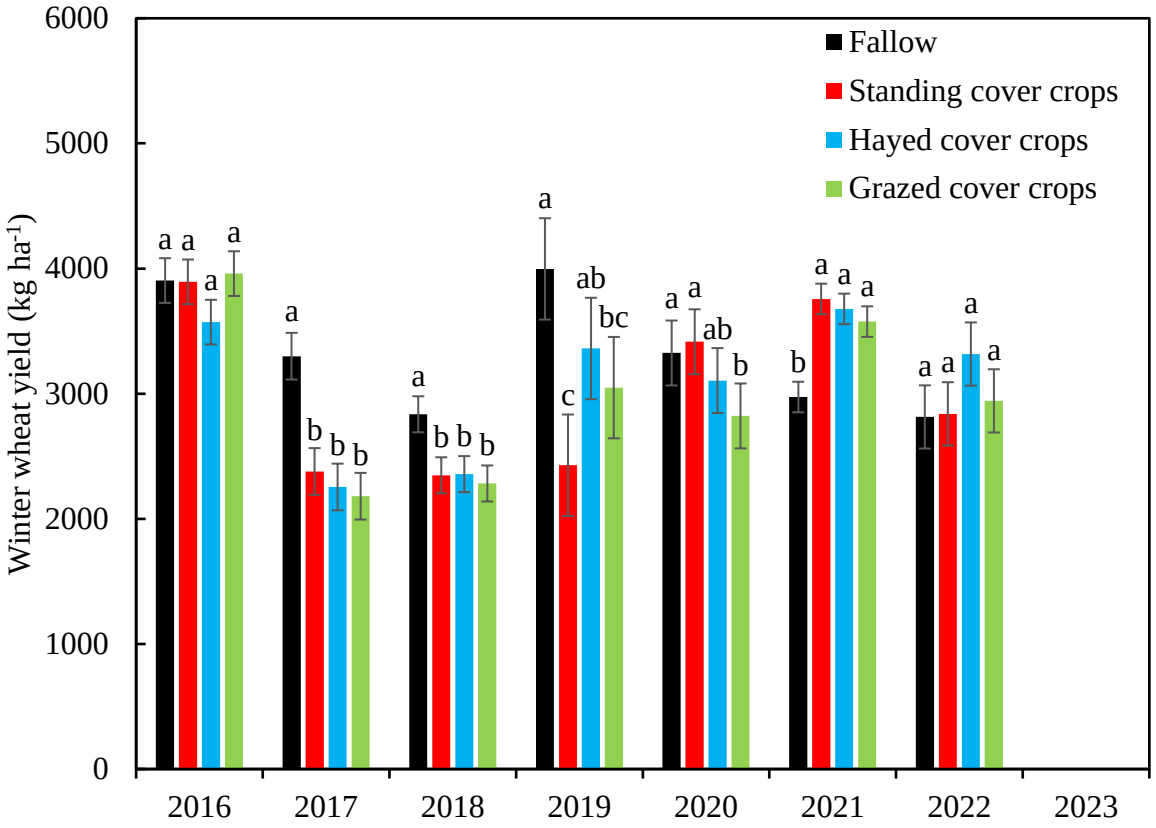

Figure 2.4. Fallow management effects on subsequent winter wheat yields from 2016 to 2023 near Brownell, KS. Exceptional drought conditions in 2023 resulted in crop failure. Means followed by the same lower-case letter are not significantly different ($\alpha = 0.05$) among cover crop management treatments and bars indicate one standard error of the mean.

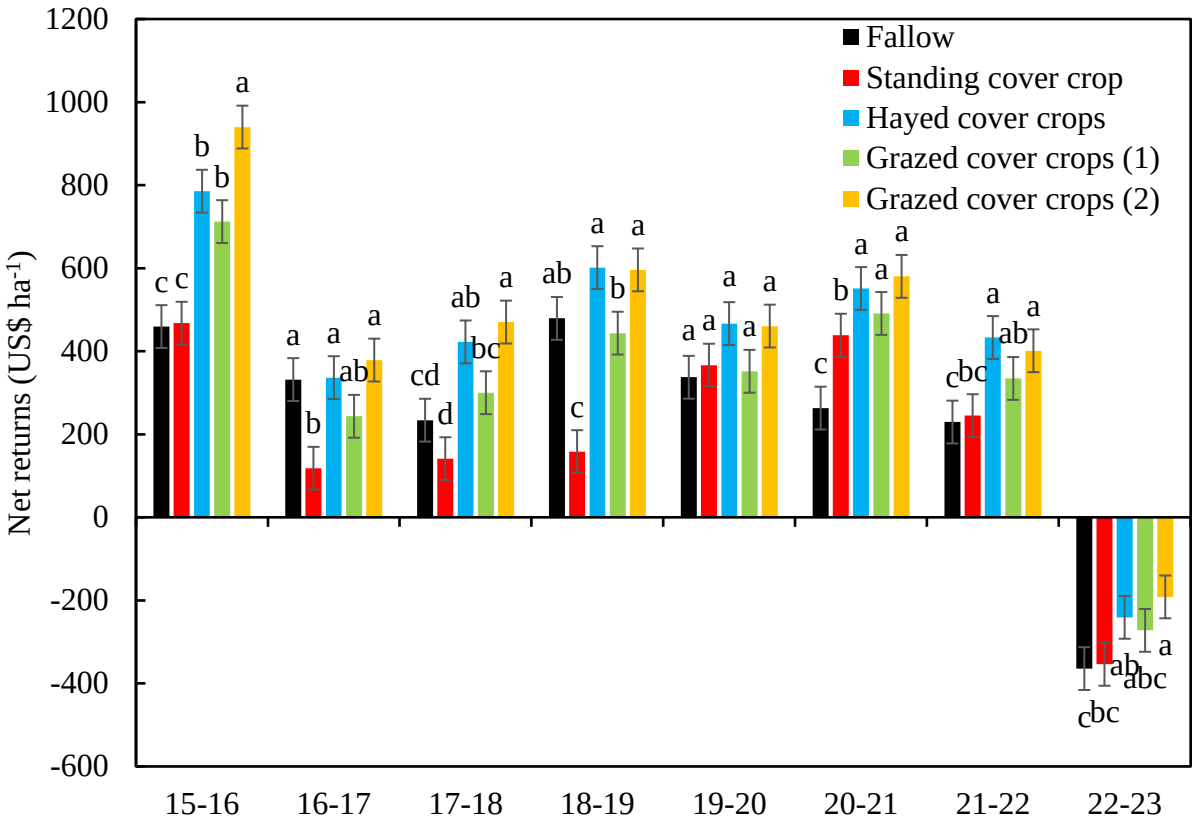

Figure 2.5. Effects of fallow management on net returns from the fallow and winter wheat phases in a winter wheat-grain sorghum-fallow rotation from 2015 to 2023 near Brownell, KS. Net returns from grazing cover crops represent scenarios where the alternative is grazing native rangeland (1) or where the alternative is confined hay feeding (2). Means followed by the same lower-case letter are not significantly different ($\alpha = 0.05$) among cover crop management treatments and bars indicate one standard error of the mean.

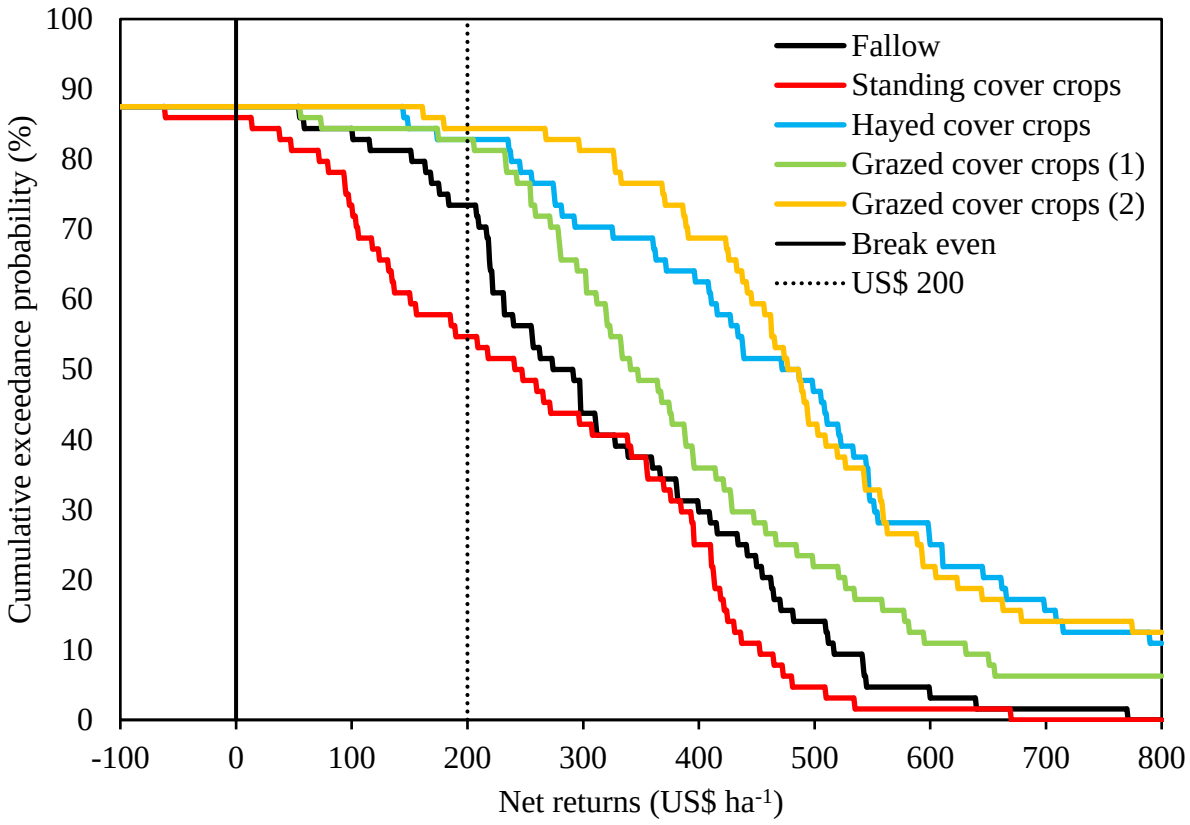

Figure 2.6. Cumulative exceedance probability of net income for fallow management strategies from 2015 to 2023 near Brownell, KS. Net returns from grazing cover crops represent scenarios where the alternative is grazing native rangeland (1) or where the alternative is confined hay feeding (2).

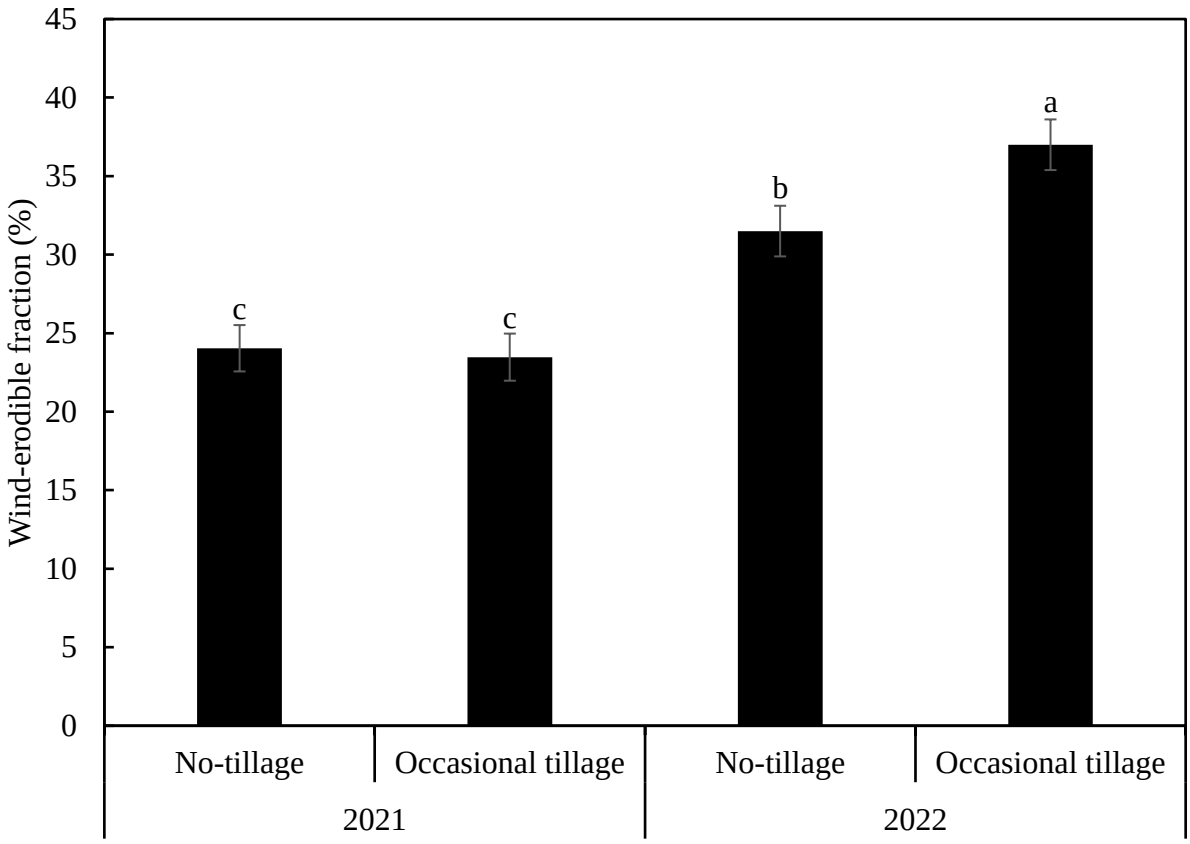

Figure 2.7. Effects of tillage on the wind-erodible fraction in the 0-5 cm soil depth at winter wheat planting in 2021 and 2022 near Brownell, KS. Means followed by the same lower-case letter are not significantly different ($\alpha = 0.05$) among cover crop management treatments and bars indicate one standard error of the mean.

Tables

Table 2.1. Fallow, cover crop, and cash crop growing season precipitation from 2014 to 2023 near Brownell, KS.

Growing season	Cover crops		Winter wheat			Grain sorghum	
	Preceding fallow (Nov.-Feb.)	Growing season (Mar.-Jun.)	Preceding fallow if after grain sorghum (Nov.-Sept.)	Preceding fallow if after cover crops (Jul.-Sept.)	Growing season (Oct.-Jun.)	Preceding fallow (Jul.-May)	Growing season (Jun.-Oct.)
	mm						
2014-2015	38	191	-	-	-	-	-
2015-2016	82	320	352	122	461	-	-
2016-2017	70	308	648	246	393	584	258
2017-2018	4	212	545	168	267	341	601
2018-2019	76	278	645	428	433	820	461
2019-2020	133	165	736	382	336	658	327
2020-2021	44	354	562	264	414	645	257
2021-2022	15	173	606	208	218	358	150
2022-2023	29	178	282	94	209	227	221
Study avg.	55	242	547	239	341	519	325
30-yr. avg.	70	248	529	211	359	491	331

Table 2.2. Cover crop biomass remaining as residue as well as fallow management and tillage effects on profile (0-120 cm) and surface (0-15 cm) plant available water (PAW) at winter wheat planting from 2015 to 2022 near Brownell, KS.

Treatments	Cover crop biomass	Profile PAW	Surface PAW
	kg ha^{-1}	mm	
Fallow management			
Fallow	-	110.1a	13.7a
Standing cover crops	3104a[†]	91.2b	12.4ab
Hayed cover crops	925c	89.2b	11.4b
Grazed cover crops	1827b	88.5b	11.1b
Tillage			
No-tillage	-	94.1a	12.0a
Occasional tillage	-	95.4a	12.3a
Year			
2015	3053a	97.9b	11.2c
2016	1728cd	102.9b	9.4c
2017	2497ab	54.6c	3.8d
2018	2244bc	134.3a	31.8a
2019	2226bc	135.4a	19.9b
2020	1462d	87.8b	10.5c
2021	1174d	-	1.3d
2022	1235d	50.4c	9.4c
Type III test of fixed effects			
Fall management (M)	<0.0001	0.0179	0.0182
Tillage (T)	-	0.7367	0.5639
M × T	-	0.8850	0.1560
Year (Y)	<0.0001	<0.0001	<0.0001
M × Y	<0.0001	0.0954	0.0072
T × Y	-	0.6354	0.1356
M × T × Y	-	0.4912	0.0942

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

Table 2.3. Effects of fallow management and tillage on subsequent wheat yields, sorghum yields, and net returns from 2015 to 2023 in a three-year winter wheat-grain sorghum-fallow rotation near Brownell, KS. Exceptional drought conditions in 2022 and 2023 resulted in crop failures.

Treatments	Wheat yield	Sorghum yield	Net returns‡
	kg ha^{-1}		US$ ha^{-1}
Fallow management			
Fallow	3307a†	5052a	246.22c
Standing cover crops	2988a	4949a	197.68d
Hayed cover crops	3092a	4830a	419.42a
Grazed cover crops (1)‡	2973a	5094a	325.51b
Grazed cover crops (2)			454.38a
Tillage			
No-tillage	3106a	4966a	324.94
Occasional tillage	3073a	4996a	332.34
Year			
2016	3832a	-	672.89a
2017	2493d	3697d	281.69d
2018	2455d	5687a	313.60cd
2019	3209bc	5599ab	455.65b
2020	3167bc	5128bc	396.52bc
2021	3496ab	4794c	464.81b
2022	2978c	-	328.60cd
2023	-	-	-284.63e
Type III test of fixed effects			
Fall management (M)	0.1039	0.6281	<0.0001
Tillage (T)	0.6829	0.7853	0.6359
M × T	0.7959	0.2183	0.8569
Year (Y)	<0.0001	<0.0001	<0.0001
M × Y	0.0051	0.7147	<0.0001
T × Y	0.2788	0.4846	0.1660
M × T × Y	0.6152	0.0755	0.7493

†Means followed by the same lower-case letter within the same column are not significantly different ($\alpha = 0.05$) among treatments.
‡Means for net returns from grazing cover crops represent scenarios where the alternative is grazing native rangeland (1) or where the alternative is confined hay feeding (2).

Table 2.4. Sensitivity analysis of cover crop biomass and wheat grain yield effects on net returns.

Cover crop biomass yield, kg ha^{-1}	Wheat grain yield, kg ha^{-1}										
	0	500	1000	1500	2000	2500	3000	3500	4000	4500	5000
	Net returns from grazing cover crops as an alternative to grazing rangeland, $US ha^{-1}										
0	-354.02	-249.02	-144.02	-39.02	65.98	170.98	275.98	380.98	485.98	590.98	695.98
500	-332.97	-227.97	-122.97	-17.97	87.03	192.03	297.03	402.03	507.03	612.03	717.03
1000	-311.93	-206.93	-101.93	3.07	108.07	213.07	318.07	423.07	528.07	633.07	738.07
1500	-290.88	-185.88	-80.88	24.12	129.12	234.12	339.12	444.12	549.12	654.12	759.12
2000	-269.84	-164.84	-59.84	45.16	150.16	255.16	360.16	465.16	570.16	675.16	780.16
2500	-248.79	-143.79	-38.79	66.21	171.21	276.21	381.21	486.21	591.21	696.21	801.21
3000	-227.75	-122.75	-17.75	87.25	192.25	297.25	402.25	507.25	612.25	717.25	822.25
3500	-206.70	-101.70	3.30	108.30	213.30	318.30	423.30	528.30	633.30	738.30	843.30
4000	-185.65	-80.65	24.35	129.35	234.35	339.35	444.35	549.35	654.35	759.35	864.35
4500	-164.61	-59.61	45.39	150.39	255.39	360.39	465.39	570.39	675.39	780.39	885.39
5000	-143.56	-38.56	66.44	171.44	276.44	381.44	486.44	591.44	696.44	801.44	906.44
	Net returns from grazing cover crops as an alternative to confined hay feeding, $US ha^{-1}										
0	-354.02	-249.02	-144.02	-39.02	65.98	170.98	275.98	380.98	485.98	590.98	695.98
500	-312.22	-207.22	-102.22	2.78	107.78	212.78	317.78	422.78	527.78	632.78	737.78
1000	-270.42	-165.42	-60.42	44.58	149.58	254.58	359.58	464.58	569.58	674.58	779.58
1500	-228.62	-123.62	-18.62	86.38	191.38	296.38	401.38	506.38	611.38	716.38	821.38
2000	-186.82	-81.82	23.18	128.18	233.18	338.18	443.18	548.18	653.18	758.18	863.18
2500	-145.02	-40.02	64.98	169.98	274.98	379.98	484.98	589.98	694.98	799.98	904.98
3000	-103.21	1.79	106.79	211.79	316.79	421.79	526.79	631.79	736.79	841.79	946.79
3500	-61.41	43.59	148.59	253.59	358.59	463.59	568.59	673.59	778.59	883.59	988.59
4000	-19.61	85.39	190.39	295.39	400.39	505.39	610.39	715.39	820.39	925.39	1030.39
4500	22.19	127.19	232.19	337.19	442.19	547.19	652.19	757.19	862.19	967.19	1072.19
5000	63.99	168.99	273.99	378.99	483.99	588.99	693.99	798.99	903.99	1008.99	1113.99
	Net returns from haying cover crops, $US ha^{-1}										
0	-354.02	-249.02	-144.02	-39.02	65.98	170.98	275.98	380.98	485.98	590.98	695.98
500	-315.52	-210.52	-105.52	-0.52	104.48	209.48	314.48	419.48	524.48	629.48	734.48

1000	-277.02	-172.02	-67.02	37.98	142.98	247.98	352.98	457.98	562.98	667.98	772.98
1500	-238.52	-133.52	-28.52	76.48	181.48	286.48	391.48	496.48	601.48	706.48	811.48
2000	-200.02	-95.02	9.98	114.98	219.98	324.98	429.98	534.98	639.98	744.98	849.98
2500	-161.52	-56.52	48.48	153.48	258.48	363.48	468.48	573.48	678.48	783.48	888.48
3000	-123.02	-18.02	86.98	191.98	296.98	401.98	506.98	611.98	716.98	821.98	926.98
3500	-84.52	20.48	125.48	230.48	335.48	440.48	545.48	650.48	755.48	860.48	965.48
4000	-46.02	58.98	163.98	268.98	373.98	478.98	583.98	688.98	793.98	898.98	1003.98
4500	-7.52	97.48	202.48	307.48	412.48	517.48	622.48	727.48	832.48	937.48	1042.48
5000	30.98	135.98	240.98	345.98	450.98	555.98	660.98	765.98	870.98	975.98	1080.98

Table 2.5. Effects of fallow management and tillage on crop residue cover as well as soil organic carbon (SOC), particulate organic carbon (POC), bulk density (BD), mean weight diameter (MWD) of water stable aggregates, and wind-erodible fraction (WEF) in the 0-5 cm soil depth at winter wheat planting in 2021 and 2022 near Brownell, KS.

Treatments	Residue cover	SOC		POC		BD	MWD	WEF
	%	g kg^{-1}	Mg ha^{-1}	g kg^{-1}	Mg ha^{-1}	g cm^{-3}	mm	%
Fallow management								
Fallow	67.5b[†]	15.19a	9.32a	5.62a	3.45a	1.22a	0.77b	27.9a
Standing cover crops	83.4a	15.71a	9.84a	6.26a	3.94a	1.25a	0.93a	28.5a
Hayed cover crops	78.4a	15.48a	9.65a	6.61a	4.14a	1.24a	1.01a	30.5a
Grazed cover crops	77.5a	15.73a	9.64a	6.29a	3.77a	1.22a	0.98a	29.1a
Tillage								
No-tillage	86.1a	15.55a	9.88a	6.36a	4.04a	1.26a	0.94a	27.8a
Occasional tillage	67.3b	15.50a	9.34a	6.03a	3.61a	1.20b	0.90a	30.2a
Year								
2021	82.0a	14.91a	8.63b	5.65a	3.21b	1.16b	0.99a	23.8b
2022	71.4b	16.15a	10.60a	6.74a	4.43a	1.31a	0.85a	34.2a
Test of Fixed Effects								
Fall management (M)	0.0069	0.7212	0.7140	0.1945	0.3135	0.8509	0.0291	0.4063
Tillage (T)	0.0036	0.8829	0.2258	0.2914	0.2421	0.0427	0.6555	0.1994
M × T	0.5605	0.2029	0.5611	0.3071	0.4389	0.1491	0.3692	0.1532
Year (Y)	0.0295	0.2427	0.0455	0.2034	0.0451	0.0246	0.2265	0.0107
M × Y	0.1338	0.4797	0.6583	0.5644	0.3400	0.6080	0.2588	0.6018
T × Y	0.3847	0.1839	0.3697	0.7336	0.9244	0.8522	0.8673	0.0483
M × T × Y	0.5281	0.4780	0.3491	0.2467	0.0611	0.7450	0.6775	0.3533

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

Table 2.6. Effects of fallow management and tillage on soil organic carbon (SOC), particulate organic carbon (POC), bulk density (BD), mean weight diameter (MWD) of water stable aggregates, and wind-erodible fraction (WEF) in the 5-15 cm soil depth at winter wheat planting in 2021 and 2022 near Brownell, KS.

Treatments	SOC		POC		BD	MWD	WEF
	g kg^{-1}	Mg ha^{-1}	g kg^{-1}	Mg ha^{-1}	g cm^{-3}	mm	%
Fallow management							
Fallow	12.27a	18.04a[†]	2.25a	3.27a	1.47a	0.59b	12.7a
Standing cover crops	12.92a	18.58a	2.15a	3.12a	1.44a	0.94a	12.3a
Hayed cover crops	12.44a	18.25a	2.20a	3.20a	1.46a	0.90a	13.2a
Grazed cover crops	13.23a	19.07a	2.30a	3.34a	1.45a	0.84a	12.2a
Tillage							
No-tillage	12.63a	18.50a	2.23a	3.36a	1.46a	0.78a	12.9a
Occasional tillage	12.81a	18.47a	2.15a	3.11a	1.45a	0.86a	13.2a
Year							
2021	12.35a	17.40b	2.21a	3.12a	1.42b	0.83a	12.5a
2022	13.08a	19.57a	2.24a	3.36a	1.50a	0.81a	13.2a
Test of Fixed Effects							
Fall management (M)	0.4550	0.6662	0.9685	0.9603	0.7645	0.0295	0.6096
Tillage (T)	0.6190	0.9709	0.6032	0.5293	0.8459	0.4865	0.8130
M × T	0.6332	0.3581	0.7457	0.7121	0.4483	0.7684	0.3655
Year (Y)	0.3797	0.0426	0.8990	0.5293	0.0492	0.8251	0.3267
M × Y	0.2848	0.5137	0.2979	0.2320	0.6852	0.3576	0.9395
T × Y	0.7474	0.5547	0.6428	0.5600	0.2467	0.8510	0.9157
M × T × Y	0.1030	0.2666	0.4995	0.4085	0.4802	0.6219	0.5755

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

Table 2.7. Pearson correlation coefficients (*r*) and *P* values from correlation analysis among cover crop biomass, crop residue cover, and soil properties across years and sampling depths.

Parameter	Residue	BD	SOC	POC	GWC	MWD	WEF
Biomass[†]							
r	0.36****[‡]	0.05	0.15	0.06	0.01	0.24**	0.03
Residue							
r		-0.11	-0.04	0.01	-0.08	0.10	-0.16
BD							
r			-0.39*****	-0.58*****	0.76*****	-0.23**	-0.50*****
SOC							
r				0.75*****	-0.49*****	0.08	0.68*****
POC							
r					-0.68*****	0.12	0.82*****
GWC							
r						-0.18*	-0.58*****
MWD							
r							0.14

[†]Biomass, cover crop biomass, Residue, percent residue cover, SOC, soil organic carbon, POC, particulate organic carbon, GWC, gravimetric water content, MWD, mean weight diameter, WEF, wind-erodible fraction.
[‡]**P*≤0.10; ***P*≤0.05; ****P*≤0.01; *****P*≤0.001; ******P*≤0.0001

Chapter 3 - Post-wheat dual-purpose cover crops reduced subsequent grain yields but maintained net returns and soil properties in the semi-arid central Great Plains

Abstract

Warm-season cover crops (CCs) planted immediately after wheat harvest (post-wheat) in the semi-arid central Great Plains (CGP) could intensify cropping systems, increase forage availability, and enhance soil health in NT dryland cropping systems. However, the costs of their establishment and potential reductions in subsequent grain yields because of reduced plant available water present major barriers to their adoption in the region. This study was conducted from 2016 to 2023 near Brownell, KS to determine post-wheat CCs effects on available forage, grain sorghum yields, net returns, as well as soil chemical and physical properties. The CC treatments were forage sorghum (*Sorghum bicolor* (L.) Moench)–pearl millet (*Cenchrus americanus* (L.) Morrone)–cowpea (*Vigna unguiculata* (L.) Walp.)–sunn hemp (*Crotalaria juncea* L.) grown post-wheat in a NT winter wheat (*Triticum aestivum* L.)-grain sorghum-fallow cropping system and either hayed, grazed, or left standing in a split-plot randomized complete block with four replications. Across years, post-wheat CCs produced about 3200 kg ha^{-1} available forage though production was variable with two years of failed CC establishment. Grazing retained about 65% of the available forage as surface residue while haying retained only about 44%. Grain sorghum yields were reduced 14% on average following CCs compared to fallow. However, average net returns with grazed or hayed CCs were similar to fallow and greater than standing CCs. Soil bulk density, nitrate-nitrogen, phosphorus, and wind-erodible fraction were unaffected by fallow management, but grazed CCs increase soil organic carbon

(SOC) stocks compared to fallow possibly because of synergistic effects of CC and grazing on SOC stocks. Mean weight diameter of water stable aggregates with grazed CCs was similar to fallow and greater than hayed CCs, which highlights the need for careful management when using CCs for forage to maintain adequate CC residue to meet soil health objectives in dryland systems. These results suggest that post-wheat CCs for grazing and haying can intensify cropping systems and increase forage availability while maintaining profitability in the semi-arid CGP. However, CCs should be planted immediately after wheat harvest to avoid soil surface drying, which creates a poor environment for crop establishment without timely rainfall. Careful management when using CCs for forage is necessary to maintain adequate CC residue to balance goals of forage production and soil health. Additional research on forage harvest cutting height and amount of residue removed by grazing is needed to refine best management practices for achieving sustainability goals.

Introduction

Dryland cropping systems of the semi-arid central Great Plains (CGP) are based around the production of winter wheat (*Triticum aestivum* L.) and rely on soil storage of plant available water (PAW) through the use of long fallow periods to supplement growing season precipitation for stable grain production (Nielsen et al., 2005; Nielsen & Vigil, 2010; Peterson & Westfall, 2004). As a water conservation practice, the 14-month fallow in the traditional dryland wheat-fallow (WF) system has been shown to increase PAW storage between crops, stabilize yields, and reduce frequency of crop failure (Aiken et al., 2013; Nielsen & Vigil, 2018; Schlegel et al. 2017). However, low-intensity cropping systems that include long fallow periods have low precipitation use efficiency (Baumhardt & Jones, 2002; Nielsen & Vigil, 2010; Peterson & Westfall, 2004) and are associated with long-term soil degradation (Peterson et al., 2020; Stewart

& Robinson, 1997; Unger et al., 2006). The wide-spread adoption of no-tillage (NT) has been successful in increasing PAW storage efficiency and dryland crop yields (Baumhardt et al., 2015; Peterson et al., 2020). Furthermore, adoption of NT facilitated the reduction in fallow frequency in the semi-arid CGP with the addition of summer crops [grain sorghum (*Sorghum bicolor* Moench), corn (*Zea mays* L.), proso millet (*Panicum milliaceum* L.), or sunflower (*Helianthus annuus* L.)] following wheat in the wheat-summer crop-fallow system (Baumhardt & Salinas-Garcia, 2006; Schlegel et al., 2019).

The wheat-summer crop-fallow system has two 11-month fallow periods ahead of wheat planting and following wheat harvest (Baumhardt & Salinas-Garcia, 2006; Obour et al., 2021a). The complete replacement of fallow is limited in the semi-arid CGP because of low and erratic annual precipitation as well as high potential evapotranspiration rates that increase the risk of crop failure with intensified grain production systems (Aiken et al., 2012; Nielsen & Vigil, 2017; 2018). Incorporating CCs to replace portions of the fallow periods in dryland cropping systems of the semi-arid CGP could regenerate soils, suppress weeds, and increase precipitation use efficiency (Blanco-Canqui et al., 2021a; Obour et al., 2021a). The replacement of fallow before wheat has received substantial attention from researchers who have shown this phase could provide an opportunity for spring-planted cool-season CCs that can be terminated in May or June, allowing for at least 90 days for soil water recharge before planting wheat (Holman et al., 2018; 2022; Obour et al., 2021a; 2021b; Nielsen et al., 2015a; 2015b; 2015c). However, the replacement of fallow after wheat has received considerably less attention. Warm-season CCs could be planted immediately after wheat harvest (hereafter referred to as post-wheat) and terminated by a killing frost in October, which allows for at least 150 days before planting a summer crop the following year (Holman et al., 2023; Jenkins et al., 2019; Titlow et al., 2014).

However, much of that time coincides with winter in the semi-arid CGP when precipitation and temperatures are both typically low. Although "double-crop" production of grain crops like soybean (*Glycine max* L.) and grain sorghum after wheat harvest is commonly practiced in regions with greater annual precipitation at the same latitude (Mahama et al, 2016a; 2016b), growing CCs or annual forages has been shown to be superior to grain crops in the semi-arid CGP as less water is required to accumulate enough biomass for an acceptable CC or forage harvest compared to the water required to produce grain (Stewart and Weil-Li, 2015; Stewart and Peterson, 2015).

In sub-humid eastern Kansas, yields of corn and grain sorghum following post-wheat legume CCs like forage soybean were similar or greater than following wheat with no CC (Blanco-Canqui et al., 2011; Preza Fontes et al., 2017; Mahama et al., 2016a; 2016b). However, grass CCs like sorghum-sudangrass (*Sorghum bicolor* × *Sorghum bicolor* var. sudanese) decreased grain sorghum yields by 50% in some instances (Preza Fontes et al., 2017), possibly because of high biomass production (9,500 kg ha^{-1}) and high C/N ratio residues (40:1) that favored N immobilization and reduced N availability for grain sorghum. Little has been reported about post-wheat CCs in the semi-arid CGP, but the costs of their establishment and potential reductions in subsequent grain yields because of reduced PAW at planting of the subsequent grain crop present major barriers to their adoption despite the benefits that CCs could provide for soil health or weed suppression (Bergtold et al., 2017; Ramsey et al., 2019; Roesch-McNalley et al., 2017). However, dual-purpose CCs used for forage may have greater potential to balance profitability and soil health goals in such water-limited environments (Holman et al., 2018; 2022; Obour et al., 2021a; 2021b; 2022).

In semi-arid western Nebraska, Jenkins et al. (2019) showed that post-wheat annual forages produced 2600 to 5100 kg ha^{-1} biomass with crude protein (CP) concentrations from 8.8 to 13.5%. The authors concluded that these annual forages could be used to extend the season for livestock grazing and potentially delay grazing of native rangelands in the region. In semi-arid western Kansas, Holman et al. (2023) showed that post-wheat forage sorghum produced about 3500 kg ha^{-1} aboveground biomass on average but reduced subsequent grain sorghum yields 35% compared to grain sorghum planted 11 months after wheat harvest because of reduced PAW at planting. Nevertheless, gross margins were similar between these two rotations, which supported the authors hypothesis that post-wheat forage sorghum could be used to intensify cropping systems and increase forage availability (Holman et al., 2023). However, the degree to which soil health can be improved with management strategies like grazing or haying dual-purpose CCs in NT dryland cropping systems of the semi-arid CGP is not fully understood (Blanco-Canqui et al., 2013; Kelly et al., 2021; Simon et al., 2021; 2022).

There is concern that removing CC biomass through grazing or haying could limit the beneficial effects of CCs for soil health (Franzluebbers & Stuedemann, 2008; 2014; 2015) and that animal hoof traffic with CC grazing could cause root-limiting soil compaction that could suppress subsequent crop yields in NT systems (Blanco-Canqui et al., 2021b; Franzluebbers & Stuedemann, 2008; Schomberg et al., 2021). However, previous research concluded that only nominal increases in soil bulk density (BD) or penetration resistance could be expected with CC grazing (Blanco-Canqui et al., 2021b; Franzluebbers & Stuedemann, 2008; Kelly et al., 2020; Schomberg et al., 2021). In fact, grazed or hayed CCs have often been shown to enhance chemical and physical indicators of soil health including soil organic carbon, water stable aggregates, dry aggregate stability, and water infiltration compared to fallow with (Blanco-

Canqui et al., 2013; Kelly et al., 2020; Simon et al., 2021; 2022). Past research indicated that dual-purpose CCs grown in place of fallow ahead of wheat had similar effects on soil properties as unharvested CCs (Simon et al., 2021). Currently, little information exists regarding management impacts of post-wheat CCs on crop production, profitability, or soil health in the dryland cropping systems of the semi-arid CGP. Therefore, the objectives of this current research were to determine the effects of post-wheat CCs on grain and forage yields, net returns, as well as soil chemical and physical properties in a NT winter wheat-grain sorghum-fallow (WSF) cropping system.

Materials and methods

Site and study description

This study was conducted from 2016 to 2023 at the Kansas State University Hearting-Beason Ranch (38˚38′23″ N, 99˚44′45″ W) near Brownell, KS to investigate best management strategies for CCs to replace fallow periods in the traditional WSF cropping system. Long-term average (30 yr) annual precipitation at the study site was 566 mm (Table 3.1), and the soil series at the study site was Harney silt loam (fine, smectitic, mesic Typic Argiustolls), a soil series of large extent formed from loess on uplands in the Rolling Plains and Breaks of west-central Kansas (National Cooperative Soil Survey, 2023). The study design was a split-plot randomized complete block with four replications. Crop phase was the main plot, and split-plots were CCs grown post-wheat in the WSF rotation (Fig. 3.1) and managed as standing cover, hayed, or grazed, which were compared with chemically controlled NT fallow for a total of four treatments. In the study, CCs were a four-species mixture of forage sorghum–pearl millet (*Cenchrus americanus* (L.) Morrone)–cowpea (*Vigna unguiculata* (L.) Walp.)–sunn hemp (*Crotalaria juncea* L.). Split-plots were 9.1 m wide and 30.5 m long. All crop phases (wheat,

grain sorghum, or fallow) of this WSF rotation were present each year, which allowed wheat, wheat/CC, grain sorghum, and fallow plots to be implemented in each year of the study.

Management

Each year, winter wheat was planted in the 1st week of October (Fig. 3.1) using a NT drill (Model 3P1006NT, Great Plains Manufacturing, Salina, KS) at 67 kg ha^{-1} with 19-cm row spacing. Each plot received 20 kg ha^{-1} P_2O_5 as monoammonium phosphate (11–52–0) with the seed at planting. At spring green up, (~approximately by 25 March), an additional application of 84 kg nitrogen (N) ha^{-1} as urea (46–0–0) was broadcast on each plot. Postemergence winter annual weed control in wheat was accomplished with metsulfuron methyl at 5.3 g ai ha^{-1} or dicamba at 140 g ae ha^{-1} across years. Wheat was harvested in early July (Fig. 3.1) using a Massey Ferguson 8XP small plot combine harvester (Massey Ferguson, Duluth, GA, USA). Immediately after wheat harvest, a CC mixture of forage sorghum, pearl millet, cowpea, and sunn hemp were planted at seeding rates of 7.8, 2.8, 22.4, and 5.6 kg ha^{-1} for each species, respectively, using the same NT drill as used for wheat planting. One herbicide application of glyphosate at 1,260 g ae ha^{-1} tank-mixed with 2,4-D at 560 g ae ha^{-1} was made following wheat harvest in the fallow plots, but not plots planted to CCs, to control volunteer wheat and weeds. Cover crop grazing generally coincided with forage sorghum/pearl millet heading stage, which was selected to optimize forage mass and nutritive value (Lyons et al., 2019). Grazing was facilitated using yearling heifers (*Bos taurus*) (454 kg each) at densities from 877 to 1,755 kg liveweight ha^{-1} for 4–7 d to utilize approximately 50% of the available forage in fenced paddocks across the four replications of this study.

On or within one week following the last day of grazing, hayed CCs were harvested at a 15-cm cutting height using a small plot forage harvester (Carter Manufacturing Company, Inc.,

Brookston, IN). These warm-season CCs were selected for their winter-sensitivity so that termination was achieved by killing frost near the third week of October (Fig. 3.1), which avoided an additional herbicide application for CC termination. All plots received an herbicide application of glyphosate at 1,260 g ae ha^{-1} and atrazine at 1,160 g ai ha^{-1} the following spring to control weeds before planting grain sorghum in the 1st week of June (Fig. 3.1) at 77,000 seeds ha^{-1}. Sorghum was planted using the same NT drill as used for wheat and CCs but with 38.1-cm row spacing. Nitrogen and P_2O_5 were applied at sorghum planting at similar rates as previously described for wheat. Grain sorghum was harvested in mid-October to 1st week in November (Fig. 3.1) using the same small plot combine harvester as used for wheat. Typically, four herbicide applications are made through the late spring and summer to control weeds through the fallow period before planting wheat. Generally, dicamba at 280 g ae ha^{-1} alone or with 1,260 g ae ha^{-1} of glyphosate was applied in March, followed by 840 g ae ha^{-1} paraquat and 0.032 g ae ha^{-1} carfentrazone in May. Two more sequential burndown applications of glyphosate at 1,260 g ae ha^{-1} with 560 g ae ha^{-1} of 2,4-D were made in July and September to control weeds prior to winter wheat planting in October.

Cover crop biomass

Each year before grazing was initiated, available CC biomass was determined by hand-clipping, to the ground level, two areas of 0.50 m^2 per plot, which were representative of the total biomass present for the standing CC. Samples were dried at approximately 50˚C for a minimum of 48 h in a forced-air oven and weighed to determine dry matter content. After grazing, plots were sampled as previously described to determine CC biomass remaining. Hayed treatments were harvested with a small plot forage harvester from a strip of 0.9 m by 30.5 m in the middle of each plot. Whole plot fresh weights were recorded, subsamples collected and weighed, and

then oven-dried to determine CC hay yield. Cover crop biomass removed with haying was subtracted from the standing CC biomass to estimate CC residue remaining. The remaining plot area in the hayed plots were harvested and forage was removed from the plots following the cutting of a sample strip. In 2019, CC biomass accumulation was very limited, so all plots were sampled by hand to determine dry biomass as previously described but plots were not grazed or hayed. No CC biomass was collected in 2017 or 2022 due to failed CC establishment.

Grain crop yields

Both grain sorghum and winter wheat yields were determined by harvesting an area 1.5 m wide by 30.5 m long from the center of each plot. Grain sorghum was harvested in October or early November, and winter wheat was harvested in July in each year of the study (Fig. 3.1). Grain moisture content was determined using a DICKEY-john grain moisture tester (DICKEY-john Inc., Auburn, IL, USA), and yield of both grain sorghum and wheat was adjusted to 13.5% moisture content. Exceptional drought conditions resulted in a failed grain sorghum crop in 2022 when preceding fallow and growing season precipitation was <50 and <60% of normal, respectively (Table 3.1).

Economic analysis

Net returns were calculated for the fallow/CC and subsequent grain sorghum phases of the WSF cropping system as total fallow/CC and grain sorghum revenue minus total fallow/CC and grain sorghum costs for each treatment and year (Table A2). Estimates of current field operations and input costs used 5-yr average custom rate values published by Kansas State University Land Use Survey Program and the Kansas Department of Agriculture (AgManager, 2021). grain sorghum and CC hay prices were obtained from the USDA Economic Research Services market reports (USDA ERS, 2021) and calculated as \$0.20 kg^{-1} for grain sorghum and

$0.13 kg^{-1} for CC hay, which was estimated from published values for good cane and sudan hay. Cover crop grazing lease rates were calculated by two strategies to represent scenarios where the alternative to grazing CCs is grazing native rangeland ($73 AUM^{-1}) or where the alternative to grazing CCs is confined feeding of hay ($128 AUM^{-1}). For the first scenario, the lease rate was calculated using the return on investment (ROI) method described by Hofstrand & Edwards (2015) using a land value of $3,778 ha^{-1} and 2.0% ROI for Trego County, Kansas (Reid, 2024). Lease rates were converted from US$ ha^{-1} to US$ animal unit month (AUM)$^{-1}$ by multiplying values by 4.9 ha divided by 6 months and then multiplying by 1.2 animal unit equivalents (Ohlenbusch & Watson, 1994). For the second scenario, the lease rate was calculated using the previously mentioned hay price of $0.13 kg^{-1} and a yardage (non-feed cost per head for every day that an animal is fed harvested feed in some form of confinement) cost of $0.50 head^{-1} day^{-1}. Lease rates were calculated as US$ AUM^{-1} by multiplying the hay price by 871.91 kg AUM^{-1} plus $0.50 head^{-1} day^{-1} multiplied by 30 days. Total variable costs were calculated as the sum of the expenses for fertilizer product and application costs, herbicide products and application, seed, planting, grain harvesting, as well as forage swathing, baling, and stacking bales at field edge. All costs and revenue were calculated on a ha^{-1} basis in US$ (Table A.2). Net returns determined across the six years of this study were used to calculate cumulative exceedance probabilities of net returns (probability of obtaining a minimum net return) for fallow management treatments to determine probabilities of at least breaking even (income = expenses) and obtaining at least $200 ha^{-1} income similar to the analyses conducted by Nielsen et al. (2016). Sensitivity analyses were performed to determine the variability in net returns and trade-offs across a range of CC biomass yields (0 to 5000 kg biomass ha^{-1}) and subsequent winter wheat yields (0 to 5000 kg grain ha^{-1}).

Soil properties

Soil samples were obtained from all split-plots within each main plot (wheat, sorghum, and fallow) in summer 2021 similar to the strategy used by Blanco-Canqui & Jasa (2019). At the time of soil sampling, winter wheat had been recently harvested, sorghum was in early vegetative development, and remaining plots were fallow. For the determination of BD, two intact soil cores (5-cm diameter) were randomly taken from the 0-5 and 5-15 cm depths within each plot. The two samples from each depth were dried separately at 105° C for 48 hr, and BD was determined as mass of oven dry soil divided by volume of the core. Additionally, 10 soil cores (2.5-cm diameter) were randomly collected within each plot, divided into the 0-5 and 5-15 cm depths, and composited by depth. Samples were air-dried, crushed, and sieved to pass through a 2 mm stainless steel screen. A portion of the 2 mm sieved 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 LECO TruSpec CN analyzer (LECO Corporation, St. Joseph, MI) after pretreating samples with 10% (v/v) HCl to remove carbonates (Nelson & Sommers, 1996). Carbon mass was calculated by multiplying SOC concentrations by soil BD and the thickness of the soil layer. Soil nitrate-nitrogen (NO_3-N) concentrations in samples were determined with a segmented flow analyzer after extracting the soil with 2 M KCl. Available phosphorus (P) was determined by the Mehlich-3 extraction method (Mehlich, 1984), and P concentration in the extract was measured using inductively coupled plasma-optical emission spectrometry (ICP-OES).

Lastly, 5 intact soils samples were collected from the 0-5 and 5-15 cm soil depths with a flat shovel for the determination of water stable aggregates and dry aggregate stability. Soil aggregates were allowed to air-dry and were then gently passed through a 19 mm sieve. From

there, two approximately 50 g subsamples of 8-4.75 mm diameter dry aggregates were obtained for each replicated treatment and used to estimate mean weight diameter (MWD) of water stable aggregates by the wet-sieving method (Nimmo & Perkins, 2002). The remaining aggregate sample of approximately 3000 g was used to estimate WEF (<0.84 mm) by the dry-sieving method (Chepil, 1962). For the wet sieving method, an approximate 50 g sample was placed on top of a stack of nested sieves of 2-, 1-, and 0.25-mm sized openings in a water column (Nimmo & Perkins, 2002). The samples were allowed to wet by capillarity for 5 minutes after which the stacks of sieves were vertically oscillated a distance of 3.7 cm at 30 oscillations minute^{-1} for 5 minutes. The amount of soil retained on each sieve was transferred into glass beakers, dried at 105° C, and weighed to determine the proportion of water stable aggregates within each size fraction. Each dry sample was then corrected for coarse sand by mixing the oven-dried aggregates with 30 ml of 0.5% sodium hexametaphosphate to disperse soil particles and allowing them to soak for a minimum of four hours. Samples were then swirled on an orbital shaker for an additional four hours. Each dispersed sample was then passed back though individual sieves with the same size openings. The recovered sand was oven-dried and weighed to correct for coarse soil particles. Sand-corrected values were used to compute MWD (Nimmo & Perkins, 2002). For the dry-sieving method, an approximately 3000 g air-dried sample was placed on top of a stack of nested sieves of 6.3-, 2-, 0.84-, and 0.42-mm sized openings (Chepil, 1962). Samples were shaken for 5 min using a portable orbital sieve shaker (W.S. Tyler Model RX-812, Mentor, OH). The soil particles remaining on each sieve were weighed and the data was used to compute wind-erodible fraction (WEF; <0.84 mm) (Chepil, 1962).

Statistical analysis

Analyses of CC biomass accumulation, grain sorghum yields, net returns, as well as soil properties were conducted using the PROC GLIMMIX procedure in SAS ver. 9.4 (SAS Institute, 2012). For CC biomass, grain yield, and net returns, treatment and year were modeled as fixed effects with replication considered random in the model. Because the interaction of rotation phase × treatment was not significant for any soil property, all statistical analyses of treatment effects on soil properties were conducted across rotation phases. For BD, SOC, NO_3-N, P, MWD, and WEF, treatment and soil depth were modeled as fixed effects with replication considered random in the model. Treatment effects were considered significant at $\alpha = 0.05$. Correlation analysis among soil properties was conducted using the PROC CORR procedure in SAS and simple linear regression analyses were conducted with the PROC REG procedure in SAS to determine the relationship between SOC and P as well as NO_3-N and P.

Results

Precipitation patterns over the study period

Typical of the semi-arid CGP, a broad range of water availability conditions was observed during the study period (2016-2023, Table 3.1) for quantifying treatment effects on the cropping system. The average precipitation received during the CC, grain sorghum, and winter wheat growing seasons was 289, 336, and 313 mm, respectively, which was near the 30-yr average for each crop. However, precipitation ranged substantially from lows of 96, 150, and 209 mm to highs of 507, 601, and 433 mm for the CC, grain sorghum, and wheat growing seasons, respectively. Similar variance was observed during the fallow periods that preceded each crop (Table 3.1). On average, precipitation received during the fallow period preceding grain sorghum if following wheat was 508 mm or approximately 1.3-fold the precipitation received during the

shortened fallow period following CCs (220 mm). Average precipitation during the fallow period preceding wheat was 563 mm (Table 3.1).

Cover crop biomass

Post-wheat CCs produced 3196 kg ha^{-1} total biomass on average (Fig. 3.2). Cover crop biomass accumulation was variable over the study period with greatest biomass production in 2016 and 2018 and relatively less especially in 2019. Cover crops failed to establish in 2017 and 2021, and because of limited biomass production in 2019, CCs were not grazed or hayed (Fig. 3.2). Hayed and grazed CCs retained less CC biomass as residue than the standing CC in 2016, 2018, and 2020. Hayed CCs retained similar CC biomass as grazed CCs in 2016 and 2020 but was only 28% of the grazed CC in 2018 (Fig. 3.2). On average, hayed and grazed CCs retained 44 and 65% of the standing CC biomass, respectively.

Grain crop yields

Cover crops reduced subsequent grain sorghum yields by about 14% compared to fallow on average (Fig. 3.3). However, fallow management effects varied across years. Grain sorghum yields were unaffected by fallow management in 2017 and 2018. However, CCs reduced grain sorghum yields 23 and 13% compared to fallow in 2019 and 2020, respectively (Fig. 3.3). Interestingly, in 2021, grain sorghum yields were 22% less following hayed or grazed CCs compared to fallow, but yields following standing CCs were not significantly different from after fallow. Exceptional drought conditions resulted in a failed grain sorghum crop in 2022 (Table 3.1).

Net returns and profitability

Average net returns with grazed and hayed CCs were similar to fallow but greater than standing CCs (Fig. 3.4). Returns with grazed and hayed CCs were similar to fallow in most

years. However, in 2018-2019, grazed CCs as an alternative to confined hay feeding provided greater net returns than fallow. In 2019-2020, net returns from hayed and grazed CCs as an alternative to grazing rangeland were less than fallow, and all CC treatments had lower net returns than fallow in 2021-2022 (Fig. 3.4). Fallow provided greater net returns than standing CCs in most years except 2017-2018 and 2020-2021 when standing CCs provided similar net returns as fallow. Cumulative exceedance probability analysis indicated that the probability of obtaining break-even net returns was least with standing CCs at 67% and greatest for grazed CCs, hayed CCs, and fallow at 83% (Fig. 3.5). The probabilities of obtaining net returns above break-even were typically greater for grazed and hayed CCs compared to standing CCs but similar to fallow (Fig. 3.6). For example, the probability of obtaining net returns equal to or greater than \$200 ha^{-1} was 83, 79, 75, 71, and 63% for grazed CCs as an alternative to confined hay feeding, grazed CCs as an alternative to grazing rangeland, hayed CCs, fallow, and standing CCs, respectively. Sensitivity analyses further showed the variability and trade-offs in potential net returns from grazed or hayed CCs depending on CC biomass yield and subsequent grain sorghum yields (Table 3.2). Analyses show that when sorghum yield was 2500 kg ha^{-1} and CC biomass was 2000 kg ha^{-1}, there was a \$42.29 ha^{-1} advantage of haying over grazing as an alternative to grazing rangeland. However, when CC biomass was 4000 kg ha^{-1} that was a \$84.56 ha^{-1} advantage of haying over grazing as an alternative to grazing rangeland (Table 3.2).

Soil chemical and physical properties

Soil BD, NO_3-N and P concentrations, and WEF were unaffected by fallow management treatments in the 0-5 or 5-15 cm soil depths (Table 3.3). However, SOC concentration in the 5-15 cm soil depth were greater with grazed CCs than standing CCs, hayed, CCs, and fallow. Though not statistically significant, a trend of greater SOC concentration with grazed CCs than

other treatments was also observed in the 0-5 cm soil depth. Soil organic carbon stock was greater with grazed CCs compared to fallow or standing CCs in the 0-5 and 5-15 cm soil depths (Table 3.3). In the 0-5 cm soil depth, SOC stock with hayed CCs were greater than standing CCs but similar to fallow, which was similar to standing CCs. In the 5-15 cm soil depth, SOC stock with hayed and standing CCs were similar to fallow and all were less than grazed CCs. In the 0-5 cm soil depth, MWD with grazed CCs was similar to fallow but greater than standing or hayed CCs (Table 3.3). The MWD with standing CCs was similar to fallow and hayed. In the 5-15 cm soil depth, MWD was unaffected by fallow management treatments.

Relationships between soil chemical and physical properties.

There was a significant negative relationship between soil BD and WEF (Table 3.4). Soil organic carbon had significant positive correlations with NO_3-N and P. Results of regression analysis showed that for every 1 g kg^{-1} increase in SOC concentration, P concentration increased approximately 6.3 g kg^{-1} (Fig. 3.6a). Soil NO_3-N was significantly and positively correlated with P and WEF (Table 3.4). Regression analysis showed that for every 1 g kg^{-1} increase in NO_3-N concentration, P concentration increased 0.6 g kg^{-1} (Fig. 3.6b). Soil P was also significantly and positively correlated with WEF (Table 3.4).

Discussion

Despite substantial research attention given to the replacement of fallow before wheat, little information is available on fallow replacement after wheat harvest. Cover crops after wheat could intensify cropping systems and increase forage availability during a time of year when traditional forage resources are limited in the semi-arid CGP (Holman et al., 2023; Jenkins et al., 2019; Titlow et al., 2014). In the present study, CC biomass remaining post-grazing was 64% of the pre-grazing biomass while haying retained only about 44% of CC biomass as crop residue.

Although post-wheat CCs can be productive, CC biomass accumulation was quite variable over the study period, including two years of failed CC establishment (because of very dry soils) and one year of very low biomass production. Planting warm-season CCs immediately after wheat harvest to take advantage of soil PAW near the soil surface will improve CC germination and emergence. When planting is delayed, the soil surface may dry, creating a poor environment for crop establishment without timely rainfall, which is unreliable in the semi-arid CGP. These results and those of others in the region (Holman et al., 2018; 2022; 2023; Obour et al., 2021b; 2022) highlight that, while CCs could be a suitable short-term feed source for livestock, they are unlikely to be a reliable long-term feed source because of variable forage accumulation. The uncertainty of CC biomass production and requirement to have alternative livestock feeding plans ready when CC biomass production is low could pose another potential barrier to CC adoption, depending on individual producer resources (i.e., stored hay and stockpiled pasture or crop residues). Holman et al. (2022, 2023) outlined how CC forage can be used in a forage plan to reduce the risk associated with highly variable precipitation and forage yield in the semi-arid Great Plains.

In semi-arid environments like the CGP, growing season precipitation alone is typically not adequate for stable grain production and is supplemented by PAW stored in soil during fallow periods (Nielsen et al., 2005; Nielsen & Vigil, 2010; Peterson & Westfall, 2004). Past research has shown CCs reduce stored PAW in soil at subsequent crop planting compared to fallow, which can limit yield potential, especially in dry years when in-season precipitation is scarce (Holman et al., 2021a; 2021b; Obour et al., 2021b). Because of this, a flex-fallow concept was developed whereby CCs are only planted when adequate soil water is available and the precipitation outlook is neutral or above average in order to minimize negative impacts of CCs

on subsequent crops in dry years (Holman et al., (2021b; 2022). In the present study, grain sorghum yields were 14% less following CCs compared to fallow on average, which agrees with the results of Holman et al. (2023), also in western Kansas. However, the authors reported a 35% yield reduction likely because of lower average annual precipitation at their site (489 mm) compared to the present study site (566 mm). Nevertheless, Holman et al. (2023) showed that post-wheat forage sorghum harvested for hay maintained similar net returns to the traditional grain-based system despite reductions in grain sorghum yield. In the present study, both grazed and hayed CCs maintained average net returns similar to fallow and greater than standing CCs. However, sensitivity analyses revealed that hayed CCs had an advantage over grazed CCs (as an alternative to grazing rangeland) when CC biomass was high and less of an advantage of when CC biomass was low. A major cost associated with CCs is the seed for planting, and the CC mixture used in the present study was a four-species mixture of forage sorghum, pearl, millet, cowpea, and sunn hemp. The increased expense of broadleaf CC seed with limited biomass production was reported by others in the semi-arid CGP (Holman et al., 2018; 2022; Nielsen et al., 2015a; 2015b; 2015c). Simple grass-dominated CC mixtures may increase net returns directly because of their lower seed cost as well as indirectly if income from grazing or haying was increased with greater biomass production.

Our results and those of others indicate that post-wheat CCs for grazing or haying could be a suitable strategy for intensifying cropping systems, increasing forage availability, and maintaining or increasing profitability in the semi-arid CGP (Holman et al., 2023; Jenkins et al., 2019; Titlow et al., 2014). However, despite the economic benefits offered by grazing or haying CCs, concerns remain that removing CC biomass through grazing or haying could limit the beneficial effects of CCs for soil health (Franzluebbers & Stuedemann, 2008; 2014; 2015). A

primary concern with grazing CCs in NT systems is the risk of root-limiting soil compaction that could suppress subsequent crop yields and require some form of tillage for remediation. However, previous reports suggest that compaction risks might be dependent upon soil texture (Baumhardt et al., 2011; 2017), and effects could be transient in those regions with regular freeze-thaw cycles through the winter season (Blanco-Canqui et al., 2016a; 2016b). In the present study, BD in the 0-5 and 5-15 cm soil depths was unaffected by fallow management treatments, which suggests that compaction was not an issue in this study. Nevertheless, care should be taken to avoid excessive stocking densities and grazing CCs on waterlogged soils, which are more compactable than dry soils (Franzluebbers & Stuedemann, 2008; 2014; 2015).

Grazed CCs on croplands could help close nutrient cycles that currently export nutrients from the soil in harvested grain and forage to centers of confined animal feeding where manure must be disposed of locally (Kronberg et al., 2021). However, fallow management had no effect on soil NO_3-N or P in the present study, which was similar to the results of Kelly et al. (2021). In the case of the present study, a lack of significant difference may have been due to the short duration of grazing (24-hr flash grazing). Additional investigation of stocking densities and grazing durations, especially at field scales, will be necessary to better understand the potential for N and P cycling when CCs are grazed. Interestingly, SOC concentrations and stock were greater with grazed CCs compared to other fallow management treatments. Most observations have shown no significant difference in SOC between grazed CCs and standing CCs (Blanco-Canqui et al., 2021b; Kelly et al., 2021; Simon et al., 2021). However, the results of the present study suggest a possible synergistic effect of CCs and grazing on SOC stock, potentially because of manure deposition by livestock and hoof traffic incorporating crop residues into the soil. Mean weight diameter of water stable aggregates with standing and grazed CCs was similar to

fallow in the 0-5 cm soil depth. Notwithstanding, MWD with grazed CCs and fallow was greater than hayed CCs. Simon et al. (2021) reported similar results from one year of their study. In their case, MWD was greater with standing and grazed CCs compared to fallow, but hayed CCs were similar to fallow. Notwithstanding, MWD was greater with all CCs (grazed, hayed, or standing) compared to fallow in the other year of their study. Based on their results and the findings of the present study, we propose careful management to maintain adequate CC residue when using CCs for forage to meet soil conservation goals. Raising the cutting height for forage harvest, leaving more standing stubble, for example might increase MWD in hayed CC.

Conclusion

Results from this six-year study showed that post-wheat CCs produced 3196 kg biomass ha^{-1} on average but biomass production was variable with significant risk for failed stand establishment. Grazing retained 65% of the standing CC biomass as residue while haying retained 44%. Grain sorghum yields were reduced 14% following CCs compared to fallow. However, average net returns with grazed or hayed CCs were similar to fallow and greater than standing CCs. Bulk density, NO_3-N, P, and WEF were unaffected by fallow management, but grazed CCs increased SOC concentration and stock compared to fallow. This finding suggests a possible synergistic effect of CCs and grazing on SOC. Mean weight diameter of water stable aggregates with grazed CCs was similar to fallow and greater than hayed CCs. These results suggest that integrating post-wheat CCs for grazing and haying into NT dryland cropping systems in the semi-arid CGP can intensify cropping systems and increase forage availability while maintaining profitability. Care should be taken to plant warm-season CCs immediately after wheat harvest to take advantage of soil water before the soil surface dries, creating a poor environment for crop establishment without timely rainfall. Careful management when using

CCs for forage is necessary to maintain adequate CC residue to balance goals of forage production and soil health. Additional research on forage harvest cutting height and amount of residue removed by grazing is needed to refine best management practices for achieving sustainability goals.

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Figures

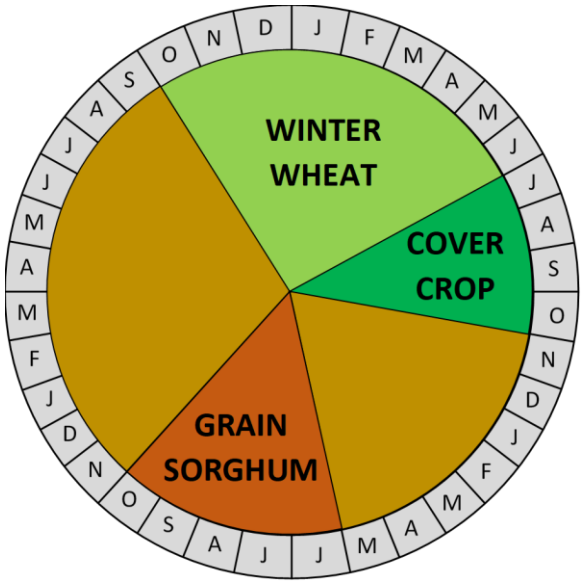

Figure 3.1. A pictorial representation of the winter wheat–grain sorghum–fallow cropping system with cover crops, which could be standing, hayed, or grazed, grown in place of traditional fallow after winter wheat harvest in the long-term cover crop management study at the Kansas State University Hearting-Beason Ranch near Brownell, KS.

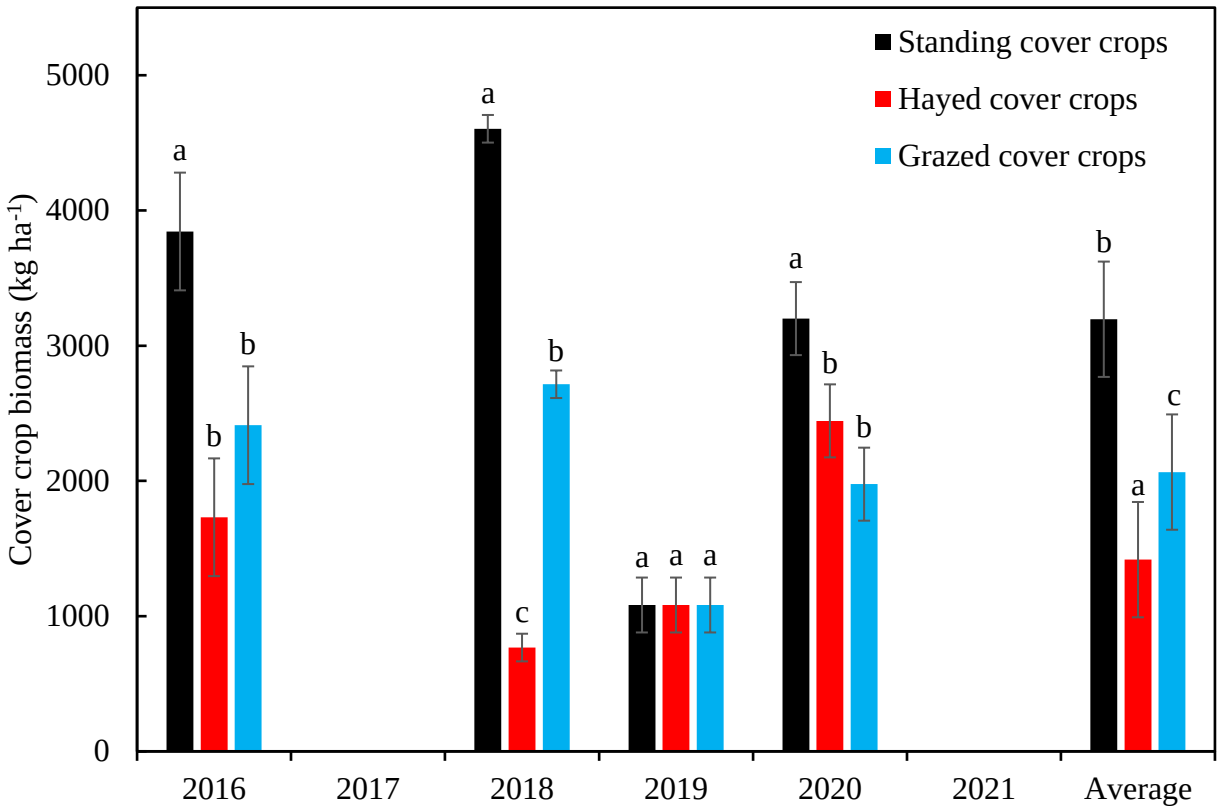

Figure 3.2. Cover crop biomass remaining as residue following cover crop grazing, haying, and termination from 2016 to 2021 near Brownell, KS. Exceptional drought conditions in 2017 and 2021 resulted in crop failures. Means followed by the same lower-case letter are not significantly different ($\alpha = 0.05$) among cover crop management treatments and bars indicate one standard error of the mean.

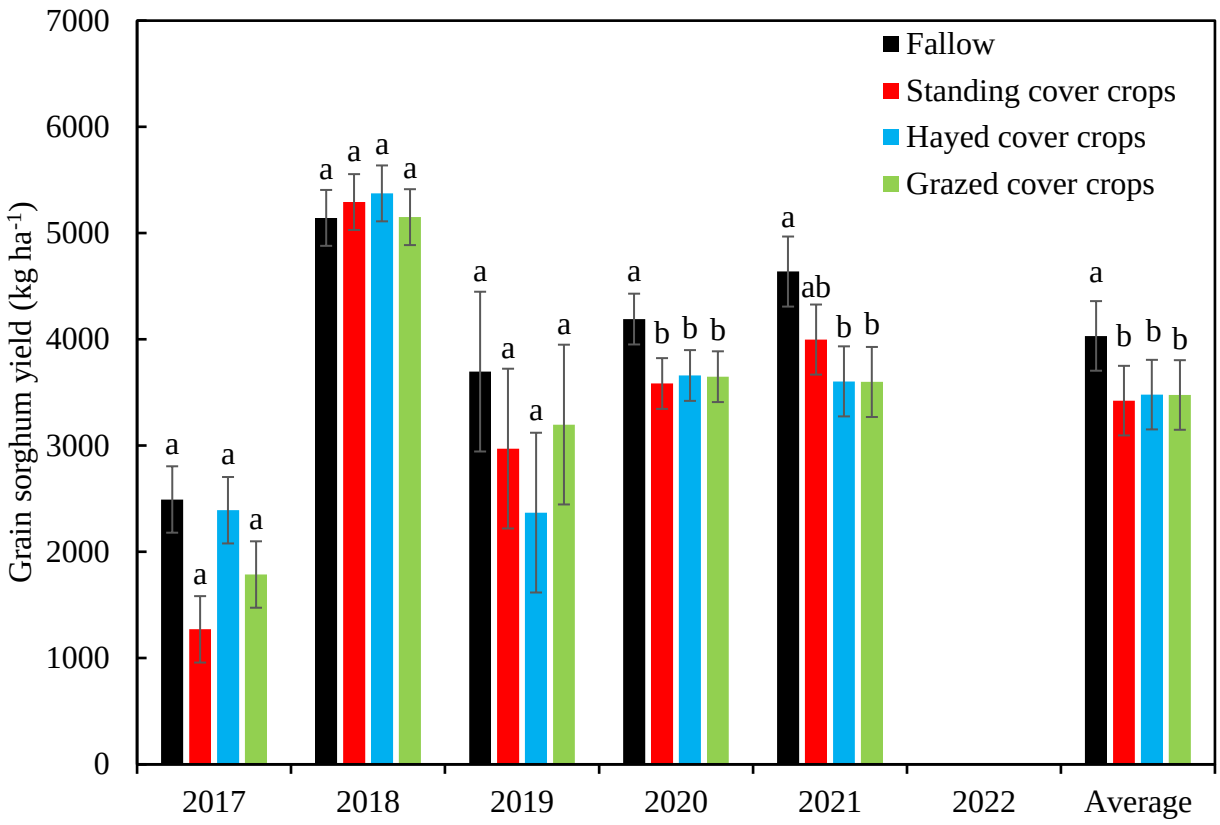

Figure 3.3. Post-wheat cover crop management effects on subsequent grain sorghum yields from 2017 to 2022 near Brownell, KS. Exceptional drought conditions in 2022 resulted in crop failures. Means followed by the same lower-case letter are not significantly different ($\alpha = 0.05$) among cover crop management treatments and bars indicate one standard error of the mean.

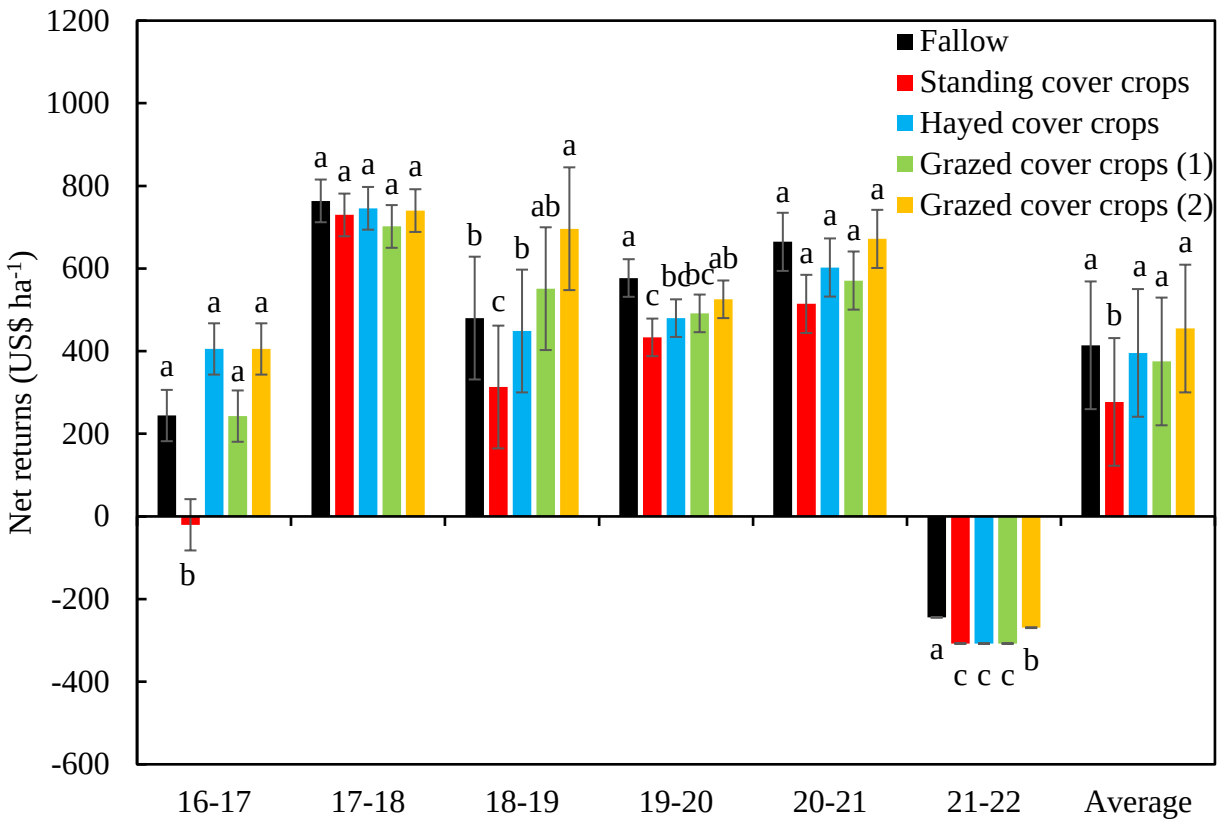

Figure 3.4. Post-wheat cover crop management effects on net returns from 2016 to 2022 near Brownell, KS. Means followed by the same lower-case letter are not significantly different (α = 0.05) among cover crop management treatments and bars indicate one standard error of the mean. Net returns from grazing cover crops represent scenarios where the alternative is grazing native rangeland (1) or where the alternative is confined hay feeding (2).

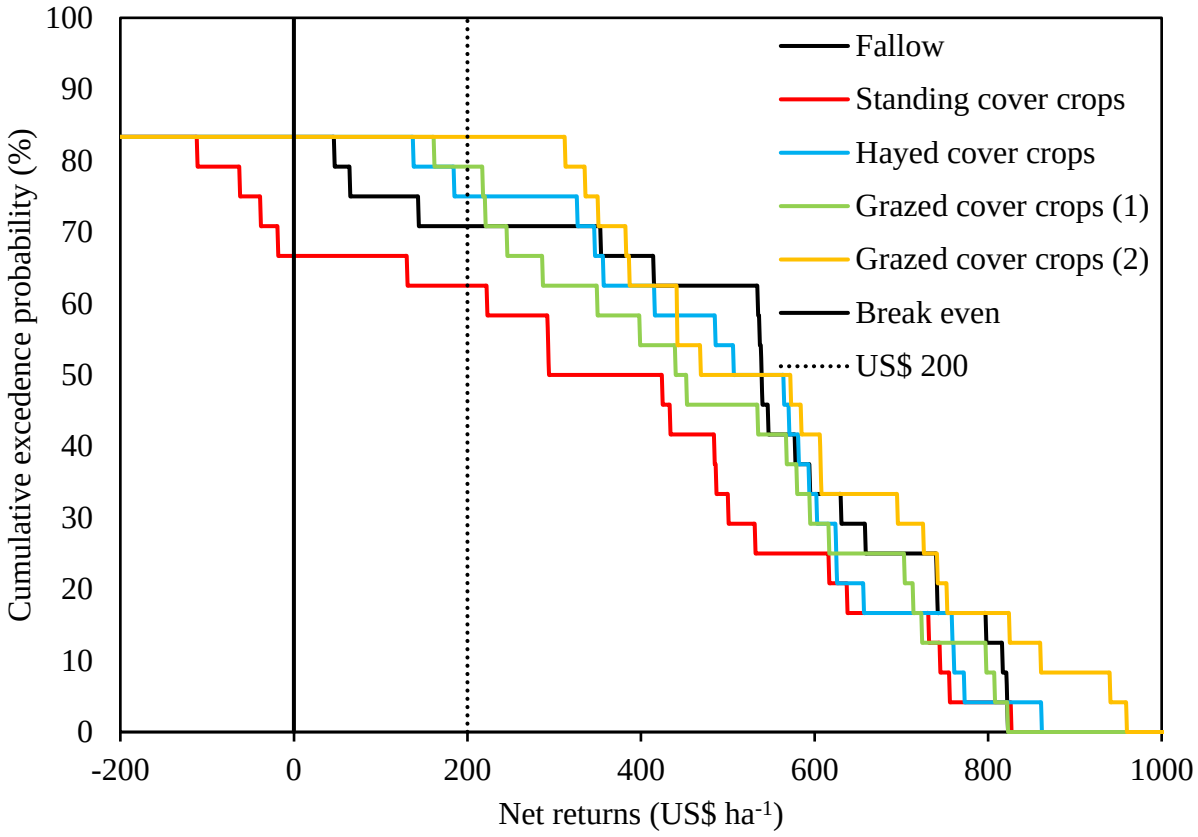

Figure 3.5. Cumulative exceedance probability of net income for post-wheat cover crop management strategies from 2016 to 2022 near Brownell, KS. Net returns from grazing cover crops represent scenarios where the alternative is grazing native rangeland (1) or where the alternative is confined hay feeding (2).

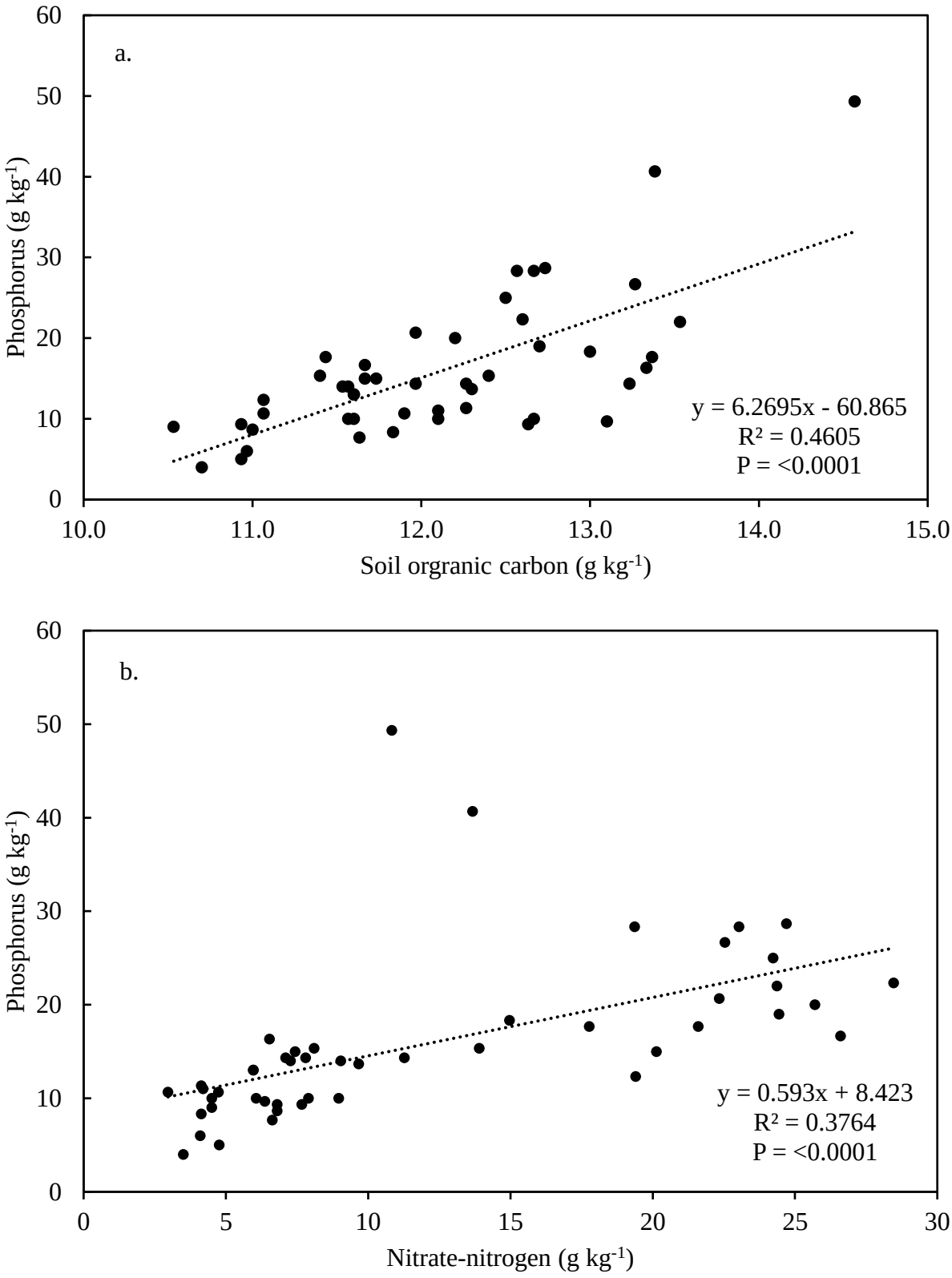

Figure 3.6. Relationships of soil organic carbon and phosphorus concentrations (a) and soil nitrate-nitrogen and phosphorus (b.) across sampling depths.

Tables

Table 3.1. Fallow, cover crop, and cash crop growing season precipitation from 2015 to 2023 near Brownell, KS.

Growing season	Cover crops	Grain sorghum			Winter Wheat	
	Growing season if post-wheat (Jul. to Oct.)	Preceding fallow if after wheat (Jul. to May)	Preceding fallow if after cover crops (Nov. to May)	Growing season (Jun. to Oct.)	Preceding fallow (Nov. to Oct.)	Growing season (Oct. to Jun.)
	mm					
2016	218	-	-	-	-	-
2017	507	341	122	601	-	-
2018	420	820	314	461	545	267
2019	266	658	237	327	645	433
2020	224	645	378	257	736	336
2021	96	358	135	150	562	414
2022	-	227	131	221	606	218
2023	-	-	-		282	209
Study avg.	289	508	220	336	563	313
30-yr. avg.	256	491	239	331	529	359

Table 3.2. Sensitivity analysis of cover crop biomass and grain sorghum yield effects on net returns.

Cover crop biomass yield, kg ha^{-1}	Grain sorghum yield, kg ha^{-1}										
	0	500	1000	1500	2000	2500	3000	3500	4000	4500	5000
	Net returns from grazing cover crops as an alternative to grazing rangeland, $US ha^{-1}										
0	-282.03	-182.03	-82.03	17.97	117.97	217.97	317.97	417.97	517.97	617.97	717.97
500	-261.10	-161.10	-61.10	38.90	138.90	238.90	338.90	438.90	538.90	638.90	738.90
1000	-240.17	-140.17	-40.17	59.83	159.83	259.83	359.83	459.83	559.83	659.83	759.83
1500	-219.24	-119.24	-19.24	80.76	180.76	280.76	380.76	480.76	580.76	680.76	780.76
2000	-198.31	-98.31	1.69	101.69	201.69	301.69	401.69	501.69	601.69	701.69	801.69
2500	-177.37	-77.37	22.63	122.63	222.63	322.63	422.63	522.63	622.63	722.63	822.63
3000	-156.44	-56.44	43.56	143.56	243.56	343.56	443.56	543.56	643.56	743.56	843.56
3500	-135.51	-35.51	64.49	164.49	264.49	364.49	464.49	564.49	664.49	764.49	864.49
4000	-114.58	-14.58	85.42	185.42	285.42	385.42	485.42	585.42	685.42	785.42	885.42
4500	-93.65	6.35	106.35	206.35	306.35	406.35	506.35	606.35	706.35	806.35	906.35
5000	-72.72	27.28	127.28	227.28	327.28	427.28	527.28	627.28	727.28	827.28	927.28
	Net returns from grazing cover crops as an alternative to confined hay feeding, $US ha^{-1}										
0	-282.03	-182.03	-82.03	17.97	117.97	217.97	317.97	417.97	517.97	617.97	717.97
500	-245.33	-145.33	-45.33	54.67	154.67	254.67	354.67	454.67	554.67	654.67	754.67
1000	-208.63	-108.63	-8.63	91.37	191.37	291.37	391.37	491.37	591.37	691.37	791.37
1500	-171.93	-71.93	28.07	128.07	228.07	328.07	428.07	528.07	628.07	728.07	828.07
2000	-135.23	-35.23	64.77	164.77	264.77	364.77	464.77	564.77	664.77	764.77	864.77
2500	-98.52	1.48	101.48	201.48	301.48	401.48	501.48	601.48	701.48	801.48	901.48
3000	-61.82	38.18	138.18	238.18	338.18	438.18	538.18	638.18	738.18	838.18	938.18
3500	-25.12	74.88	174.88	274.88	374.88	474.88	574.88	674.88	774.88	874.88	974.88
4000	11.58	111.58	211.58	311.58	411.58	511.58	611.58	711.58	811.58	911.58	1011.58
4500	48.28	148.28	248.28	348.28	448.28	548.28	648.28	748.28	848.28	948.28	1048.28
5000	84.98	184.98	284.98	384.98	484.98	584.98	684.98	784.98	884.98	984.98	1084.98
	Net returns from haying cover crops, $US ha^{-1}										
0	-282.02	-182.02	-82.02	17.98	117.98	217.98	317.98	417.98	517.98	617.98	717.98

500	-250.52	-150.52	-50.52	49.48	149.48	249.48	349.48	449.48	549.48	649.48	749.48
1000	-219.02	-119.02	-19.02	80.98	180.98	280.98	380.98	480.98	580.98	680.98	780.98
1500	-187.52	-87.52	12.48	112.48	212.48	312.48	412.48	512.48	612.48	712.48	812.48
2000	-156.02	-56.02	43.98	143.98	243.98	343.98	443.98	543.98	643.98	743.98	843.98
2500	-124.52	-24.52	75.48	175.48	275.48	375.48	475.48	575.48	675.48	775.48	875.48
3000	-93.02	6.98	106.98	206.98	306.98	406.98	506.98	606.98	706.98	806.98	906.98
3500	-61.52	38.48	138.48	238.48	338.48	438.48	538.48	638.48	738.48	838.48	938.48
4000	-30.02	69.98	169.98	269.98	369.98	469.98	569.98	669.98	769.98	869.98	969.98
4500	1.48	101.48	201.48	301.48	401.48	501.48	601.48	701.48	801.48	901.48	1001.48
5000	32.98	132.98	232.98	332.98	432.98	532.98	632.98	732.98	832.98	932.98	1032.98

Table 3.3. Post-wheat cover crop management effects on bulk density (BD), soil organic carbon (SOC), nitrate-N (NO_3-N), phosphorus (P), mean weight diameter (MWD) of water stable aggregates, and wind-erodible fraction (WEF) in the 0-5 and 5-15 cm soil depths at in summer 2021 near Brownell, KS.

Management	BD	SOC		NO_3-N	P	MWD	WEF
	g cm^{-3}	g kg^{-1}	Mg ha^{-1}	kg ha^{-1}	kg ha^{-1}	mm	%
	0-5 cm						
Fallow	1.17a[†]	13.5a	7.86bc	21.65a	17.76a	0.84ab	34.0a
Standing cover crops	1.14a	13.4a	7.65c	21.66a	15.31a	0.65bc	31.8a
Hayed cover crops	1.21a	13.9a	8.41ab	21.18a	17.74a	0.59c	35.9a
Grazed cover crops	1.22a	14.3a	8.73a	23.29a	19.55a	0.84a	34.3a
	5-15 cm						
Fallow	1.43a	11.1b	15.90b	6.44a	11.45a	0.59a	16.8a
Standing cover crops	1.40a	11.0b	15.41b	6.04a	9.32a	0.69a	19.7a
Hayed cover crops	1.39a	11.1b	15.41b	5.55a	10.65a	0.66a	16.3a
Grazed cover crops	1.43a	12.0a	17.11a	7.23a	19.51a	0.72a	15.1a

[†]Means followed by the same lower-case letter within the same column and soil depth are not significantly different ($\alpha = 0.05$) among treatments.

Table 3.4. Correlation coefficients (*r*) and *P* values from correlation analysis among soil properties across sampling depths.

Parameter	SOC[†]	NO_3-N	P	MWD	WEF
BD					
r	0.07	-0.10	0.01	0.06	-0.33**[‡]
SOC					
r		0.35**	0.70*****	-0.10	0.13
NO_3-N					
r			0.57*****	0.05	0.42***
P					
r				-0.07	0.33**
MWD					
r					-0.08

[†] SOC, soil organic carbon, NO_3-N, nitrate-nitrogen, P, phosphorus, MWD, mean weight diameter, WEF, wind-erodible fraction.

[‡]**P*≤0.10; ***P*≤0.05; ****P*≤0.01; *****P*≤0.001; ******P*≤0.0001

Chapter 4 - Flexible Fallow Replacement Cover Crops in a Water-Limited High Plains Cropping System

Abstract

Flexible cover crop (CC) management systems based on measurements of plant available water (PAW) and the climate outlook could better balance goals of enhancing soil health, water use efficiency, and system profitability in water-limited cropping systems compared to CCs in a set crop rotation. The objectives of this study were to determine PAW, grain and forage yield, net returns, as well as soil chemical and physical property impacts of flexible fallow replacement with dual-purpose CCs in a no-till (NT) dryland winter wheat (*Triticum aestivum* L.)–grain sorghum (*Sorghum bicolor* Moench)–fallow cropping system. The study was conducted from 2015 to 2023 near Brownell and Garden City, KS with spring oat (*Avena sativa* L.)/triticale (×*Triticosecale* Wittm.) CCs grown in place of fallow and managed as standing or hayed in fixed rotations or flex-hayed. Flex-CCs were planted if a minimum of 30 cm of moist soil (~50 mm PAW) was measured and the National Weather Service Seasonal Precipitation Outlook for the season was neutral or above average, otherwise plots remained fallow. Results from this study showed that hayed CCs yielded 2218 kg forage ha^{-1} at Brownell but flex-hayed CCs yielded 26% less on average because flex-CCs were planted only 75% of the time. Profile PAW with CCs was less than fallow. However, hayed and flex-hayed CCs maintained average subsequent wheat and sorghum yields and increased net returns compared to standing CCs or fallow. The net returns from flex-hayed CCs were similar to hayed CCs in a fixed rotation. Hayed and flex-hayed CCs increased mean weight diameter of water stable aggregates at Brownell which suggests that hayed CCs provide similar benefits to soil health as standing CCs and flex-hayed CCs provide similar benefits as CC in fixed rotations. However, fallow management had no other effect on

soil properties across locations, which was likely because long-term NT adoption at Brownell and Garden City masked potential differences with CCs compared to fallow. These results suggest that hayed CCs in fixed rotation was the best strategy to produce forage, increase net returns, and potentially enhance soil health. Nevertheless, flexible CC management systems might still be a useful strategy in the semi-arid CGP to avoid severe wheat yield reductions following CCs in extremely dry years. More site-year observations are needed to better understand the impact of flex-CCs on PAW, crop yields, net returns, and soil properties. Additionally, increased accuracy of precipitation outlook models will be required for flex-CCs to successfully be adopted in this region.

Introduction

Replacing fallow with cover crops (CCs) could enhance soil health, suppress herbicide-resistant weeds, and increase precipitation use efficiency in dryland cropping systems (Blanco-Canqui et al., 2021; Obour et al., 2021). However, a major limitation to their adoption in the semi-arid U.S. High Plains is the water use of CCs compared to fallow and potential reductions in subsequent grain crop yields (Holman et al. 2018; 2021a; Obour et al., 2022). Fallow periods of 11 to 14 months are a water conservation practice in semi-arid regions like the High Plains to store plant available water (PAW) in the soil profile and stabilize water-limited crop production (Nielsen et al., 2005; Nielsen & Vigil, 2010; Peterson & Westfall, 2004). Nevertheless, fallow is associated with increased soil loss by wind and water erosion as well as depletion of soil organic carbon (SOC) compared to continuous cropping because less crop residue is produced in cropping systems that include fallow (Nielsen & Calderón, 2011; Peterson et al., 2020). Previous research has shown that growing CCs increased SOC and mean weight diameter (MWD) of water stable aggregates (WSA) and reduced bulk density (BD) and wind-erodible fraction (WEF)

in semi-arid western Kansas (Blanco-Canqui et al., 2013; Simon et al., 2021; 2022). This suggests CCs have the potential to improve soil health in water-limited cropping systems similar to that reported for more humid regions despite limited rainfall and high evaporative demand (Blanco-Canqui et al., 2021).

Despite benefits of CCs for soil health, Holman et al. (2018; 2021a) showed that in years of below average precipitation, subsequent wheat (*Triticum aestivum* L.) yields were reduced by as much as 70% when CCs were grown in place of fallow. Notwithstanding, in years when precipitation was above average, wheat yields were unaffected. Similarly, Obour et al. (2022) showed that CCs reduced wheat yields compared to fallow in three of four years at one study site, but wheat yields were less with CCs in just one of four years at the other site. Other studies showed that under extremely dry or wet conditions, wheat yields in semi-arid regions were unaffected by CCs grown in place of fallow (Holman et al., 2021b; 2022). Both scenarios of extremely dry or wet in-season precipitation masked any differences in soil water availability following a CC compared to fallow. However, the authors showed that net returns were greater when CCs were harvested for hay compared to unharvested CCs (Holman et al., 2018; 2021b). In semi-arid eastern Colorado, Nielsen et al. (2015a; 2015b; 2015c) showed that for every 20.7 kg ha^{-1} of CC biomass produced, PAW at subsequent wheat planting was reduced 1 mm. These result were similar to those of Holman et al. (2018) in semi-arid western Kansas who showed that PAW at subsequent wheat planting was reduced 1 mm for every 125 kg ha^{-1} of CC biomass produced.

A meta-analysis from Garba et al. (2022) showed that the costs of CCs exceeded the benefits in environments with less than 700 mm average annual precipitation. The authors concluded that careful site-specific plans are required to successfully incorporate CCs in such

environments. To overcome grain yield penalties following CCs in dry years, flexible CC management systems have been introduced as a possible strategy to take advantage of PAW in wet years while saving PAW for primary grain crops in dry years (Holman et al., 2021b; 2022). Flexible CC management systems based on measurements of PAW and the climate outlook could better balance goals of enhancing soil health, maintaining or increasing grain yield, and improving precipitation use efficiency in water-limited cropping systems compared to CCs in a set crop rotation (Holman et al., 2021b; 2022; Obour et al., 2021). This strategy is based on previous investigations of flexible fallow replacement in the semi-arid U.S. Great Plains and Canadian Prairies, which has also been referred to as dynamic cropping systems or opportunity cropping (Felter et al., 2006; Halvorson and Kresge, 1982; Liebig et al., 2007; Zentner et al., 1993). In their forum on dynamic cropping systems, Tanaka et al. (2002) referred to the concept as a long-term strategy for crop selection and sequence that could optimize productivity, profitability, and resource conservation in dryland crop production. The key instrument used in the implementation of such systems is the Paul Brown soil moisture probe (Brown, 1959; 1960) which was developed as a quick and easy to operate tool for determining the depth of moist soil for making crop management decisions. Because subsoil moisture is critical for dryland crop production, with crops often experiencing drought conditions at the time of seed-fill (terminal drought), the depth of moist soil can be used to make decisions of crop selection, seeding rate, as well as fertilizer rate (Felter et al., 2006; Halvorson and Kresge, 1982; Liebig et al., 2007; Zentner et al., 1993).

Nielsen et al. (2011; 2016) investigated fixed and flexible integrated grain and forage cropping systems to increase precipitation use efficiency and net returns. The authors found that the flexible cropping system that included grain and forage crops and assumed an expected 70%

or 100% of normal precipitation increased precipitation use efficiency on a value basis (US$ ha^{-1} mm^{-1}) by 53% compared to the average of all fixed cropping systems that only included grain crops. From 2011 to 2015, flexible crops were selected based on PAW at planting and the expectation of average growing season precipitation (Nielsen et al., 2016). The authors found that continuous forage-based cropping systems and flexible cropping systems that included wheat and forages substantially increased average annual net income compared to fixed grain-only cropping systems when crop insurance was excluded. In fact, continuous forage-based cropping systems and flexible cropping systems that included wheat and forages had >90% and >75% probability of breaking even (total income is equal to total costs) or generating a net income of at least \$200 ha^{-1} compared to <40% and <5% with the traditional fixed wheat-corn-fallow system, respectively. These results show the potential for dynamic cropping systems that include both grain and forage crops to increase precipitation use efficiency as well as system profitability in semi-arid dryland crop production.

The adoption of flexible CC management systems in dryland cropping systems could take advantage of PAW in the soil in wet years to produce more biomass and increase residue cover while minimizing negative effects in dry years by saving PAW for the main grain crop. Additionally, dual-purpose CCs harvested for forage could supply high-quality forage for livestock to further compensate for their production costs (Franzluebbers & Stuedemann, 2007; Drewnoski et al., 2018; Schomberg et al., 2014). Past research in the semi-arid High Plains has indicated that dual-purpose CCs grown in place of fallow had similar effects on soil chemical and physical properties but provided greater net returns compared to unharvested CCs or fallow (Holman et al., 2018; 2021b; Obour et al., 2022; Simon et al., 2021; 2022). However, the effects of flexible fallow replacement with dual-purpose CCs on PAW, crop production, system

profitability, and soil health are not fully understood. Therefore, the objectives of this study were to determine PAW at planting, grain and forage yield, net returns, as well as soil chemical and physical property impacts of flexible fallow replacement with dual-purpose CCs in a NT dryland winter wheat–grain sorghum (*Sorghum bicolor* Moench)–fallow (WSF) cropping system.

Materials and methods

Sites and study description

This study was conducted from 2015 to 2023 at the Kansas State University Hearting Beason Ranch (38˚38′23″ N, 99˚44′45″ W) near Brownell, KS and Southwest Research-Extension Center (37°59'58" N, 100°48'48" W) near Garden City, KS to investigate best management strategies for CCs to replace fallow in the traditional dryland cropping systems of the semi-arid High Plains. Fallow management effects on PAW, grain and forage yield, as well as net returns at Garden City were previously reported (Holman et al., 2021b; 2022). The soil series at Brownell was Harney silt loam (fine, smectitic, mesic Typic Argiustolls), a series of large extent formed from loess in the Rolling Plains and Breaks of west-central Kansas (National Cooperative Soil Survey, 2023). Long-term average (30 yr) annual precipitation at this site was 566 mm (Table 4.1). The soil series at Garden City was Ulysses silt loam (Fine-silty, mixed, superactive, mesic Torriorthentic Haplustolls), a series of large extent formed from loess in the Central High Tablelands of western Kansas. Long-term average precipitation at this site was 489 mm (Table 4.2). The study design at both locations was a split-plot randomized complete block with four replications. Crop phase (wheat, sorghum, and fallow) was the main plot and split-plots were fallow and an oat (*Avena sativa* L.)−triticale (× *Triticosecale* Wittm.) mixed CC that was left standing, hayed, or flex-hayed for a total of four treatments. Oat and triticale were selected based on their past performance in the region, consistently producing substantial biomass, as

well as low seed cost (Holman et al., 2018; Holman et al., 2021b; Obour et al., 2019, 2020). Split-plots were 9 m wide and 30 m long at Brownell and 4.5 m wide and 36 m long at Garden City. All crop phases (wheat, sorghum, or fallow) of this WSF rotation were present every year at each location, which allowed wheat, sorghum, and CC treatments to be implemented in every year of the study.

Management across sites

Each year at Brownell, winter wheat was planted at 67 kg ha^{-1} the 1st week of October using a NT drill (Model 3P1006NT, Great Plains Manufacturing, Salina, KS) with 19-cm row spacing. Each plot received 20 kg P_2O_5 ha^{-1} as monoammonium phosphate (11–52–0) in-furrow with the seed at planting. At spring green up, (~approximately by 25 March), an additional application of 84 kg nitrogen (N) ha^{-1} as urea (46–0–0) was broadcast on each plot. Postemergence winter annual weed control in wheat was accomplished with metsulfuron methyl at 5.3 g ai ha^{-1} or dicamba at 140 g ae ha^{-1} across years. Wheat was harvested in early July (Fig. 4.1) using a Massey Ferguson 8XP small plot combine harvester (Massey Ferguson, Duluth, GA, USA). At Garden City, winter wheat was planted at 63 kg ha^{-1} the 1st week of October using a small-plot NT drill (Fabro, Swift Current, SK) with John Deere double disk openers and 20.5-cm row spacing. Each plot received 20 P_2O_5 kg ha^{-1} as monoammonium phosphate (11–52–0) in-furrow with the seed at planting. At spring green up, (~approximately by 25 March), an additional application of 45 kg nitrogen (N) ha^{-1} as 32% UAN (32–0–0) was made on each plot. Postemergence winter annual weed control in wheat was accomplished with metsulfuron methyl at 5.3 g ai ha^{-1} or dicamba at 140 g ae ha^{-1} across years. Wheat was harvested in early July (Fig. 4.1) using a Wintersteiger Model Delta small plot combine harvester (Wintersteiger Inc., Salt

Lake City, UT, USA) equipped with a Model CX stripper header (Shelbourne Reynolds Inc., Colby, KS).

Typically, one herbicide application of glyphosate at 1,260 g ae ha^{-1} tank-mixed with 2,4-D at 560 g ae ha^{-1} was made following wheat harvest to control weeds through the later summer and another application of glyphosate at 1,260 g ae ha^{-1} and atrazine at 1,160 g ai ha^{-1} was made the following spring to control weeds before planting grain sorghum. Following an 11-month fallow period, sorghum at Brownell was planted at 77,000 seeds ha^{-1} the 1st week of June using the same NT drill as used for wheat except with 38.1-cm row spacing. Nitrogen and phosphorus were applied at sorghum planting at similar rates as previously described for wheat. Grain sorghum was harvested in mid-October to 1st week in November (Fig. 4.1) using the same small plot combine harvester as used for wheat. At Garden City sorghum was planted at 59,000 seeds ha^{-1} the 1st week of June using a four-row John Deere planter with max-emerge openers (John Deere, Moline, IL) and 76-cm row spacing. Before planting, 45 kg nitrogen (N) ha^{-1} as 32% UAN (32–0–0) was applied to each plot. Grain sorghum was harvested in mid-October to 1st week in November (Fig. 4.1) using the same small plot combine harvester as used for wheat but equipped with a 2-row crop header.

Cover crops were planted in mid-March as field conditions allowed using the same NT drill as used for wheat at each location with 20 cm row spacing at CC mix component seeding rates of 36 and 43 kg ha^{-1} for oat and triticale, respectively, in the fallow period between grain sorghum harvest and the planting of the next winter wheat crop in the rotation (Fig. 4.1). For the flex-hayed CC treatment, CCs were planted only if a minimum of 30 cm of moist soil (corresponding to ~50 mm PAW) was present at spring planting, determined using a Paul Brown soil moisture probe (Brown, 1959; 1960) and the National Weather Service Seasonal

Precipitation Outlook (National Oceanic and Atmospheric Administration, 2023) was neutral or favorable. Based on these criteria, the flex-hayed CC at Brownell was planted in 2015, 2016, 2017, 2019, 2020, and 2021 but remained fallow only in 2018 and 2022 (Table 4.3). However, at Garden City, the flex-hayed CCs were planted only in 2016, 2019, and 2022 but remained fallow in 2015, 2017, 2018, 2020, and 2021 (Table 4.3). Typically, four herbicide applications were made through the late spring and summer to control weeds through the fallow period before planting winter wheat again. Generally, dicamba at 280 g ae ha^{-1} alone or with 1,260 g ae ha^{-1} of glyphosate was applied in March, followed by 840 g ae ha^{-1} paraquat and 0.032 g ae ha^{-1} carfentrazone in May. Two more sequential burndown applications of glyphosate at 1,260 g ae ha^{-1} with 560 g ae ha^{-1} of 2,4-D were made in July and September to control weeds prior to winter wheat planting in October. Two herbicide applications were eliminated when CCs replaced a portion of the fallow period. Cover crops were hayed and chemically terminated by mid- to late June in an effort to minimize negative effects on subsequent winter wheat yields (Holman et al., 2018; 2021b). Hayed and flex-hayed CCs were harvested at a 15-cm cutting height using a small plot forage harvester (Carter Manufacturing Company, Inc., Brookston, IN) with a 0.9 m wide header at Brownell and a small lot forager harvester (Alpha-Omega, R-Tech Industries, Homewood, MB) with a 0.3 m wide header at Garden City. Hay harvest generally coincided with oat/triticale heading (Zadoks growth stages 51–59; Zadoks et al., 1974), which was selected to optimize forage mass and nutritive value (Landry et al., 2018). Cover crops were chemically terminated within one week following hay harvest with glyphosate and 2,4-D or paraquat and carfentrazone to control herbicide-resistant kochia [*Bassia scoparia* (L.) A.J. Scott].

Cover crop biomass

Each year, standing CC biomass was determined immediately prior to chemical termination by hand-clipping to the ground level from two areas of 0.50 m^2 per plot. Samples were dried at approximately 50 ˚C for a minimum of 48 h in a forced-air oven and weighed to determine dry matter content. Hayed treatments were harvested with a small plot forage harvester from a strip of 0.9 or 0.3 m wide in the middle of each plot. Whole plot fresh weights were recorded, subsamples collected and weighed, and then oven-dried to determine CC hay yield on a dry matter basis. Cover crop biomass removed with haying was subtracted from the standing CC biomass to estimate CC residue remaining. At Brownell, the remaining plot area in the hayed plots were harvested with the same equipment, and forage was removed from the plots following the cutting of a sample strip. At Garden City, the remaining plot area in the hayed plots were harvested with field scale equipment except in years of very low CC biomass production (usually because of drought) when remaining biomass was left standing following the cutting of a sample stip.

Plant available soil water

Plant available water at winter wheat planting in the 120-cm soil profile was determined gravimetrically each year in September at Brownell. The depth of soil water sampling at Brownell was limited by a gravel layer around 120 to 150 cm, which was not present at Garden City where measurement of PAW extended to 180 cm. Two soil cores were taken from each plot with a hydraulic probe (Giddings Machine Company, Windsor, CO) and samples were portioned into 30 cm increments. Samples were weighed fresh and then dried at 105 °C for at least 48 h or until constant weight to estimate BD by mass of oven dry soil divided by volume of the core, and gravimetric water content (GWC) was computed as the difference between wet soil weight and

weight after drying at 105 °C, divided by dry weight of the sample. Data for the two cores were averaged for a single soil water content measurement, which was converted to volumetric water content using measured BD at each sampling depth. The equivalent depth of plant available soil water was then calculated as measured volumetric soil water content minus soil water content at permanent wilting point (−1.5 MPa matric potential) multiplied by the length of the soil core.

Grain crop yields

Both winter wheat and grain sorghum yields were determined by harvesting an area from the center of each plot. Winter wheat was harvested in July and grain sorghum was harvested in October each year of the study (Fig. 4.1). Grain moisture content was determined using a DICKEY-john grain moisture tester (DICKEY-john Inc., Auburn, IL, USA), and yield of both wheat and grain sorghum was adjusted to 13.5% moisture content. Exceptional drought conditions at Brownell resulted in a failed grain sorghum crop in 2022 (<75 and <50% of normal preceding fallow and growing season precipitation, respectively) and failed winter wheat (<50% of normal preceding fallow and growing season precipitation) and grain sorghum crops (<50 and <75% of normal preceding fallow and growing season precipitation, respectively) in 2023 (Table 4.1).

Economic analysis

Net returns were calculated for the fallow/CC and subsequent wheat phase of the WSF cropping system as total fallow/CC and wheat revenue minus total fallow/CC and wheat costs for each treatment and year (Table A.3). Estimates of current field operations and input costs used 5-yr average custom rate values published by Kansas State University Land Use Survey Program and the Kansas Department of Agriculture (AgManager, 2021). Winter wheat grain and CC hay prices were determined from the USDA Economic Research Services market reports (USDA

ERS, 2021) for Kansas and calculated as \$0.21 kg^{-1} for winter wheat and \$0.15 kg^{-1} for CC hay, which was estimated from published values for good brome and alfalfa hay. Total variable costs were calculated as the sum of the expenses for fertilizer product and application costs, herbicide products and application, tillage operations, seed, planting, grain harvesting, as well as forage swathing, baling, and stacking bales at field edge. All costs and revenue were calculated on a ha^{-1} basis in US\$ (Table A.3). Net returns determined across the eight years of this study were used to calculate cumulative exceedance probabilities of net returns (probability of obtaining a minimum net return) for Fallow Management treatments to determine probabilities of at least breaking even (income = expenses) and obtaining at least \$200 ha^{-1} income similar to analyses conducted by Nielsen et al. (2016). Sensitivity analyses were performed to determine the variability in net returns and trade-offs across a range of CC biomass yields (0 to 5000 kg biomass ha^{-1}) and subsequent winter wheat yields (0 to 5000 kg grain ha^{-1}).

Residue cover and soil properties

Crop residue cover measurements and soil samples were collected at Brownell and Garden City from each split-plot in fall 2021 and fall 2022 following the termination of CCs but before winter wheat planting. The line-transect method was used to determine surface residue cover (USDA-NRCS, 2002). Briefly, a 3.05-m long wooden rod with marks at every 0.305-m interval was randomly placed at two 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 two sub-measurements were averaged to obtain one value for each plot.

For the determination of BD, two intact soil cores (5-cm diameter) were randomly taken from the 0-5 and 5-15 cm depths within each plot. The two samples from each depth were dried

separately at 105° C for 48 hr, and BD was determined as mass of oven dry soil divided by volume of the core. Additionally, 10 soil cores (2.5-cm diameter) were randomly collected within each plot, divided into the 0-5 and 5-15 cm depths, and composited by depth. Samples were air-dried, crushed, and sieved to pass through a 2 mm stainless steel screen. A portion of the 2 mm sieved 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 LECO TruSpec CN analyzer (LECO Corporation, St. Joseph, MI) after pretreating samples with 10% (v/v) HCl to remove carbonates (Nelson & Sommers, 1996). Carbon mass was calculated by multiplying SOC concentrations by soil BD and the thickness of the soil layer. Particulate organic carbon (POC, >53 μm) was determined by the procedure outlined by Cambardella & Elliott (1992). Briefly, the POC fraction was isolated by dispersing soil in 5 g L^{-1} hexametaphosphate and passing the dispersed soil samples through a 53 μm sieve. Samples were dried in a forced-air oven and POC content was determined by dry combustion (Nelson & Sommers, 1996). Particulate organic carbon mass was calculated as previously described.

Lastly, 5 intact soils samples were collected from the 0-5 and 5-15 cm soil depths in each plot with a flat shovel for the determination of water stable aggregates and dry aggregate stability. Soil aggregates were allowed to air-dry and were then gently passed through a 19 mm sieve. From there, two approximately 50 g subsamples of 8-4.75 mm diameter dry aggregates were obtained for each replicated treatment and used to estimate MWD of water stable aggregates by the wet-sieving method (Nimmo & Perkins, 2002). The remaining aggregate sample of approximately 3000 g was used to estimate WEF (<0.84 mm) by the dry-sieving method (Chepil, 1962). For the wet sieving method, an approximate 50 g sample was placed on top of a stack of nested sieves of 2-, 1-, and 0.25-mm sized openings in a water column (Nimmo

& Perkins, 2002). The samples were allowed to wet by capillarity for 5 minutes after which the stacks of sieves were vertically oscillated a distance of 3.7 cm at 30 oscillations minute^{-1} for 5 minutes. The amount of soil retained on each sieve was transferred into glass beakers, dried at 105° C, and weighed to determine the proportion of water stable aggregates within each size fraction. Each dry sample was then corrected for coarse sand by mixing the oven-dried aggregates with 30 ml of 0.5% sodium hexametaphosphate to disperse soil particles and allowing them to soak for a minimum of four hours. Samples were then swirled on an orbital shaker for an additional four hours. Each dispersed sample was then passed back through individual sieves with the same size openings. The recovered sand was oven-dried and weighed to correct for coarse soil particles. Sand-corrected values were used to compute MWD (Nimmo & Perkins, 2002). For the dry-sieving method, an approximately 3000 g air-dried sample was placed on top of a stack of nested sieves of 6.3-, 2-, 0.84-, and 0.42-mm sized openings (Chepil, 1962). Samples were shaken for 5 min using a portable orbital sieve shaker (W.S. Tyler Model RX-812, Mentor, OH). The soil particles remaining on each sieve were weighed and the data was used to compute WEF (Chepil, 1962).

Statistical analysis

Analyses of CC biomass, crop residue cover, grain yields, net returns, as well as soil chemical and physical properties at each location were performed using the PROC GLIMMIX procedure in SAS ver. 9.4 (SAS Institute, 2012). As previously mentioned, fallow management effects on PAW, grain and forage yield, as well as net returns at Garden City have been previously reported (Holman et al., 2021b; 2022). For CC biomass at Brownell, CC management (standing, hayed, or flex-hayed), year, and their interactions were modeled as fixed effects while replication and its interaction with fixed effects were considered random in the model. For PAW,

grain yields, and net returns at Brownell, fallow management (fallow, standing CCs, hayed CCs, and grazed CCs), year, and their interactions were modeled as fixed effects, while replication and its interaction with fixed effects were considered random in the model. Analyses of crop residue cover at Brownell and Garden City were conducted as previously described for PAW, grain yields, and net returns at Brownell. For BD, SOC, POC, MWD, and WEF at Brownell and Garden City, fallow management (fallow, standing CCs, hayed CCs, and grazed CCs), depth, year, and their interactions were modeled as fixed effects while replication and its interaction with fixed effects were considered random in the model. Interactions and treatment effects were considered significant at $\alpha = 0.05$. Correlation analysis among crop residue cover, BD, GWC, SOC, POC, MWD, and WEF was conducted using the PROC CORR procedure in SAS. Correlations were considered significant at $\alpha = 0.05$.

Results

Precipitation patterns over the study period

Precipitation during the study period (2015-2023, Table 4.1; 4.2) varied year-to-year, as is typical of the semi-arid climate of the High Plains and provided a broad range of water availability conditions for quantifying cropping system productivity. At Brownell, the average precipitation received during the CC, wheat, and sorghum growing seasons was 242, 341, and 325 mm, respectively, which was near the 30-yr average for each period (Table 4.1). However, the average precipitation received at Garden City during the CC, wheat, and sorghum growing seasons was 206, 277, and 257 mm, respectively, which was less than the 30-year average for each period (Table 4.2). In-season precipitation at both locations was highly variable over the years. At Brownell, precipitation during the fallow period preceding wheat if following sorghum was 547 mm or 2.3-fold the precipitation received during the shortened fallow period if

following CCs (239 mm) (Table 4.1). Similarly, precipitation received at Garden City during the fallow period preceding wheat if following sorghum was 412 or 2.4-fold the precipitation received during the shortened fallow period following CCs (175 mm) (Table 4.2).

Cover crop biomass

Cover crop biomass retained as crop residue at Brownell was significantly affected by the two-way interaction of Fallow Management (M) and Year (Y) (Table 4.4). Cover crop biomass varied substantially over the study period (Fig. 4.1). Cover crop biomass remaining after haying was less than the standing CC in all years and was similar between hayed and flex-hayed CCs except in 2018 and 2022 when flex-hayed CCs were not planted. The main effects of Fallow Management and Year were both significant for CC biomass accumulation (Table 4.4). On average, standing CCs produced 3104 kg biomass ha^{-1}, and average biomass remaining after haying was 31 and 24% of the standing CC with hayed and flex-hayed CCs, respectively. Averaged across treatments, CC biomass retained as crop residue was >2000 kg ha^{-1} in two years, 2000 to 1000 kg ha^{-1} in five years, and <1000 kg ha^{-1} in one year (Table 4.4).

Plant available water and grain crop yields

At Brownell, the two-way interaction of M × Y was significant for surface (0-15 cm) PAW at winter wheat planting but not profile (0-120 mm) PAW (Table 4.4). In five of eight years, PAW at the surface was not significantly different between fallow management treatments (Fig. 4.2). However, CCs decreased surface PAW by 47 to 89% compared to fallow in 2016. In 2020, flex-hayed CCs had 78% more surface PAW than fallow but were similar to standing and hayed CCs in the fixed rotations (Fig. 4.2). However, in 2022, flex-hayed CCs had 70% less PAW at the soil surface compared to standing or hayed CCs but was similar to fallow. The main effects of Fallow Management and Year were significant for profile PAW but only Year was

significant for surface PAW. On average (Table 4.4), PAW in the soil profile was 17% less with CCs (standing, hayed, or flex-hayed) compared to fallow. Profile PAW ranged from a low of 47 mm in 2022 to a high of 150 mm in 2019, and surface PAW ranged from a low of 4 mm in 2017 to a high of 32 mm in 2018.

The two-way interaction of M × Y was significant for winter wheat yields but not grain sorghum yields at Brownell (Table 4.5). Winter wheat yields were not different across fallow management treatments in four years with one year of crop failure for all fallow management treatments due to exceptional drought when preceding fallow and growing season precipitation were <50% of normal (Fig. 4.3; Table 4.1). However, wheat yields following CCs (standing, hayed, or flex-hayed) were 30% less than following fallow in 2017. In 2019, standing CCs decreased wheat yields 43% compared to fallow, which was similar to wheat yield following hayed or flex-hayed CCs. Wheat yields following standing or hayed CCs were 30% greater than fallow in 2021, but flex-hayed CCs were similar to fallow. The main effect of Year but not Fallow Management was significant for winter wheat and grain sorghum yields (Table 4.5). Winter wheat yield varied over the study period from a low of 2499 kg ha^{-1} in 2018 to a high of 3752 kg ha^{-1} in 2016 with one year of crop failure in 2023. Grain sorghum yield varied from a low of 2408 kg ha^{-1} in 2017 to a high of 5164 kg ha^{-1} in 2019 with two years of crop failure in 2022 and 2023 because of severe drought (Table 4.5).

Net returns

The two-way interaction of M × Y had a significant effect on cropping system net returns at Brownell (Table 4.5). Net returns with flex-hayed CCs were similar to hayed CCs in the fixed rotation in seven years and less than hayed CCs in fixed rotation in one year (Fig. 4.4). Flex-hayed CCs had greater net returns than standing CCs in five of eight years and greater than

fallow in one year. However, hayed CCs in the fixed rotation had greater net returns than standing CCs in five of eight years and greater than fallow in four years (Fig. 4.4). Net returns with standing CCs were less than fallow in two years. The main effects of Fallow Management and Year were significant for cropping system net returns (Table 4.5). Averaged across years, net returns of fallow management treatments were in the order of hayed CCs > flex-hayed CCs > fallow > standing CCs. Cumulative exceedance probability analysis indicated that the probability of obtaining break-even net returns was similar among treatments but the probabilities of obtaining net returns above break-even were generally greater for hayed or flex-hayed CCs compared to fallow or standing CCs (Fig. 4.5). For example, the probability of obtaining net returns equal to or greater than \$200 ha^{-1} was 84, 81, 69, and 44% with hayed CCs, flex-hayed CCs, fallow, and standing CCs, respectively. Sensitivity analyses further showed the variability and trade-offs in potential net returns from hayed CCs depending on CC biomass yield and subsequent winter wheat yields (Table 4.6). Analyses show that with the average CC biomass production of ~3000 kg ha^{-1} net returns would be at least break-even when wheat grain yield is between 500 and 1000 kg ha^{-1} and net returns would be equal to or greater than \$200 ha^{-1} when wheat grain yield is near 1500 kg ha^{-1}.

Residue cover and soil properties

At Brownell, the two-way interaction of M × Y had a significant effect on crop residue cover at winter wheat planting (Table 4.7). In 2021, crop residue cover was 5% greater with CCs (standing, hayed, or flex-hayed) compared to fallow (Fig. 4.6). However, in 2022, crop residue cover was 21 and 13% greater with standing and hayed CCs compared to fallow, which was similar to flex-hayed CCs. The main effects of Fallow Management and Year were also significant (Table 4.7). On average, residue cover with standing CCs were 14% greater than

fallow, which was similar to hayed and flex-hayed CCs. Crop residue cover in 2021 was 14% greater than in 2022. Only the main effects of Depth (D) and Year had a significant effect on BD (Table 4.7) with 32% lower BD in the 0-5 cm soil depth compared to the 5-15 cm depth and 9% lower BD in 2021 compared to 2022. Only Depth had a significant effect on SOC concentration and stock at Brownell. Soil organic carbon concentration was 23% greater in the 0-5 cm soil depth than the 5-15 cm depth while SOC stock was nearly 2-fold greater in the 5-15 cm soil depth than the 0-5 cm depth. Only Depth has a significant effect on POC concentration though there were no significant interaction or main effects on POC stock (Table 4.7). Particulate organic carbon concentration was 2.9-fold greater in the 0-5 cm soil depth than the 5-15 cm depth.

The three-way interaction of M × D × Y had a significant effect on MWD of water stable aggregates (Table 4.7). In 2021, the MWD in the 0-5 cm soil depth was 34% greater with CCs (standing, hayed, and flex-hayed CCs) compared to fallow (Table 4.8). However, there was no significant difference in MWD among fallow management treatments in the 5-15 cm soil depth that year. In 2022, the MWD in the 5-15 cm soil depth was 49% greater with standing and hayed CCs compared to fallow, which was similar to flex-hayed CCs. (Table 4.8). There was no significant difference in MWD among fallow management treatments in the 0-5 cm soil depth that year. The main effect of Fallow Management was also significant for MWD (Table 4.7). On average, CCs (standing, hayed, and flex-hayed CCs) increased MWD 27% compared to fallow. The two-way interaction of D × Y was significant for WEF (Table 4.7). The WEF in the 0-5 cm soil depth was greater in 2022 than 2021, but WEF in the 5-15 cm soil depth was similar between years (Fig. 4.7). The main effect of Depth was significant for WEF (Table 4.7). On average, the WEF in the 0-5 cm soil depth was 2.3-fold greater than the 5-15 cm depth.

At Garden City, only the main effect of Fallow Management had a significant effect on crop residue cover (Table 4.9). Across years, crop residue cover with standing CCs was 22% greater than fallow, which was similar to hayed and flex-hayed CCs. Only the main effect of Depth had a significant effect on BD, SOC stock, POC concentrations, and WEF, and there were no significant interaction or main effects on SOC concentrations, POC stock, or MWD (Table 4.9). Bulk density in the 5-15 cm soil depth was 10% greater than the 0-5 cm depth, and the SOC stock in the 5-15 cm soil depth was 1.9-fold greater than the 0-5 cm depth. Particulate organic carbon concentration was 2.1-fold greater in the 0-5 cm soil depth than the 5-15 cm depth, and the WEF in the 0-5 cm soil depth was 1.7-fold greater than the 5-15 cm depth.

Relationships between soil chemical and physical properties.

There were significant negative correlations of crop residue cover with BD but positive correlations with SOC, POC, and WEF (Table 4.10). Bulk density was significantly and positively correlated with GWC, SOC, and WEF but negatively correlated with POC and MWD. There were significant positive correlations of GWC with SOC and WEF but negative correlations with POC and MWD (Table 4.10). Soil organic carbon was significantly and positively correlated with WEF but negatively correlated with POC and MWD. There was a significant positive correlation of POC with MWD but a negative correlation with WEF (Table 4.10). Mean weight diameter was significantly and negatively correlated with WEF.

Discussion

Flexible CC management systems based on measurements of PAW and the climate outlook could better balance goals of enhancing soil health, maintaining or increasing grain yield, and improving precipitation use efficiency in water-limited cropping systems compared to CCs in a set crop rotation (Holman et al., 2021b; 2022; Obour et al., 2021). In the present study,

standing CCs at Brownell produced >3000 kg biomass ha^{-1} on average but biomass production varied considerably across years, which was mostly a factor of variation in preceding fallow and growing season precipitation. Average CC hay yield in the fixed rotation was greater than the flex-hayed CCs because the flex-hayed CC was not planted 25% of the time at Brownell. This represents an opportunity cost associated with flexible CC management that producers should be aware of when considering this practice. At Garden City, Holman et al. (2021b) showed that average CC hay yield in fixed rotations were substantially greater than flex-CCs because flex-CCs were not planted 80% of the time. Cover crops were planted more frequently at Brownell than Garden City, which was a factor of differences in average annual rainfall, 566 and 489 mm at Brownell and Garden City, respectively.

Nevertheless, average PAW was similar across fixed and flex-CC management treatments at Brownell with reduced profile PAW at subsequent wheat planting with CCs (standing, hayed, or grazed) compared to fallow but no difference in surface PAW between CCs and fallow. This may be the result of soil water recharge near the soil surface following CC termination before subsequent wheat planting and the fact that CCs in the flexible treatment were planted in the majority of years (75%) at Brownell. At Garden City, Holman et al. (2022) showed that average profile PAW at wheat planting with flex-CCs was similar to fallow likely because flex-CCs were not planted 80% of the time. However, average profile PAW with flex-CCs was also not significantly different from CCs in fixed rotations, which suggests that water use of the CCs at Garden City was low likely because CC biomass yields were also low (about 650 to 1500 kg ha^{-1}). Additionally, the lack of a clear advantage with flex-CCs was mostly because of poor accuracy of precipitation outlook models in predicting seasonal precipitation in the semi-arid High Plains.

Average wheat and sorghum yield at Brownell were not significantly different across fallow management treatments, which was similar to that reported by Holman et al. (2022) in Garden City. However, CCs reduced wheat yields by as much as 43% compared to fallow in some years at Brownell. Here reductions in subsequent wheat yields in some years were balanced by an increase in wheat yield following CCs compared to fallow in another year, which has not been widely reported in the semi-arid High Plains and should not be expected to occur regularly (Holman et al., 2018; 2021a; Nielsen et al., 2015a; 2015b; 2015c). Additionally, complete wheat crop failure, including the fallow and flex-hayed CC treatments, in 2023 because of exceptional drought probably also masked potential fallow management effects on wheat yields at Brownell. Notwithstanding, average wheat yields at Garden City were likely unaffected by fallow management because of extremely dry or wet in-season moisture availability over the years that also masked any differences in soil water availability following a CC compared to fallow at that site. These observations differ from those previously reported in the semi-arid High Plains where CCs frequently reduced subsequent wheat yields, especially in dry years (Holman et al., 2018; 2021a). In fact, the results of Nielsen et al. (2015a; 2015b; 2015c) and Holman et al. (2018) suggested that a CC that produced 2500 kg biomass ha^{-1} could potentially reduce PAW at wheat planting by 120.8 mm and wheat grain yield potential by 1510 kg ha^{-1}. However, Holman et al. (2018; 2021a) and Obour et al. (2022) showed that harvesting CCs as hay increased net returns even when subsequent wheat yields were reduced compared to fallow.

At Brownell, average net returns with hayed and flex-hayed CCs were greater than fallow and standing CCs. However, Holman et al., (2021b; 2022) showed no difference in net returns between CCs and fallow at Garden City during this study period. Notwithstanding, in an earlier phase of their study, Holman et al. (2018; 2021b) showed that hayed CCs increased net returns

compared to fallow or standing CCs. This is because of the high value of forage in the High Plains, which is driven by the large beef and dairy cattle (*Bos taurus* L.) industries in the region (Nielsen et al., 2011; 2016). In semi-arid eastern Colorado, Nielsen et al. (2011; 2016) showed that flexible cropping systems that included wheat and forages or continuous forage-based cropping systems substantially increased average annual net income compared to fixed grain-only cropping systems. In fact, flexible cropping systems that included wheat and forages or continuous forage-based cropping systems had >90% probability of breaking even (total income is equal to total costs) compared to <40% with the traditional fixed wheat-corn-fallow system. These results and those from the present study suggest that incorporating hayed CCs in either fixed or flexible systems could increase net returns compared to fallow or standing CCs. As previously mentioned, the lack of a clear advantage with flex-CCs was mostly because of poor accuracy of precipitation outlook models in predicting seasonal precipitation in the semi-arid High Plains. In the present study at Brownell, hayed CCs in fixed rotations provided the greatest net returns despite reduction in subsequent wheat yields in dry years.

A concern with harvesting dual purpose CCs for hay is that removing CC biomass could limit the beneficial effects of CCs for soil health (Franzluebbers & Stuedemann, 2008; 2014; 2015). In the present study, standing CCs increase crop residue cover compared to fallow at both Brownell and Garden City. However, hayed and flex-hayed CCs were similar to fallow. Nevertheless, CCs (standing, hayed, and flex-hayed CCs) increased MWD of water stable aggregates compared to fallow at Brownell, which suggests that hayed CCs could provide similar benefits to soil health as standing CCs and flex-hayed CCs could provide similar benefits as CC in fixed rotations. Simon et al. (2021; 2022) and Blanco-Canqui et al. (2013) reported similar findings with hayed and grazed CCs in western Kansas. However, fallow management had no

significant effect on other soil properties at Brownell or Garden City. In the semi-arid High Plains, researchers have frequently shown no differences in soil properties between CCs and fallow (Obour et al., 2021), especially in long-term NT systems (Simon et al., 2022). This suggests that the substantial effect of long-term NT adoption, as was the case for the present study, on soil properties may mask any potential difference with CCs compared to fallow and that NT adoption may be as much or more important as adopting CCs for enhancing soil health in dryland cropping systems (Blanco-Canqui & Jasa, 2019).

Conclusion

Results from this study showed that hayed CCs yielded 2218 kg forage ha^{-1} at Brownell but flex-hayed CCs yielded 26% less on average because flex-CCs were planted only 75% of the time. Producers should consider this opportunity cost associated with flexible CC management. However, hayed and flex-hayed CCs maintained average subsequent wheat and sorghum yields and increased net returns compared to standing CCs or fallow at Brownell. The lack of a clear advantage with flex-CCs was mostly because of poor accuracy of precipitation outlook models in predicting seasonal precipitation in the semi-arid High Plains, which must be improved for flex-CCs to be successful in the region. Hayed and flex-hayed CCs increased MWD of water stable aggregates at Brownell which suggests that hayed CCs provide similar benefits to soil health as standing CCs and flex-hayed CCs provide similar benefits as CC in fixed rotations. Fallow management had no significant effect on other soil properties across locations, which was likely because long-term NT adoption at both Brownell and Garden City masked potential differences with CCs compared to fallow. These results suggest that hayed CCs in the fixed rotation was the best strategy to produce forage, increase net returns, and potentially enhance soil health. Nevertheless, flexible CC management systems might still be a useful strategy in the semi-arid

High Plains to avoid severe wheat yield reductions following CCs in extremely dry years. More site-year observation will be required to better understand the impact of flex-CCs on PAW, crop yields, net returns, and soil properties. Additionally, increased accuracy of precipitation outlook models will be required for flex-CCs to successfully be adopted in this region.

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Figures

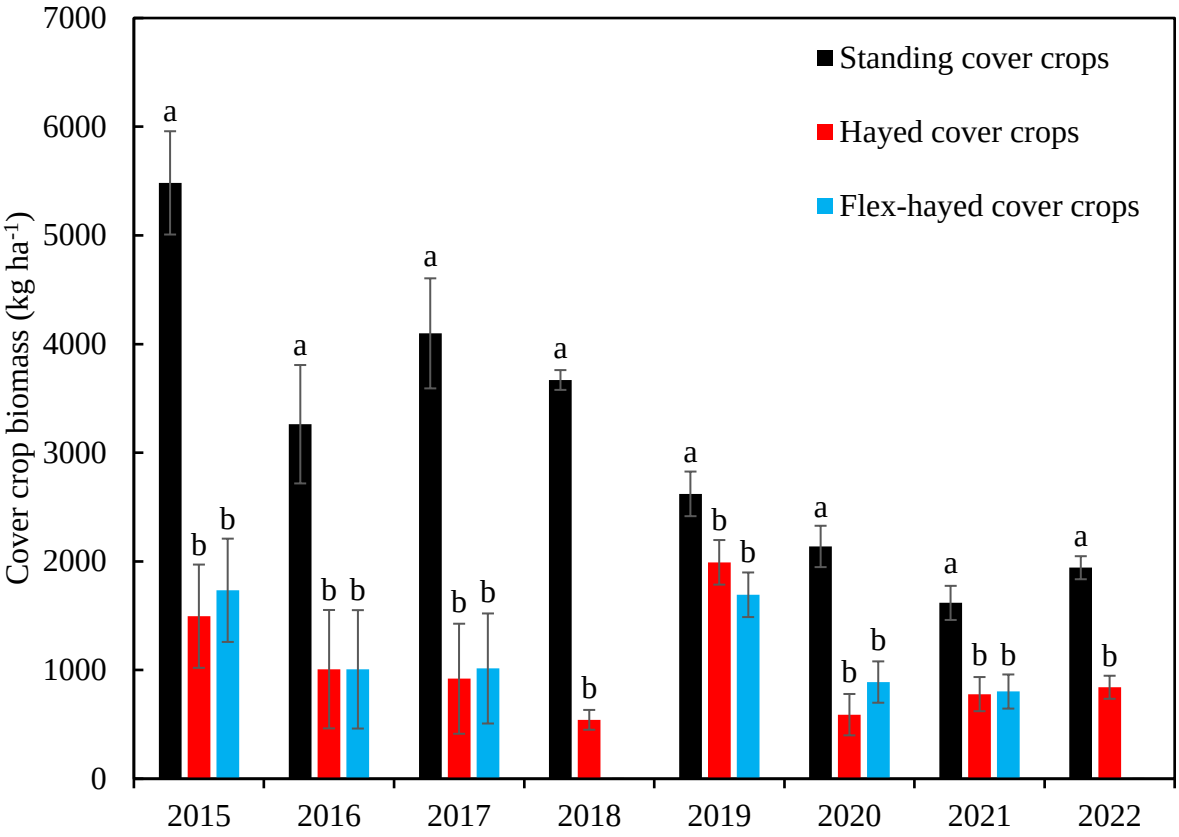

Figure 4.1. Cover crop biomass remaining as residue following cover crop haying and termination from 2015 to 2022 near Brownell, KS. Means followed by the same lower-case letter are not significantly different ($\alpha = 0.05$) among cover crop management treatments and bars indicate one standard error of the mean.

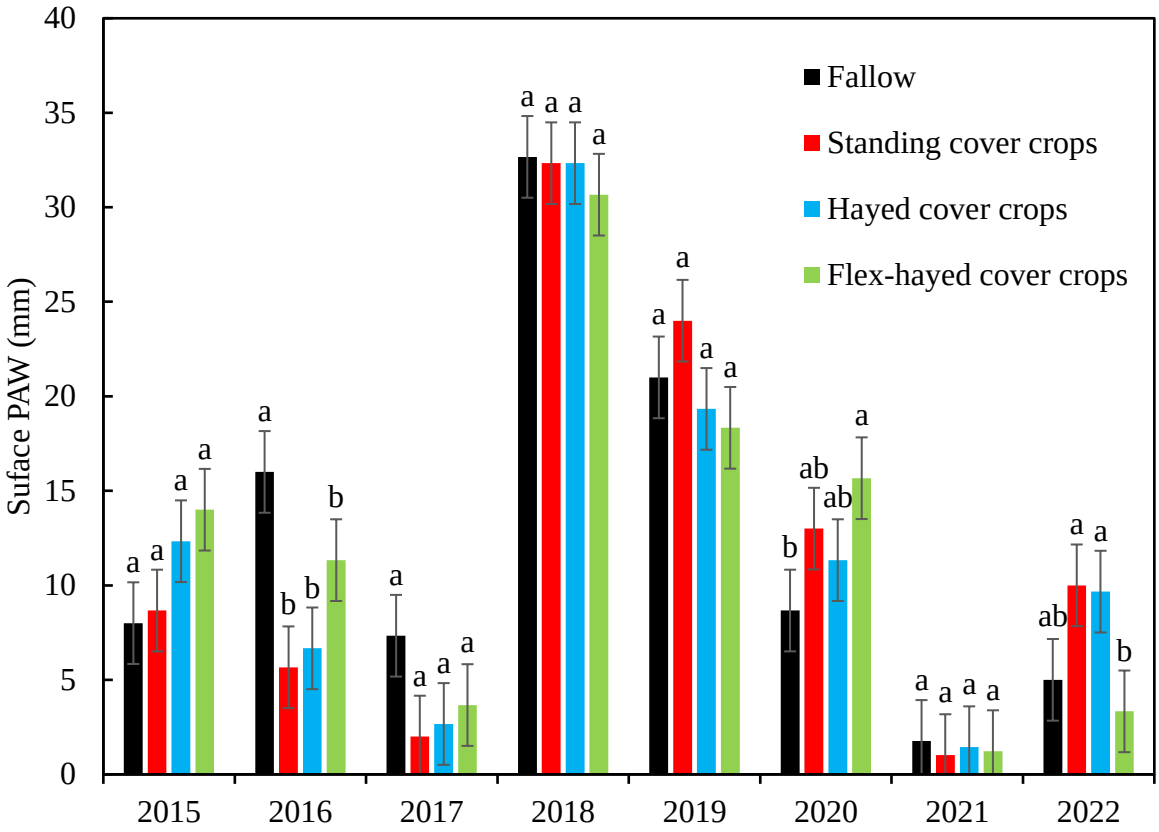

Figure 4.2. Fallow management effects on surface (0-15 cm) plant available water (PAW) at winter wheat planting from 2015 to 2022 near Brownell, KS. Means followed by the same lower-case letter are not significantly different ($\alpha = 0.05$) among cover crop management treatments and bars indicate one standard error of the mean.

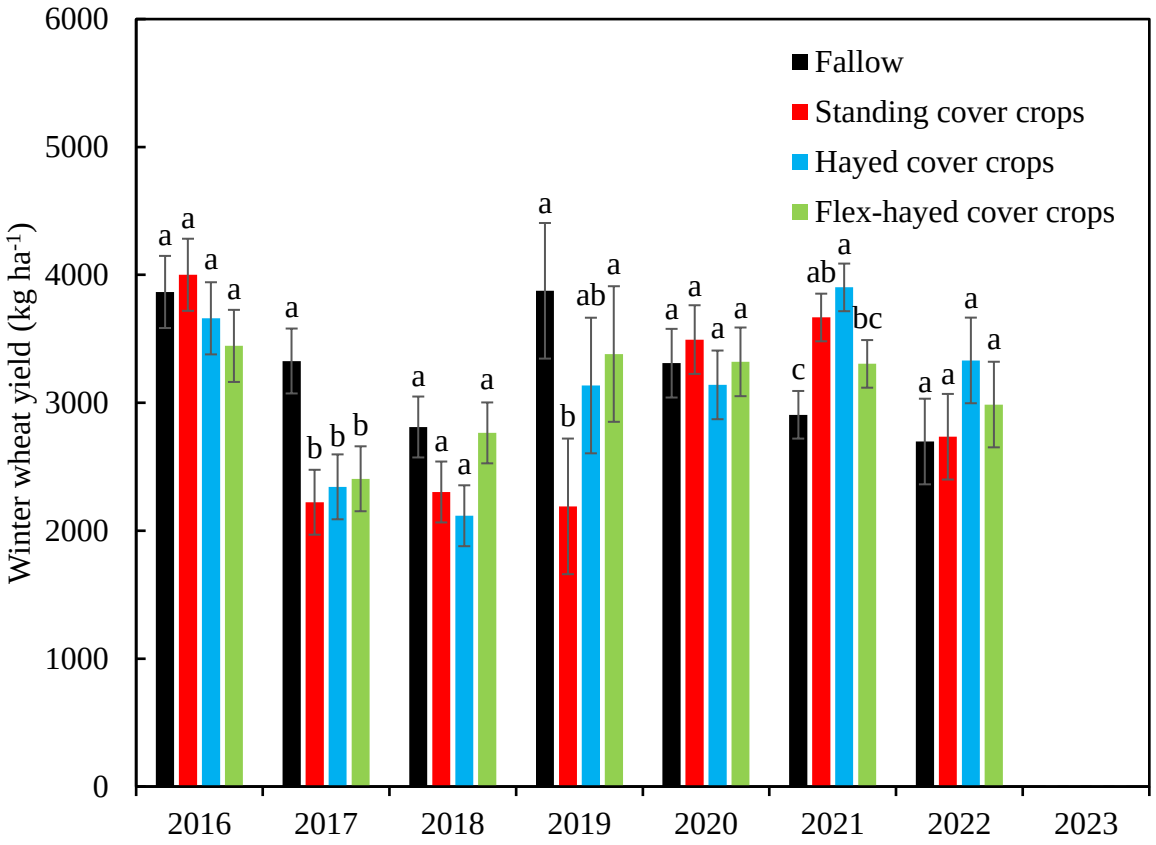

Figure 4.3. Fallow management effects on subsequent winter wheat yields from 2016 to 2023 near Brownell, KS. Exceptional drought conditions in 2023 resulted in crop failure. Means followed by the same lower-case letter are not significantly different ($\alpha = 0.05$) among cover crop management treatments and bars indicate one standard error of the mean.

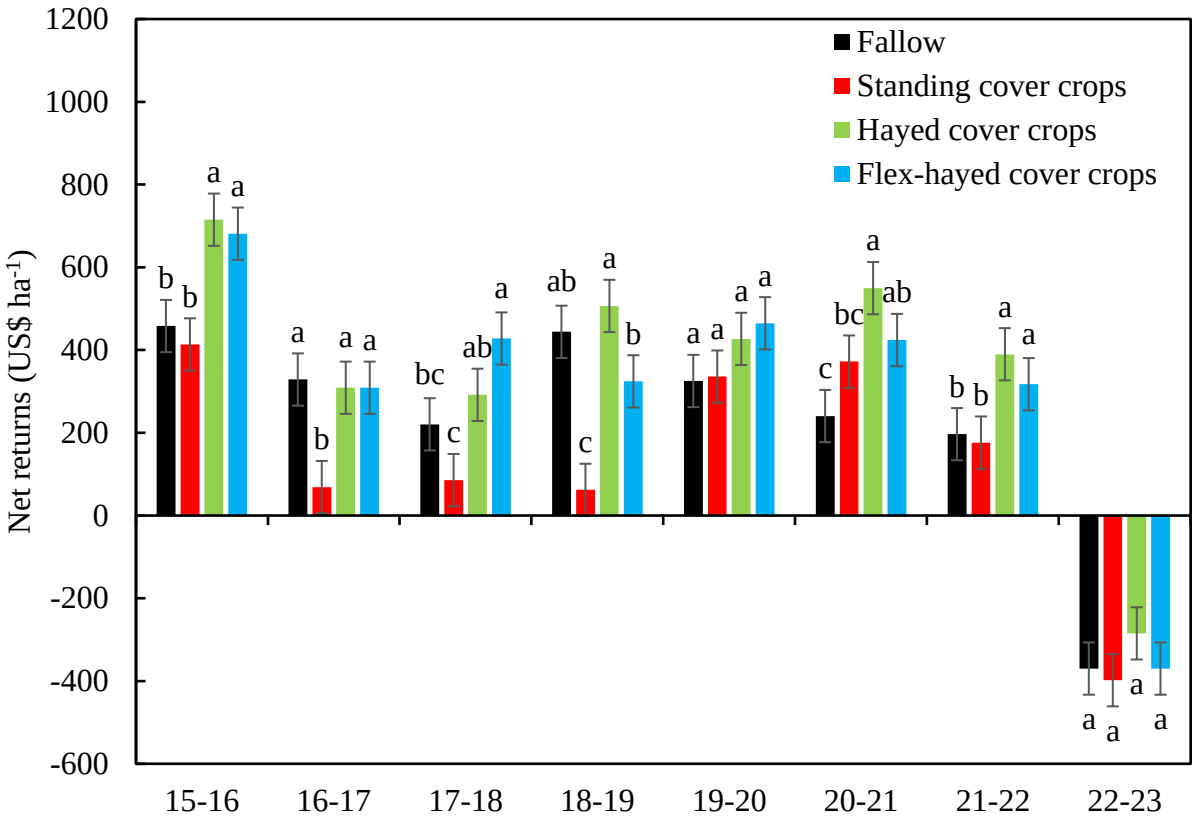

Figure 4.4. Effects of fallow management on net returns from the fallow and winter wheat phases in a winter wheat-grain sorghum-fallow rotation from 2015 to 2023 near Brownell, KS. Means followed by the same lower-case letter are not significantly different (α = 0.05) among cover crop management treatments and bars indicate one standard error of the mean.

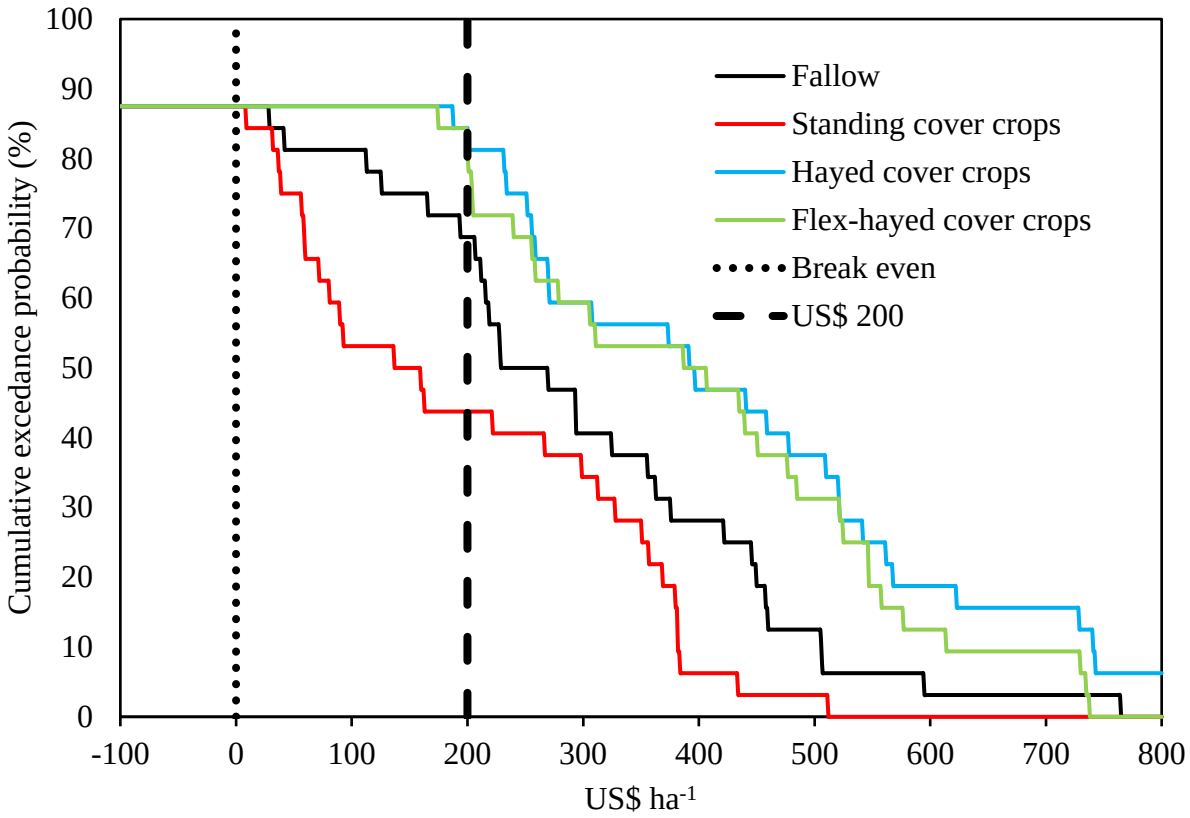

Figure 4.5. Cumulative exceedance probability of net income for fallow management strategies from 2015 to 2023 near Brownell, KS

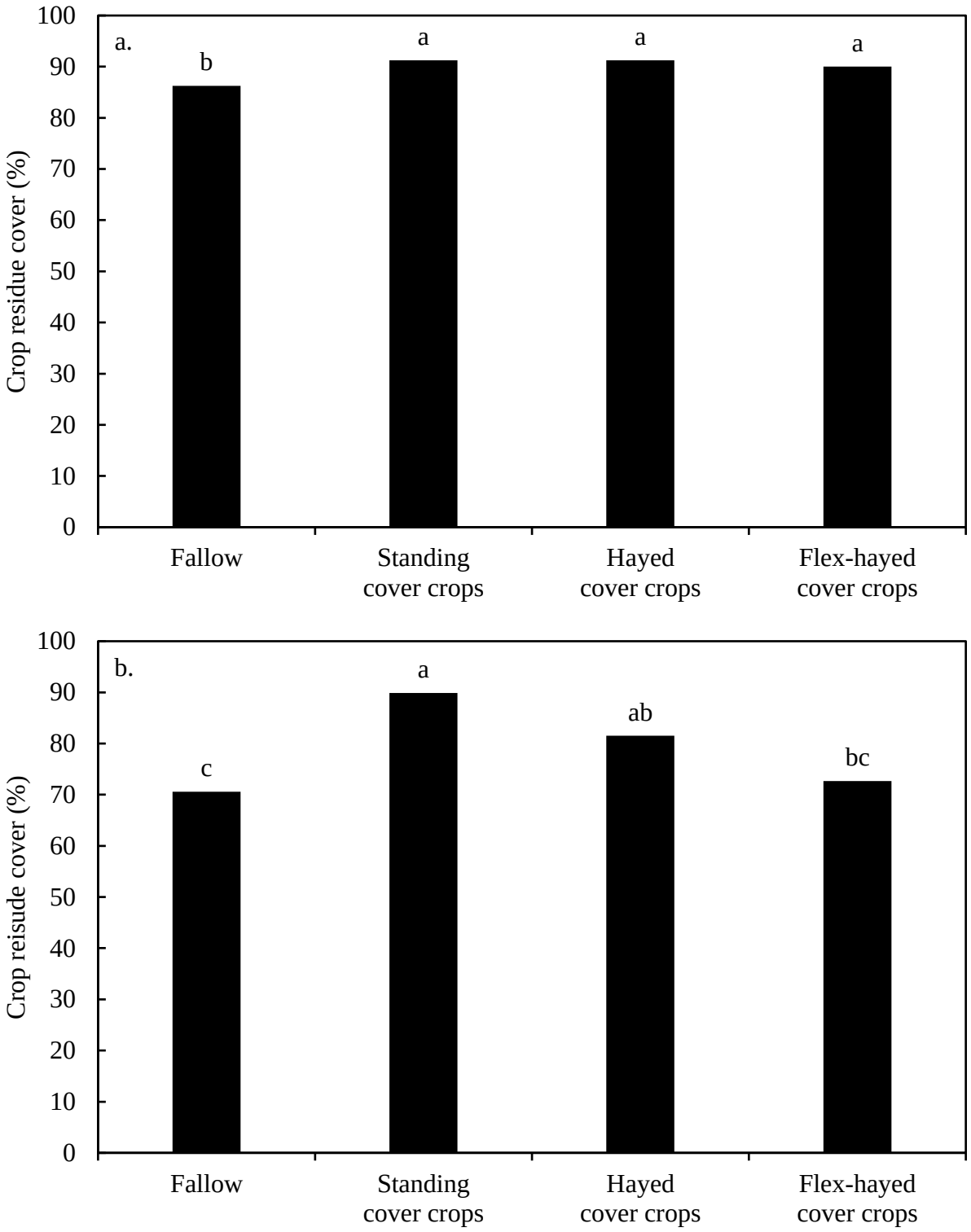

Figure 4.6. Effects of fallow management on crop residue cover at winter-wheat planting in fall 2021 (a.) and 2022 (b.) near Brownell, KS. Means followed by the same lower-case letter are not significantly different ($\alpha = 0.05$) among cover crop management treatments and bars indicate one standard error of the mean.

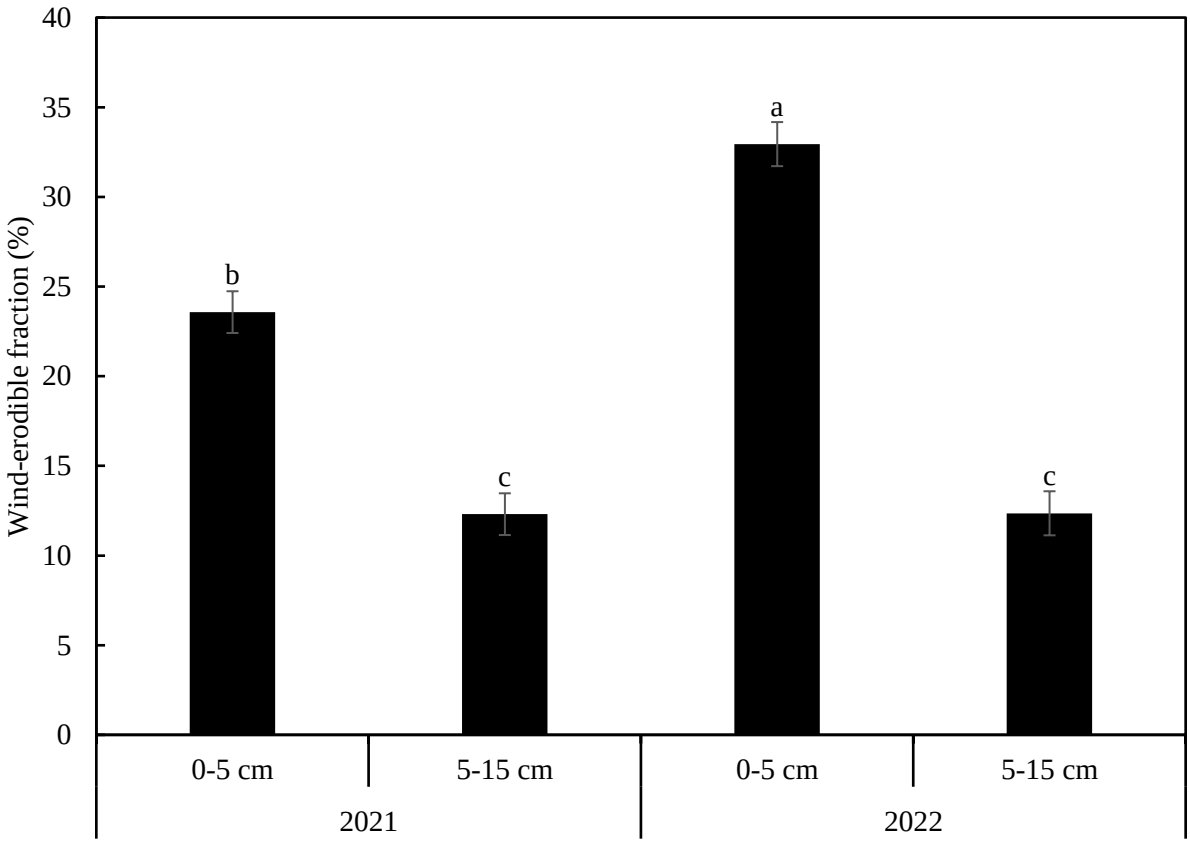

Figure 4.7. Effect of depth on the wind-erodible fraction at winter wheat planting in 2021 and 2022 near Brownell, KS. Means followed by the same lower-case letter are not significantly different ($\alpha = 0.05$) among cover crop management treatments and depths. Bars indicate one standard error of the mean.

Tables

Table 4.1. Fallow and growing season precipitation from 2014 to 2023 near Brownell, KS.

Growing season	Cover crops		Winter wheat			Grain sorghum	
	Preceding fallow (Nov.-Feb.)	Growing season (Mar.-Jun.)	Preceding fallow if after grain sorghum (Nov.-Sept.)	Preceding fallow if after cover crops (Jul.-Sept.)	Growing season (Oct.-Jun.)	Preceding fallow (Jul.-May)	Growing season (Jun.-Oct.)
	mm						
2014-2015	38	191					
2015-2016	82	320	352	122	461		
2016-2017	70	308	648	246	393	584	258
2017-2018	4	212	545	168	267	341	601
2018-2019	76	278	645	428	433	820	461
2019-2020	133	165	736	382	336	658	327
2020-2021	44	354	562	264	414	645	257
2021-2022	15	173	606	208	218	358	150
2022-2023	29	178	282	94	209	227	221
Study avg.	55	242	547	239	341	519	325
30-yr. avg.	70	248	529	211	359	491	331

Table 4.2. Fallow and growing season precipitation from 2014 to 2023 near Garden City, KS.

Growing season	Cover crops		Winter wheat			Grain sorghum	
	Preceding fallow (Nov.-Feb.)	Growing season (Mar.-Jun.)	Preceding fallow if after grain sorghum (Nov.-Sept.)	Preceding fallow if after cover crops (Jul.-Sept.)	Growing season (Oct.-Jun.)	Preceding fallow (Jul.-May)	Growing season (Jun.-Oct.)
	mm						
2014-2015	19	212					
2015-2016	58	246	437	198	371		
2016-2017	46	237	502	198	283	450	269
2017-2018	1	185	476	193	233	327	500
2018-2019	75	232	495	309	400	681	133
2019-2020	78	81	411	95	169	216	271
2020-2021	32	258	378	219	294	479	167
2021-2022	17	104	401	110	143	221	111
2022-2023	22	299	199	79	321	270	348
Study avg.	39	206	412	175	277	378	257
30-yr. avg.	56	216	464	192	312	424	310

Table 4.3. Fallow management treatments implemented in the fallow phase of the winter wheat–grain sorghum–fallow rotation near Brownell and Garden City, KS from 2015 to 2022.

Treatments	Year							
	2015	2016	2017	2018	2019	2020	2021	2022
	Brownell							
Fallow	X[†]	X	X	X	X	X	X	X
Standing cover crops	X	X	X	X	X	X	X	X
Hayed cover crops	X	X	X	X	X	X	X	X
Flex-hayed cover crops	X	X	X	np	X	X	X	np
	Garden City							
Fallow	X	X	X	X	X	X	X	X
Standing cover crops	X	X	X	X	X	X	X	X
Hayed cover crops	X	X	X	X	X	X	X	X
Flex-hayed cover crops	np	X	np	np	X	np	np	X

[†]X, if planted or fallow; np, if not planted as part of treatment structure.

Table 4.4. Standing cover crop biomass accumulation and hay removal and fallow management effects on profile (0-120 cm) and surface (0-15 cm) plant available water (PAW) at winter wheat planting from 2015 to 2022 near Brownell, KS.

Treatments	Cover crop biomass	Profile PAW	Surface PAW
	kg ha^{-1}	mm	mm
Cover crop management			
Fallow	-	109a	16a
Standing cover crops	3104a[†]	90b	15a
Hayed cover crops	950b	88b	15a
Flex-hayed cover crops	748b	93b	15a
Year			
2015	2878a	99b	11d
2016	1240bc	104b	10de
2017	1956abc	53c	4f
2018	1404bc	135a	32a
2019	2102ab	140a	21c
2020	1219bc	88b	12d
2021	1080bc	-	27b
2022	928c	47c	7ef
Type III test of fixed effects			
Fallow management (M)	<0.0001	0.0165	0.6227
Year (Y)	0.0391	<0.0001	<0.0001
M × Y	<0.0001	0.4342	0.0092

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

Table 4.5. Effects of fallow management on subsequent winter wheat yields, grain sorghum yields, and net returns from 2016 to 2023 in a three-year winter wheat-grain sorghum-fallow rotation near Brownell, KS. Exceptional drought conditions in 2022 and 2023 resulted in crop failures.

Treatments	Wheat yield	Sorghum yield	Net returns
	kg ha^{-1}		US$ ha^{-1}
Fallow management			
Fallow	2853a[†]	3422a	230.47b
Standing cover crops	2576a	3221a	139.52c
Hayed cover crops	2707a	3179a	362.98a
Flex-hayed cover crops	2701a	3175a	322.33a
Year			
2015-2016	3752a		566.94a
2016-2017	2575c	3408c	253.82d
2017-2018	2499c	5065ab	256.41d
2018-2019	3146ab	5164a	334.21bcd
2019-2020	3316ab	4551b	388.19bc
2020-2021	3445ab	4556b	396.62b
2021-2022	2938bc	-	270.06cd
2022-2023	-	-	-355.66e
Type III test of fixed effects			
Fallow management (M)	0.4548	0.2080	0.0007
Year (Y)	<0.0001	<0.0001	<0.0001
M × Y	0.0018	0.2035	0.0009

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

Table 4.6. Sensitivity analysis of cover crop biomass and wheat grain yield effects on net returns.

Cover crop biomass yield, kg ha^{-1}	Wheat grain yield										
	kg ha^{-1}										
	0	500	1000	1500	2000	2500	3000	3500	4000	4500	5000
	Net returns from haying cover crops, US$ ha^{-1}										
0	-354.02	-249.02	-144.02	-39.02	65.98	170.98	275.98	380.98	485.98	590.98	695.98
500	-315.52	-210.52	-105.52	-0.52	104.48	209.48	314.48	419.48	524.48	629.48	734.48
1000	-277.02	-172.02	-67.02	37.98	142.98	247.98	352.98	457.98	562.98	667.98	772.98
1500	-238.52	-133.52	-28.52	76.48	181.48	286.48	391.48	496.48	601.48	706.48	811.48
2000	-200.02	-95.02	9.98	114.98	219.98	324.98	429.98	534.98	639.98	744.98	849.98
2500	-161.52	-56.52	48.48	153.48	258.48	363.48	468.48	573.48	678.48	783.48	888.48
3000	-123.02	-18.02	86.98	191.98	296.98	401.98	506.98	611.98	716.98	821.98	926.98
3500	-84.52	20.48	125.48	230.48	335.48	440.48	545.48	650.48	755.48	860.48	965.48
4000	-46.02	58.98	163.98	268.98	373.98	478.98	583.98	688.98	793.98	898.98	1003.98
4500	-7.52	97.48	202.48	307.48	412.48	517.48	622.48	727.48	832.48	937.48	1042.48
5000	30.98	135.98	240.98	345.98	450.98	555.98	660.98	765.98	870.98	975.98	1080.98

Table 4.7. Effects of fallow management on soil organic carbon (SOC), particulate organic carbon (POC), bulk density (BD), mean weight diameter (MWD) of water stable aggregates, and wind-erodible fraction (WEF) in the 0-5 and 5-15 cm soil depths at winter wheat planting in 2021 and 2022 near Brownell, KS.

Treatments	Residue cover	BD	SOC		POC		MWD	WEF
	%	g cm^{-3}	g kg^{-1}	Mg ha^{-1}	g kg^{-1}	Mg ha^{-1}	mm	%
Fallow management								
Fallow	78b[†]	1.35a	13.65a	18.7a	4.82a	4.11a	0.68b	20.3a
Standing cover crops	91a	1.35a	14.23a	19.3a	5.16a	4.32a	0.93a	20.4a
Hayed cover crops	86ab	1.35a	13.92a	19.0a	5.38a	4.48a	0.94a	21.8a
Flex-hayed cover crops	81b	1.35a	13.44a	18.4a	4.77a	3.98a	0.90a	18.7a
Depth								
0-5 cm	-	1.24b	15.22a	12.8b	7.46a	4.64a	0.93a	28.3a
5-15 cm	-	1.46a	12.40b	25.0a	2.61b	3.80a	0.79a	12.3b
Year								
2021	90a	1.29b	13.51a	17.8a	4.80a	3.94a	0.93a	22.6a
2022	79b	1.41a	14.11a	19.9a	5.27a	4.51a	0.79a	17.9b
Test of Fixed Effects								
Fallow management (M)	0.0500	0.9996	0.4042	0.5178	0.2052	0.4457	0.0212	0.0589
Depth (D)	-	0.0114	0.0118	0.0022	0.0101	0.1304	0.1221	0.0095
M × D	-	0.6296	0.5276	0.9943	0.0515	0.2969	0.5158	0.1487
Year (Y)	0.0361	0.0181	0.4205	0.0812	0.2362	0.1310	0.1348	0.0179
M × Y	0.0497	0.6548	0.2261	0.1522	0.3009	0.3244	0.2042	0.1378
D × Y	-	0.0981	0.6513	0.8563	0.0981	0.0625	0.6043	0.0120
M × D × Y	-	0.7138	0.5228	0.4969	0.6693	0.6165	0.0293	0.2385

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

Table 4.8. Effects of fallow management on mean weight diameter of water stable aggregates in the 0-5 and 5-15 cm soil depths at winter wheat planting in 2021 and 2022 near Brownell, KS.

Treatments	Mean weight diameter	
	mm	
	0-5 cm	5-15 cm
	2021	
Fallow management		
Fallow	0.71b[†]	0.71a
Standing cover crops	0.99a	1.00a
Hayed cover crops	1.09a	0.78a
Flex-hayed cover crops	1.14a	1.01a
	2022	
Fallow	0.84a	0.46b
Standing cover crops	0.86a	0.86a
Hayed cover crops	0.96a	0.93a
Flex-hayed cover crops	0.83a	0.61ab

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

Table 4.9. Effects of fallow management on soil organic carbon (SOC), particulate organic carbon (POC), bulk density (BD), mean weight diameter (MWD) of water stable aggregates, and wind-erodible fraction (WEF) in the 0-5 and 5-15 cm soil depths at winter wheat planting in 2021 and 2022 near Garden City, KS.

Treatments	Residue cover	BD	SOC		POC		MWD	WEF
	%	g cm^{-3}	g kg^{-1}	Mg ha^{-1}	g kg^{-1}	Mg ha^{-1}	mm	%
Fallow management								
Fallow	63b[†]	1.42a	9.01a	13.8a	3.68a	3.56a	0.74a	25.5a
Standing cover crops	77a	1.40a	9.61a	14.1a	4.18a	3.83a	0.89a	25.2a
Hayed cover crops	59b	1.43a	9.69a	14.5a	4.60a	3.89a	0.85a	25.8a
Flex-hayed cover crops	66b	1.43a	9.22a	14.0a	4.10a	4.30a	0.74a	26.7a
Depth								
0-5 cm	-	1.35b	10.16a	9.7b	5.64a	3.78a	0.82a	32.8a
5-15 cm	-	1.49a	8.60a	18.4a	2.64b	4.02a	0.79a	18.8b
Year								
2021	69a	1.39a	9.48a	14.0a	3.56a	3.29a	0.92a	27.5a
2022	64a	1.45a	9.29a	14.2a	4.72a	4.50a	0.68a	24.2a
Test of Fixed Effects								
Fallow management (M)	0.0105	0.6968	0.4977	0.6504	0.1776	0.1754	0.4591	0.9516
Depth (D)	-	0.0195	0.0607	0.0029	0.0073	0.4910	0.8542	0.0117
M × D	-	0.7646	0.2323	0.8686	0.1733	0.3745	0.7105	0.4521
Year (Y)	0.4261	0.1025	0.8846	0.8890	0.1079	0.0992	0.3062	0.2192
M × Y	0.5337	0.4301	0.4518	0.2912	0.0985	0.0786	0.1069	0.0780
D × Y	-	0.1434	0.1718	0.8684	0.1761	0.4596	0.7398	0.6117
M × D × Y	-	0.2218	0.2328	0.1370	0.1283	0.1913	0.3434	0.7435

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

Table 4.10. Pearson correlation coefficients (*r*) and *P* values from correlation analysis among crop residue cover and soil properties across locations, years, and sampling depths.

Parameter	BD	GWC	SOC	POC	MWD	WEF
Residue						
r	-0.39***	-0.05	0.58*****	0.28**	0.13	0.56*****
BD						
r		0.94*****	0.83*****	-0.74*****	-0.80*****	0.90*****
GWC						
r			0.88*****	-0.83*****	-0.83*****	0.90*****
SOC						
r				-0.62*****	-0.71*****	0.70*****
POC						
r					0.77*****	-0.76*****
MWD						
r						-0.77*****

†Residue, percent residue cover, BD, bulk density, GWC, gravimetric water content, SOC, soil organic carbon, POC, particulate organic carbon, MWD, mean weight diameter, WEF, wind-erodible fraction.

‡*$P \leq 0.10$; **$P \leq 0.05$; ***$P \leq 0.01$; ****$P \leq 0.001$; *****$P \leq 0.0001$

Chapter 5 - Cover crop grazing effects on soil properties in no-tillage systems in the central Great Plains

Abstract

Integrating ruminant livestock such as beef cattle (*Bos taurus* L.) to graze cover crops (CCs) could balance goals of short-term profitability and long-term environmental sustainability when CCs are grown in water-limited environments like the central Great Plains (CGP), USA. However, little information currently exists about the effects of CC grazing on soil properties in no-tillage (NT) dryland cropping systems, especially after multiple cycles of grazing. This study was conducted from 2018 to 2021 to evaluate the effects of beef cattle grazing CCs on residue return, soil bulk density (BD) and penetration resistance (PR), water stable aggregates (WSA) and wind-erodible fraction (WEF), as well as soil pH and nutrient concentrations on three producer fields in central and western Kansas. Across sites, CC biomass left as residue post-grazing was similar to pre-grazing and was 60% of the ungrazed CCs (3704 kg ha^{-1}) because of CC regrowth after the 30-40 day grazing period. Soil BD, PR, WSA, WEF, pH, particulate organic carbon, nitrate-nitrogen, and phosphorus concentration were not different between grazed and ungrazed CCs. However, soil organic carbon (SOC) stocks and potassium concentrations were greater with grazed CCs compared to ungrazed CCs possibly due to substantial CC residue retention following grazing coupled with manure and urine deposition. Regression and correlation analyses showed that increased SOC was associated with decreased soil BD and increased WSA, which suggests decreased soil erosion potential as well as possible improvements in water infiltration and underscores the importance of SOC for overall soil health in this water-limited environment. Based on these results, we conclude that grazing of CCs is a viable management option for producers to intensify NT dryland cropping systems to improve

soil health and maintain or increase overall system profitability in the CGP. Longer (>3 years) grazing studies are needed, and results are likely to vary based on grazing animal stocking rate, categories, duration of grazing, and available CC biomass for grazing.

Introduction

Integrating cover crops (CCs) into no-tillage (NT) dryland cropping systems has been recommended to regenerate soil properties diminished after many years of conventionally-tilled low-intensity crop production in the central Great Plains (CGP) of the United States (Blanco-Canqui et al., 2022; Obour et al., 2021a; Peterson et al., 2020; Rosenzweig et al., 2019). Potential benefits of adopting CCs include increased soil organic carbon (SOC) sequestration, nutrient cycling, soil structure and aggregation, water infiltration, as well as soil microbial activity and diversity (Blanco-Canqui et al., 2015; Blanco-Canqui & Ruis, 2022; McClelland et al., 2020; Muhammad et al., 2021). However, CC impacts on subsequent cash crop yields, with CCs frequently having either no effect or significantly reducing subsequent cash crop yields, especially in water-limited environments such as the CGP (Aiken et al., 2013; Blanco-Canqui et al., 2022; Holman et al., 2018; 2021; Nielsen et al., 2015; Obour et al., 2022; Schlegel & Havlin, 1997). Costs associated with planting CCs and penalties to subsequent cash crop yields are major barriers to CC adoption in this region (Bergtold et al., 2017; Ramsey et al., 2019; Roesch-McNally et al., 2017). Indeed, in a recent meta-analysis, Garba et al. (2022) showed that the costs of CCs exceeded the benefits in environments with less than 700 mm average annual precipitation and concluded that careful site-specific plans are required to successfully incorporate CCs in such environments. To overcome this economic risk, some producers have adopted the practice of grazing or haying CCs to take advantage of supplemental forage provided

by CCs (Franzluebbers & Stuedemann, 2007a; Holman et al., 2018; 2021; Jenkins et al., 2019; Landry et al., 2018; Obour et al., 2022; Sanderson et al., 2018).

Integrated crop-livestock systems where CCs are grazed by ruminant livestock, usually beef cattle (*Bos taurus* L.) could balance goals of short-term profitability and long-term sustainability of agricultural production (Drewnoski et al., 2018; Russelle et al., 2007; Sanderson et al., 2013). Previous research has demonstrated increased system profitability with integrated livestock (Franzluebbers & Stuedemann, 2007a; Schomberg et al., 2014) though subsequent cash crop yields have been variable. Some have observed increases (Li et al., 2013; Maughan et al., 2009; Tracy & Zhang, 2008), decreases (Dhakal et al., 2022; Lesoing et al., 1997), or no differences (Anderson et al., 2022; Blanco-Canqui et al., 2021; Franzluebbers & Stuedemann, 2007a; Kelly et al., 2021) in subsequent corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), sorghum (*Sorghum bicolor* Moench), or winter wheat (*Triticum aestivum* L.) yields. In semi-arid western Kansas, Holman et al. (2018; 2021) observed that CCs reduced subsequent winter wheat yield 0 to 34% compared to fallow in years of above average precipitation and by as much as 40 to 70% compared to fallow in years of below average precipitation. Despite these yield penalties, the overall increase in system profitability from integrating livestock to graze CCs makes such diversifying practices desirable for producers, especially if a flex-fallow management concept, planting CCs only when adequate soil water is available and the precipitation outlook is neutral or above average, was implemented (Holman et al., (2018; 2021). Additionally, integrated crop-livestock systems have been reported to improve weed management (MacLaren et al., 2018) in crop production, though this benefit could be dependent upon conservative grazing intensities (Schuster et al., 2016). These results suggest there is an opportunity for producers in the CGP to implement this practice for increased cropping system profitability and enhanced soil health.

Past research in the CGP has shown the potential of CCs to enhance nutrient cycling and improve soil aggregation and hydraulic properties. In the eastern sub-humid areas (650 to 900 mm average annual precipitation) of the region, integration of legume CCs supplied available nitrogen (N) to subsequent grain crops (Blanco-Canqui et al., 2012; Janke et al., 2002; Mahama et al., 2016a; 2016b). Additionally, CCs have been shown to enhance soil structure and water infiltration under such conditions (Blanco-Canqui et al., 2011; Blanco-Canqui & Jasa, 2019). Limited results from the western semi-arid areas (300 to 650 mm average annual precipitation) suggests that similar benefits to soil physical and hydraulic properties could be accrued with CCs despite limited rainfall and high evaporative demand (Blanco-Canqui et al., 2013; Kelly et al., 2021; Obour et al., 2022; Preza Fontes et al., 2017; Simon et al., 2021; 2022). In semi-arid western Kansas, Blanco-Canqui et al. (2013) observed increased water stable aggregates (WSA) as well as reduced wind-erodible fraction (WEF) and runoff loss of sediment with CCs compared to fallow. Similar observations were made by Simon et al. (2022) from the same study area nine years later. This suggests CCs have the potential to reduce soil erosion and increase soil health in the dryland cropping systems of the CGP. However, economic constraints still limit CC adoption as benefits to soil properties are long-term goals with frequent short-term penalties to productivity, especially in water-limited regions (Garba et al., 2022; Holman et al., 2018; 2021; Nielsen et al., 2015; Obour et al., 2022).

Although some have reported on the immediate influences of single CC grazing events on soil chemical and physical properties in irrigated (Anderson et al., 2022; Blanco-Canqui et al., 2021) and dryland (Kelly et al., 2021) cropping systems in the CGP, information gaps remain regarding the effects of multiple cycles of CC grazing on soil properties, especially in NT dryland cropping systems. Without sufficient information regarding the potential compounding

effects of multiple cycles of CC grazing in NT dryland cropping systems, concerns remain regarding the risk of diminished soil health (Blanco-Canqui et al., 2015). One potential negative effect of grazing CCs could be the development of excessive soil compaction from animal trampling that could suppress subsequent crop yields and require some form of tillage for remediation (Obour et al., 2021b). Additional concerns associated with grazing CCs include losses of soil structure and reductions in SOC and water infiltration rates. However, the potential for diminished soil health will be dependent upon grazing time, grazing intensity, and the amount of residue remaining after grazing (Schuster et al., 2016). Because the climate of the CGP is semi-arid and soils are typically dry and rarely saturated, risk of soil compaction may be less compared to regions of greater annual precipitation where soils are frequently wet and at greater risk for compaction (Franzluebbers et al., 2007b; 2008; Schomberg et al., 2014; 2021).

Previous research showed that grazing CCs resulted in only mild increases in soil bulk density (BD) or penetration resistance (PR) compared to ungrazed CCs (Maughan et al. 2009; Franzluebbers et al., 2007b; 2008; Schomberg et al., 2014; 2021). Further, grazing CCs increased SOC, WSA, dry aggregate stability, and water infiltration compared to fallow (Maughan et al., 2009; Simon et al., 2021). Still, others have reported no differences in soil properties with grazed CCs compared to when CCs were not grazed (Anderson et al., 2022; Blanco-Canqui et al., 2021; Franzluebbers et al., 2007b; 2008). Across ten on-farm sites in the semi-arid CGP, Kelly et al. (2021) reported grazing CCs increased near-surface (0-5 cm) soil BD compared to ungrazed CCs. Nevertheless, the authors reported no differences between these treatments for any other soil chemical or physical properties evaluated in their study. The results of their study represent the immediate impacts of integrating cover crop grazing in NT dryland cropping systems (Kelly et al., 2021). To our knowledge, little information currently exists about the effects of multiple

cycles of CC grazing on soil properties in the NT dryland cropping systems of the CGP. Notwithstanding, past experience with corn, sorghum, and wheat residue grazing in the region suggests that grazing time, duration, and stocking rates are key considerations to prevent diminished soil health (Baumhardt et al., 2011; 2017; Blanco-Canqui et al., 2016a; 2016b). Therefore, the objective of this current research was to investigate impacts of multiple cycling of CC grazing on residue return, soil BD and PR, aggregate stability and WEF, as well as soil pH and nutrient concentrations in NT dryland cropping systems on producer fields in central and western Kansas.

Materials and methods

Site and study description

This study was conducted from fall 2018 through summer 2021 on producer fields in central and western Kansas (Table 5.1). The first site was a 32-ha field located near Alexander, Rush County, Kansas, which receives 584 mm average annual precipitation (Kansas State Weather Data Library, 2023). The soil series at the Alexander site was the Harney series (fine, smectic, mesic Typic Argiustolls), a soil series of large extent formed from loess on uplands in west-central Kansas (Soil Survey Staff, 2019). The second site was a 20-ha field located near Hays, Ellis County, Kansas, which receives 559 mm average annual precipitation (Kansas State Weather Data Library, 2023). The soil series at the Hays site was the Hord series (fine-silty, mixed, superactive, mesic Cumulic Haplustolls), a soil of extensive distribution formed from mixed loess and alluvium on foot slopes and stream terraces in north central Kansas (Soil Survey Staff, 2019). The third site was a 37-ha field located near Marquette, Ellsworth County, Kansas, which receives 737 mm average annual precipitation. Similar to the Hays site, the soil series at Marquette was the Hord series. Additional soil physical and chemical properties for each site

measured at study initiation are presented in Table 5.2. The experiments at each site compared two treatments, grazed and ungrazed CCs in a randomized complete block design with four replications for a total of eight plots at each location. The ungrazed CC treatments were fenced off using electric wire fencing materials to restrict access by cattle grazing adjacent plots. The area of individual grazed plots was approximately 5.3, 3.3, and 6.2 ha at Alexander, Hays, and Marquette, respectively. Ungrazed plots were smaller compared to grazed plots and were approximately 2.7, 1.7, and 3.1 ha at Alexander, Hays, and Marquette, respectively. Treatments and plots remained fixed throughout the 3-year study period with CCs grown in place of fallow periods twice at each location and either grazed or left ungrazed across both periods within the respective crop rotations practiced at each producer field (Table 5.1; Fig. 5.1).

Management across sites

The field at Alexander was managed under a three-year NT winter wheat-corn-fallow cropping system with warm-season CCs planted in the summer immediately after wheat was harvested and cool-season CCs planted in the spring following corn harvest (Fig. 5.1). A cool-season CC mixture of oats (*Avena sativa* L.), triticale (×*Triticosecale* Wittm.), barley (*Hordeum vulgare* L.), pea (*Lathyrus oleraceus* Lam.), rapeseed (*Brassica napus* L.), and sunflower (*Helianthus annuus* L.) was planted in March 2019 following corn harvest in September 2018 (Table 5.1). A warm-season CC mixture of sorghum-sudangrass (*Sorghum bicolor* Moench × *Sorghum bicolor var. Sudanese*)/millet (*Pennisetum glaucum* L.)/sunn hemp (*Crotalaria juncea* L.)/sunflower (*Helianthus annuus* L.)/radish (*Raphanus sativus* L.) was planted immediately after wheat harvest in June 2020 (Table 5.1). The field at Hays was managed under a three-year NT winter triticale-grain sorghum-fallow cropping system with triticale managed as an annual forage that was grazed in the fall and spring (Fig. 5.1). Similar to CCs grown after wheat at the

Alexander site, at Hays, warm-season CCs were planted in the summer after cattle were removed from the triticale and it was chemically terminated (Table 5.1). Cool-season CCs were planted in the spring following grain sorghum harvest. Cover crop mixtures grown at the Hays site had the same species composition and seeding rates as those previously described at Alexander (Table 5.1). The field at Marquette was managed under a three-year NT winter wheat-winter wheat-soybean (*Glycine max* L.) cropping system with cool-season CCs planted in the fall after wheat was harvested (Fig. 5.1). At this site, a cool-season CC mixture of triticale, radish, and rapeseed was planted in August 2018 following wheat harvest in June 2018 (Table 5.1). Soybeans were planted in this field in June 2019 and harvested in October followed immediately by winter wheat planting, which was harvested in June 2020. A cool-season CC mixture with the same species composition and seeding rates as previously mentioned was again planted in August 2020 (Table 5.1). At each site, cattle type, stocking density, and date to start grazing was determined by the collaborating producers usually based on their other available forage resources and cattle nutritional needs. A full description of CC and grazing management across site-years is reported in Table 5.1. The date to end grazing at each site was also determined by the collaborating producers and was based on cattle nutritional needs [CC nutritive value was expected to decline with maturity (Coblentz et al., 2018)] and concern about leaving sufficient residue on the soil surface. At the time of this study, the Natural Resources Conservation Service (NRCS) recommendation in Kansas was 50% CC biomass removal (also referred to as "take-half-leave-half") (United States Department of Agriculture-Natural Resources Conservation Service, 2022). Across sites, cattle were given unlimited access to grazed areas, day or night, with water provided at a single watering area on one side of the field. No additional feed sources

(hay or concentrated feed stuff) aside from CCs alone were provided to cattle in order to avoid introducing nutrients from outside sources.

Cover crop biomass accumulation

Across each study site-year, CC biomass accumulation was measured in grazed plots shortly before grazing was initiated and in both grazed and ungrazed plots shortly before CC termination. Prior to grazing, CC biomass in grazed plots was collected from two 0.5 m^2 quadrats randomly placed in each plot with all aboveground CC biomass clipped about 2.5 cm from the soil surface. Clipped samples were then dried at approximately 50° C in a forced-air oven until they reached a constant weight. Shortly before termination of CCs, grazed and ungrazed CCs were sampled, and biomass accumulation was again determined as described previously.

Soil Measurements

At the initiation of the study in August 2018 at Marquette, March 2019 at Alexander, and June 2019 at Hays before the first CCs were planted at each site, soil samples were collected by replication from the 0-5 and 5-15 cm soil depths for initial characterization of soil chemical and physical properties at each site (Table 5.2). Again in 2021, soil samples were collected for the analysis of soil chemical and physical properties from grazed and ungrazed CC plots across sites after CC termination and before subsequent cash crop planting (Table 5.1). At this sampling time, CCs had been grown and either grazed or left ungrazed twice within the respective crop rotations practiced at each producer field (Fig. 5.1). At each location, care was taken to avoid collecting soil samples around water sites, which are expected to have higher rates of concentrated hoof traffic than would be expected for the majority of the field. Briefly, two intact soil cores (5-cm diameter) were randomly taken from the 0-5 and 5-15 cm depths within each plot for the determination of BD. The two samples from each depth were weight fresh, dried at

105° C for 48 hr, and weighed dry. Bulk density was determined as mass of oven dry soil divided by volume of the core. Gravimetric water content (GWC) was determined as mass of fresh soil minus the mass of oven-dried soil divided by the mass of over-dried soil. Data for the two cores were averaged to produce single BD and GWC measurements for each plot. At Alexander and Marquette, PR in the 0-15 cm soil depth was also measured at 10 random points within each plot using a hand cone penetrometer (Eijkelkamp Co., Giesbeek, The Netherlands), and readings were divided by the area of the cone (2 cm^2). The values of PR were adjusted (Busscher, 1990) to a standard field capacity GWC of 0.30 (g g^{-1}) for silt loam soils (Ratliff et al., 1983) to account for potential differences in GWC across plots, which can have a sizeable effect on PR observations.

Additionally, 10 soil cores (2.5-cm diameter) were randomly collected within each plot, divided into the 0-5 and 5-15 cm depths, and composited by depth. Samples were air-dried, crushed, and sieved to pass through a 2 mm stainless steel screen. Subsamples were used to determine percent sand, silt, and clay by the hydrometer method (Gee & Bauder, 1996). Additional subsamples were analyzed for pH and soil extractable nutrients at the Kansas State University Soil Testing Laboratory using standard soil testing procedures. Briefly, soil pH was determined potentiometrically by an electrode (Thomas, 1996). Soil nitrate-nitrogen (NO_3-N) concentrations in samples were determined with a segmented flow analyzer after extracting the soil with 2 M KCl. Available phosphorus (P) was determined by the Mehlich-3 extraction method (Mehlich, 1984), and P concentration in the extract was measured using inductively coupled plasma-optical emission spectrometry (ICP-OES). Exchangeable potassium (K) concentrations were determined on an ICP-OES after ammonium acetate extraction (Knudsen et al., 1982). A portion of the 2 mm sieved samples were ground with a mortar and pestle to pass

through a 0.25 mm sieve, and SOC concentration was determined by dry combustion using a CN analyzer after pretreating samples with 10% (v/v) HCl to remove carbonates (Nelson & Sommers, 1996). Soil organic carbon stocks were calculated for CC management treatments across sites and depths on an equivalent mass basis to account for differences in soil BD between CC management treatments using the minimum equivalent soil mass approach used by Mikha et al. (2013). Particulate organic carbon (POC, >53 μm) was determined by the procedure outlined by Cambardella and Elliott (1992). Briefly, the POM fraction was isolated by dispersing soil in 5 g L^{-1} hexametaphosphate and passing the dispersed soil samples through a 53 μm sieve. Samples were dried in a forced-air oven and POM content was determined by loss-on-ignition (Nelson & Sommers, 1996). The POM values were then converted to particulate organic carbon (POC) using a calibrated equation generated from SOM and SOC analysis. Particulate organic carbon stocks were calculated for CC management treatments across sites and depths as previously described for SOC (Mikha et al., 2013).

Lastly, five intact soils samples were collected from the 0-5 and 5-15 cm soil depths in each plot with a flat shovel for a total approximately 3000 g soil from each depth for the determination of WSA and dry aggregate stability. Soil aggregate samples were allowed to air-dry and were then gently passed through a 19 mm sieve. A portion of each soil aggregate sample was then passed through 8 and 4.75 mm sieves to obtain two approximately 50 g subsamples of 8-4.75 mm diameter dry aggregates for each replicated treatment to use to estimate mean weight diameter (MWD) of WSA by the wet-sieving method (Nimmo & Perkins, 2002). The remaining aggregate sample was used to estimate WEF (<0.84 mm) by the dry-sieving method (Chepil, 1962). For the wet sieving method, an approximately 50 g sample of 8 to 4.75 mm soil aggregates was placed on top of a stack of nested sieves of 2-, 1-, and 0.25-mm sized openings in

a water column (Nimmo & Perkins, 2002). The samples were allowed to wet by capillarity for 5 minutes after which the stacks of sieves were vertically oscillated a distance of 3.7 cm at 30 oscillations minute^{-1} for 5 minutes. The amount of soil retained on each sieve was transferred into glass beakers, dried at 105° C, and weighed to determine the proportion of WSA within each size fraction. Each dry sample was then corrected for coarse sand by mixing the oven-dried aggregates with 30 mL of 0.5% sodium hexametaphosphate to disperse soil particles and allowing to soak for a minimum of four hours. Samples were then swirled on an orbital shaker for an additional four hours. Each dispersed sample was then passed back though individual sieves with the same size openings. The recovered sand was oven-dried and weighed to correct for coarse soil particles. Sand-corrected values were used to compute MWD (Nimmo & Perkins, 2002). For the dry-sieving method, an approximately 3000 g air-dried sample of <19-mm soil aggregates was placed on top of a stock of nested sieves of 6.3-, 2-, 0.84-, and 0.42-mm sized openings (Chepil, 1962). Samples were shaken for 5 min using a portable orbital sieve shaker (W.S. Tyler Model RX-812, Mentor, OH). The soil particles remaining on each sieve were weighed and the data was used to compute WEF (Chepil, 1962).

Statistical analysis

Analyses of CC biomass accumulation as well as soil chemical and physical properties were performed using the PROC GLIMMIX procedure in SAS ver. 9.4 (SAS Institute, 2012). First, CC biomass accumulation was analyzed by site-year with CC management (M) as a fixed effect and replication as a random variable in the model. Cover crop biomass was then analyzed across six site-years with grazed (pre-grazing and post-grazing) and ungrazed CC treatments as a fixed effect and replication nested within site treated as a random variable in the model. For soil BD, PR, SOC, POC, pH, extractable nutrient concentrations, MWD, and WEF, we modeled M,

site (S), sampling depth (D), and their interactions as fixed effects while replication and its interaction with fixed effects were considered random in the model. Interactions and treatment effects were considered significant when F test *P*-values (probability values) were ≤ 0.10 to avoid dismissing any real CC grazing effects on soil properties and residue retention. Correlation analysis among soil chemical and physical properties was conducted using PROC CORR procedures in SAS, and simple linear regression analyses were conducted with the PROC REG procedure in SAS to determine the relationship between SOC and BD, SOC and P, BD and MWD, as well as NO_3-N, and pH, across the three study sites.

Results

Cover crop productivity and residue retention

Averaged across site-years, post-grazing CC biomass was similar to pre-grazing biomass but 40% less than ungrazed (Table 5.3). This suggests that on average, approximately 60% of the ungrazed CC biomass produced was left as residue on the soil surface after grazing. Similar trends in CC biomass accumulation and residue retention were observed across the site-years (Table 5.3). At Alexander, post-grazing CC residue retention was 38 and 57% of the ungrazed CC biomass in 2019 and 2020 with spring and summer CCs, respectively. Post-grazing, summer and spring CCs at Hays retained 77 and 30% of the ungrazed CC biomass in 2019 and 2021, respectively. At Marquette, post-grazing CC residue retention was 42 and 71% of the ungrazed CC biomass in 2019 and 2021, respectively (Table 5.3).

Bulk soil and particulate organic carbon

Only the main effects of Site and Depth were significant for SOC concentration (Table 5.4). The SOC was unaffected by Management or interactions of Management with other main effects. However, SOC stock was 1.40 Mg ha^{-1} more with grazed CCs compared to ungrazed

CCs (Fig. 5.2a). Across treatments and depths, SOC concentration at Hays was greater than Marquette and Alexander, respectively, and SOC concentration at Marquette was greater than Alexander (Table 5.4). In the 0-5 cm soil depth, SOC concentration was greater than in the 5-15 cm depth. Only the two-way interaction of S × D and main effects of Site and Depth were significant for POC concentration with no significant effect of Management or interactions of Management with other main effects (Table 5.4). Although not statistically significant, there was a numeric trend of greater POC stock with grazed CCs compared to ungrazed CCs (Fig. 5.2b). In the 0-5 cm soil depth, POC concentration at Hays were greater than Marquette and Alexander, respectively, and POC concentration are Marquette were greater than at Alexander (Fig 5.3a). In the 5-15 cm soil depth, POC concentration at Hays was similar to Marquette and both were greater than at Alexander. The POC concentration at Hays was greater than Marquette and Alexander, respectively, and POC at Marquette was greater than at Alexander (Table 5.4). Particulate organic carbon concentration in the 0-5 cm soil depth was greater than that measured in the 5-15 cm depth.

Soil pH, nitrate-nitrogen, phosphorus, and potassium

Only the two-way interaction of S × D and main effects of Site and Depth were significant for soil pH and NO_3-N concentrations (Table 5.5). Soil pH and NO3-N were unaffected by Management or interactions of Management with other main effects. In the 0-5 cm soil depth, pH at Marquette was similar to Alexander and both were lower than Hays (Fig. 5.3b). Soil pH in the 5-15 cm depth at Alexander was similar to Hays and both were greater than Marquette. Soil pH at Alexander was similar to Hays and both were greater than Marquette (Table 5.5). In the 0-5 cm soil depth, pH was less than in the 5-15 cm depth. In the 0-5 cm soil depth, NO_3-N at Alexander was similar to Hays, but NO_3-N at Marquette was greater than

Alexander or Hays (Fig 5.3c). Soil NO_3-N in the 5-15 cm depth was not different across sites. Across treatments and depths, NO_3-N at Alexander was similar to Hays, and both were less than at Marquette (Table 5.5). Across treatments and sites, NO_3-N in the 0-5 cm soil depth was greater than in the 5-15 cm depth.

Only the two-way interaction of S × D and main effects of Site and Depth were significant for soil P concentrations with no significant effect of Management or interactions of Management with other main effects (Table 5.5). In the 0-5 cm depth, soil P at Marquette was greater than Alexander, though both were similar to Hays (Fig. 5.3d). In the 5-15 cm soil depth, P at Marquette was similar to Hays, and both were greater than Alexander. Across treatments and depths, soil P at Marquette was similar to Hays, and both were greater than Alexander (Table 5.5). Across treatments and sites, P in the 0-5 cm soil depth was greater than the 5-15 cm depth. The two-way interaction effects of S × D and M × S as well as the main effects of Management, Site, and Depth were significant for soil K concentration (Table 5.5). In the 0-5 cm soil depth, K concentration at Alexander was similar to Hays, and both were greater than Marquette (Fig. 5.3e). In the 5-15 cm depth, soil K at Hays was greater than Alexander and Marquette, and soil K at Alexnader was greater than Marquette. In the 0-5 cm soil depth, K was not different between grazed and ungrazed CCs (Fig. 5.3f). However, in the 5-15 cm depth, soil K under grazed CCs was 22% greater than ungrazed CCs. In general, grazed CCs had 11% more soil K than ungrazed CCs. Soil K at Alexander was similar to Hays, and both were greater than Marquette (Table 5.5). Soil K in the 0-5 cm soil depth was greater than the 5-15 cm soil depth.

Soil bulk density, penetration resistance, water stable aggregates, and wind-erodible fraction

Only the main effects of Site and Depth were significant for soil BD with no significant effect of Management or interactions of Management with other main effects (Table 5.6). Soil BD at Alexander was similar to Marquette, and both were greater than Hays. The BD at the 5-15 cm soil depth was greater than the 0-5 cm depth. Only the main effect of Site was significant for PR with no significant effect of Management or interaction of Management and Site (Table 5.6). Soil PR at Alexander was greater compared to Marquette. There was a significant three-way interaction effect of M × S × D on MWD of WSA (Table 5.6). However, within each site-depth, MWD was not different between grazed and ungrazed CCs (Table 5.7). Other than the three-way interaction, only the main effect of Site was also significant for MWD with no significant effect of Management or interactions of Management with other main effects (Table 5.6). The MWD at Alexander was similar to Marquette and both were lower than Hays. Only the main effect of Site was significant for WEF with no significant effect of Management or interaction of Management with other main effect (Table 5.6). The WEF in Hays was greater than Marquette and both were similar to WEF at Alexander.

Relationships between soil chemical and physical properties.

Soil organic carbon concentration had significant positive correlations with POC, P, K, and MWD, but was negatively correlated with BD (Table 5.8; 5.9). Regression analyses showed that for every 1 g kg^{-1} increase in SOC, soil BD decreased approximately -0.04 g cm^{-3} (Fig. 5.4a) and P increased 2.1 mg kg^{-1} (Fig. 5.4b). The POC concentration was significantly and positively correlated with NO3-N and P but negatively correlated with BD and PR. Soil pH was positively correlated with K but negatively correlated with NO3-N (Table 5.8; 5.9). In fact, for every 1 mg

kg^{-1} increase in soil NO_3-N, soil pH decreased approximately 0.04 (Fig. 5.4c). Soil NO_3-N had a significant positive correlation with P but a negative correlation with K, and P was positively correlated with K (Table 5.8). Soil BD was significantly and negatively associated with MWD and WEF (Table 5.9). Regression analysis showed that for every 1 g cm^{-3} increase in BD, MWD decreased by 0.20 mm (Fig. 5.4d). Penetration resistance was significantly and positively correlated with WEF (Table 5.9).

Discussion

In the present study, average post-grazing CC biomass was not different compared to when biomass was measured pre-grazing, which occurred because annual grass CC species used in this study (oats, triticale, barley, sorghum-sudangrass, and millet) had significant regrowth after cattle were removed. This resulted in additional aboveground CC growth to compensate for biomass removed by grazing. Across site-years, CC residue retained following grazing averaged 60% residue retention, which was near the Natural Resources Conservation Service (NRCS) recommendation in Kansas (50% removal, "take-half-leave-half") at the time of this study (USDA-NRCS, 2022). Similarly, high levels of residue cover (>70%) was retained following CC grazing averaged across 10 on-farm sites in the semi-arid CGP (Kelly et al., 2021). Other recommendations for CC grazing in the CGP suggest retaining at least 30% residue cover on the soil surface or approximately 1120 kg ha^{-1} residue biomass (Brummer et al., 2018; Johnson et al., 2020). Other studies saw significantly less biomass retention than the present study (Blanco-Canqui et al., 2021l Franzluebbers & Stuedemann, 2007a) Likely because of differences in goals with CC grazing (forage production only vs. forage production and enhancing soil health), which influenced decisions on stocking rates and the number of grazing days.

Reduction in residue cover on the soil surface when CCs are grazed can lead to decreased SOC with less organic residue available to decompose on the surface. However, the substantial amount of residue retained following grazing coupled with manure deposition from grazing cattle in the present study resulted in increased SOC stock with grazed CCs compared to ungrazed plots, which differ from others who showed no difference in SOC stock when CCs were grazed compared to when they were left ungrazed (Anderson et al., 2021; Blanco-Canqui et al., 2021; Kelly et al. 2021; Franzluebbers & Stuedemann, 2007b). However, these studies were either of a shorter duration than the present study with CCs grazed only once before soil sample collection or CC biomass removal rates with grazing were substantially greater than the present study. Although we did not have fallow treatment without a CC for comparison in the present study, results indicate that intensifying dryland cropping systems by integrating either grazed or ungrazed CCs could increase SOC stock compared to fallow as reported in previous studies in the semi-arid CGP (Blanco-Canqui et al., 2011; 2013; Simon et al., 2021; 2022).

Cattle grazing CCs had no effect on soil pH, NO_3-N, or P concentration compared to the ungrazed treatment. However, there was an apparent increase in soil K with grazed CCs compared to ungrazed plots. This increase in soil K was mainly in the 5-15 cm soil depth, which was unexpected. Most studies have shown no differences in soil pH or nutrient concentrations with CC grazing (Blanco-Canqui et al., 2021; Kelly et al., 2021). However, manure and urine deposition from livestock grazing CCs could enhance nutrient cycling and increase available N, P, and K for subsequent crops. Although K mobility in soil is generally considered to be low, there may have been some K movement resulting in K accumulation in the 5-15 cm soil depth (Kuchenbuch et al., 1986), which is still a fairly shallow soil depth (<15 cm). All of these chemical properties were stratified in these NT soils. Soil pH in the 0-5 cm soil depth was

significantly lower than in the 5-15 cm depth and below pH 6.0 at all the study sites. This low soil pH was likely due to long-term N fertilizer application to these NT annual production fields with minimum soil disturbance because of the nitrification process involved in the conversion of NH_4 to NO_3 when ammonium-based N fertilizers are applied (Obour et al., 2017; 2023). Additionally, the significantly greater N, P, and K concentrations in the 0-5 cm soil depth compared to the 5-15 cm depth was likely due to regular applications of inorganic fertilizer (N, P, and K) inputs with no soil disturbance for fertilizer incorporation in these NT soils. Relationships between soil chemical properties (pH, NO_3-N, P, and K) observed in this study through correlation and regression analyses are in part a product of stratification under NT (Obour et al., 2017; 2023). Notwithstanding, the significant relationship of SOC and other soil properties including P, K, MWD, WEF, BD, and PR underscores the importance of SOC for overall soil health in this water-limited environment.

A major source of producer apprehension to crop-livestock integration in NT cropping systems is the risk of soil compaction following grazing that could limit subsequent crop yields and require some form of tillage to remediate (Obour et al., 2021b). However, previous reports suggest that compaction risks might be dependent upon soil texture (Baumhardt et al., 2011; 2017), and effects could be transient in those regions that experience regular freeze-thaw cycles through the winter season (Blanco-Canqui et al., 2016a; 2016b). In the present study, soil BD and PR under grazed CCs were similar to the ungrazed plots, which agrees with previous short-term studies that concluded CC grazing had no effect on soil BD or PR (Anderson et al., 2021; Franzluebbers & Stuedemann, 2007; Kelley et al, 2021, Simon et al., 2021). Further, our results indicated CC grazing had no effect on MWD of WSA or WEF compared to ungrazed CCs, which was consistent with the findings of others (Blanco-Canqui et al., 2021; Kelly et al., 2021).

Conclusion

Results from this study across three producer fields in the CGP showed grazing CCs with approximately 40% CC biomass removal had no negative effect on soil physical or chemical properties compared to ungrazed CCs after two cycles of CCs and grazing in NT dryland cropping systems. Our results showed grazing CCs was associated with increased SOC stock compared to ungrazed CCs possibly due to substantial CC residue retention following grazing coupled with manure deposition from grazing cattle. Furthermore, our findings showed MWD and WEF were not different between grazed and ungrazed CCs. Based on these results, we conclude that grazing CCs is a viable management option to intensify NT dryland cropping systems to improve soil health and maintain or increase overall system profitability in the CGP though results are likely to vary based on grazing animal stocking rate, categories, duration of grazing, and available CC biomass for grazing. Further research will be needed to determine the long-term effects of CC grazing in NT systems as well as to determine optimum rates of CC biomass removal with grazing to optimize farm income and enhance soil health in NT dryland cropping systems.

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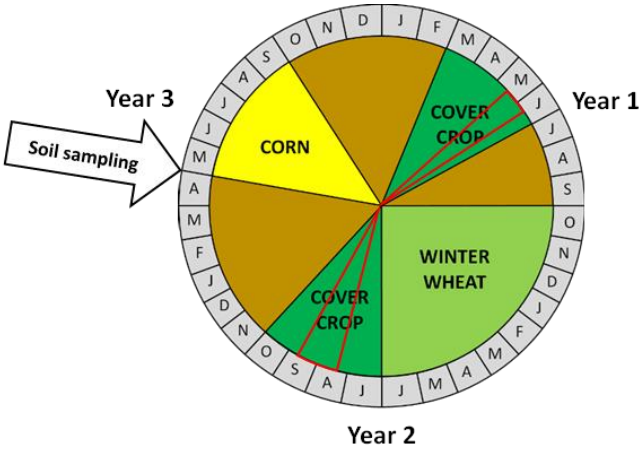
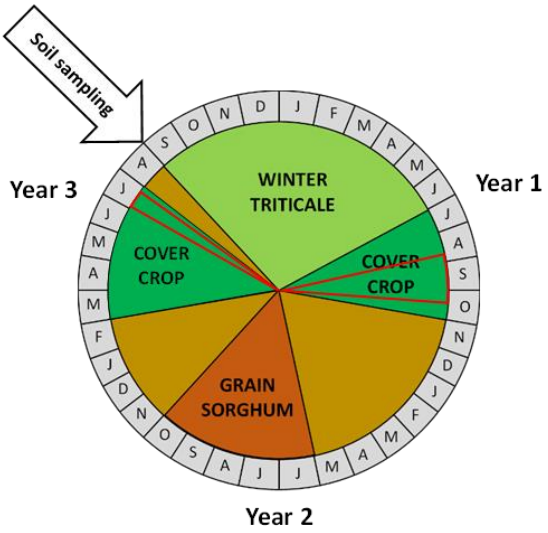
Figures

a.


Year 3
Year 1
Year 2
Soil sampling
CORN
COVER CROP
WINTER WHEAT
COVER CROP

b.


Soil sampling
Year 3
Year 1
Year 2
WINTER TRITICALE
COVER CROP
COVER CROP
GRAIN SORGHUM

c.

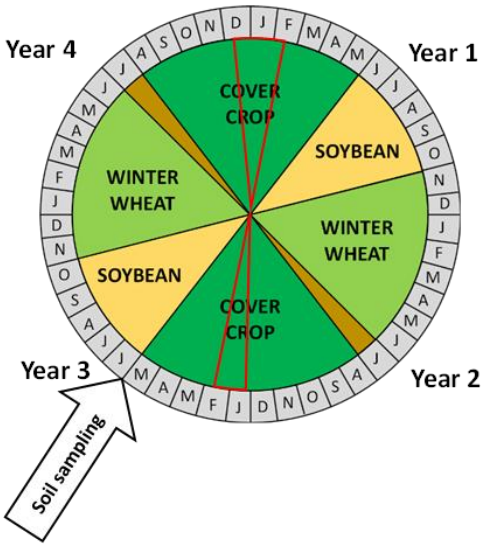

Year 4
Year 1
Year 3
Year 2
Soil sampling
COVER CROP
SOYBEAN
WINTER WHEAT
WINTER WHEAT
SOYBEAN
COVER CROP

Figure 5.1. A pictorial representation of the implementation of cover crops in the respective crop rotations at Alexander (a.), Hays (b.), and Marquette (c.) in west central Kansas. The red outlines in cover crop phases indicate grazing periods and arrows indicate time of soil sample collection.

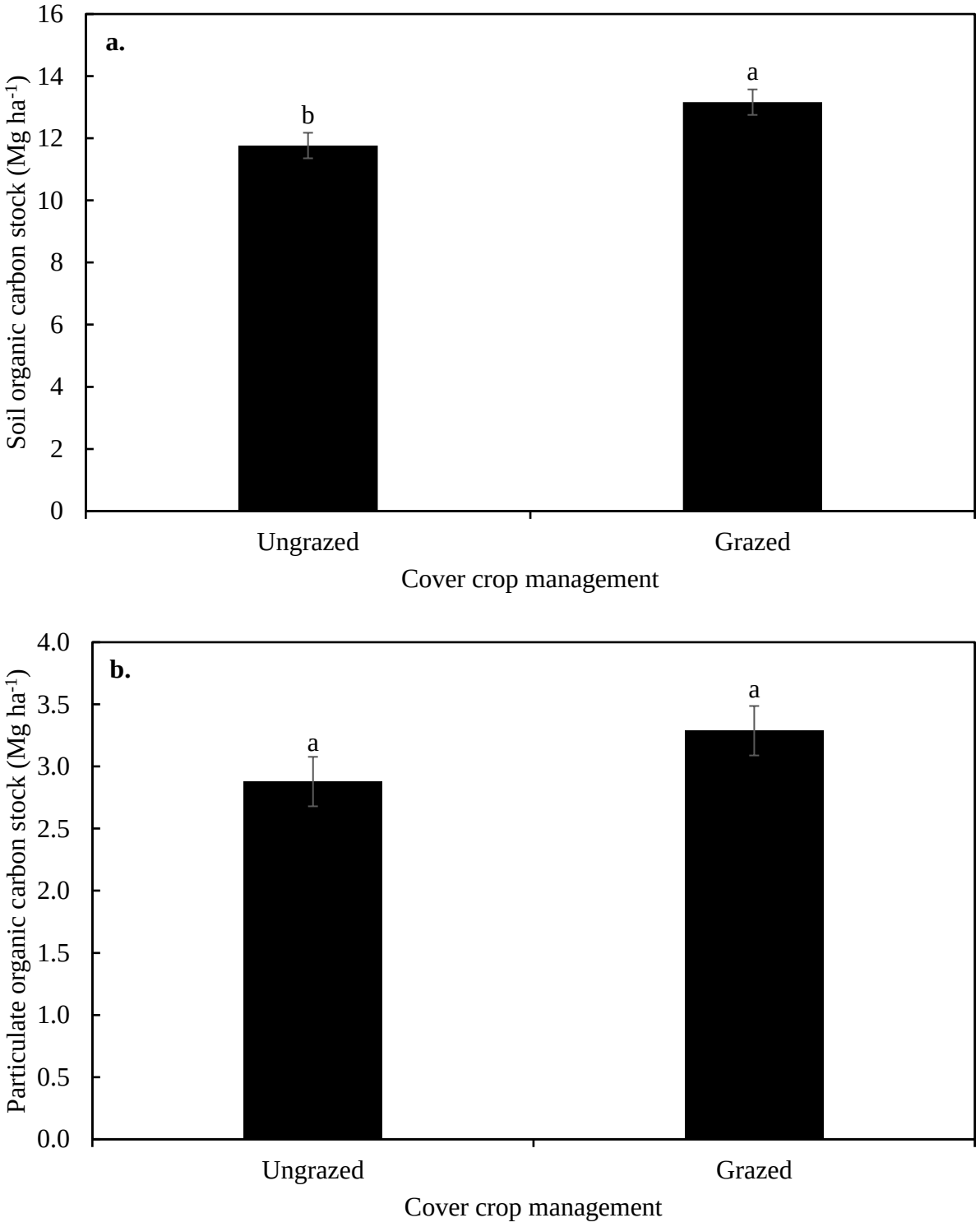


Figure 5.2. Mean effects of cover crop management on bulk soil organic carbon (SOC, a.) and particulate organic carbon (POC, b.) stock across on-farm sites in central and western Kansas. Means followed by the same lower-case letter are not significantly different ($\alpha = 0.10$) among cover crop management treatments and bars indicate one standard error of the mean.

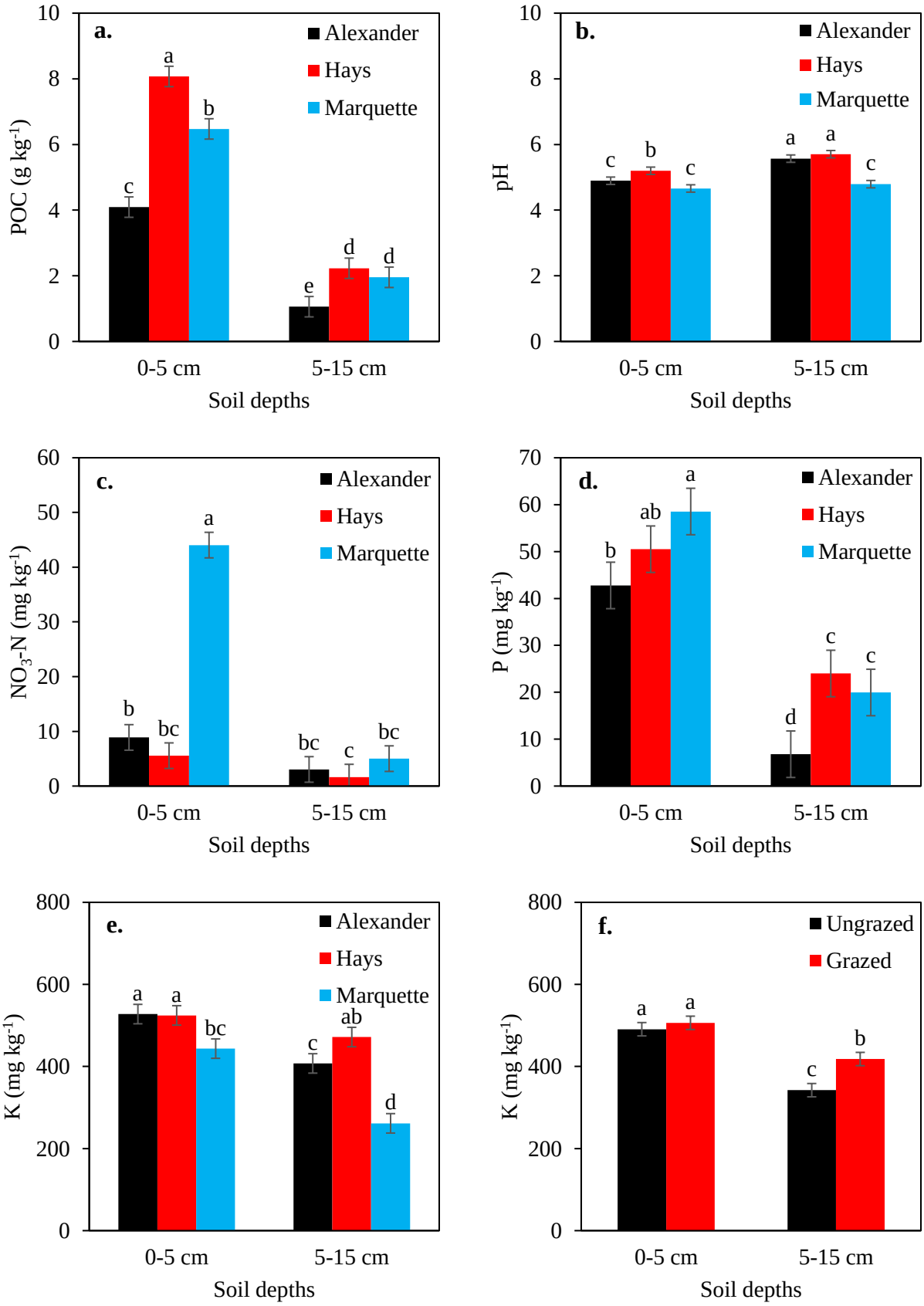

a.
Alexander
Hays
Marquette
POC (g kg-1)
0
2
4
6
8
10
c
a
b
e
d
d
0-5 cm
5-15 cm
Soil depths
b.
Alexander
Hays
Marquette
pH
0
2
4
6
8
10
c
b
c
a
a
c
0-5 cm
5-15 cm
Soil depths
c.
Alexander
Hays
Marquette
NO3-N (mg kg-1)
0
10
20
30
40
50
60
b
bc
a
bc
c
bc
0-5 cm
5-15 cm
Soil depths
d.
Alexander
Hays
Marquette
P (mg kg-1)
0
10
20
30
40
50
60
70
b
ab
a
d
c
c
0-5 cm
5-15 cm
Soil depths
e.
Alexander
Hays
Marquette
K (mg kg-1)
0
200
400
600
800
a
a
bc
c
ab
d
0-5 cm
5-15 cm
Soil depths
f.
Ungrazed
Grazed
K (mg kg-1)
0
200
400
600
800
a
a
c
b
0-5 cm
5-15 cm
Soil depths

Figure 5.3. Particulate organic carbon (POC, a.), pH (b), nitrate-nitrogen (NO_3-N, c.), phosphorus (P, d.), and potassium (K, e.) concentrations as affected by the interaction effects of site and depth and K concentration as affected by the interaction effects of management and depth (f.) across on-farm sites in central and western Kansas. Means followed by the same lower-case letter are not significantly different ($\alpha = 0.10$) among cover crop management treatments and bars indicate one standard error of the mean.

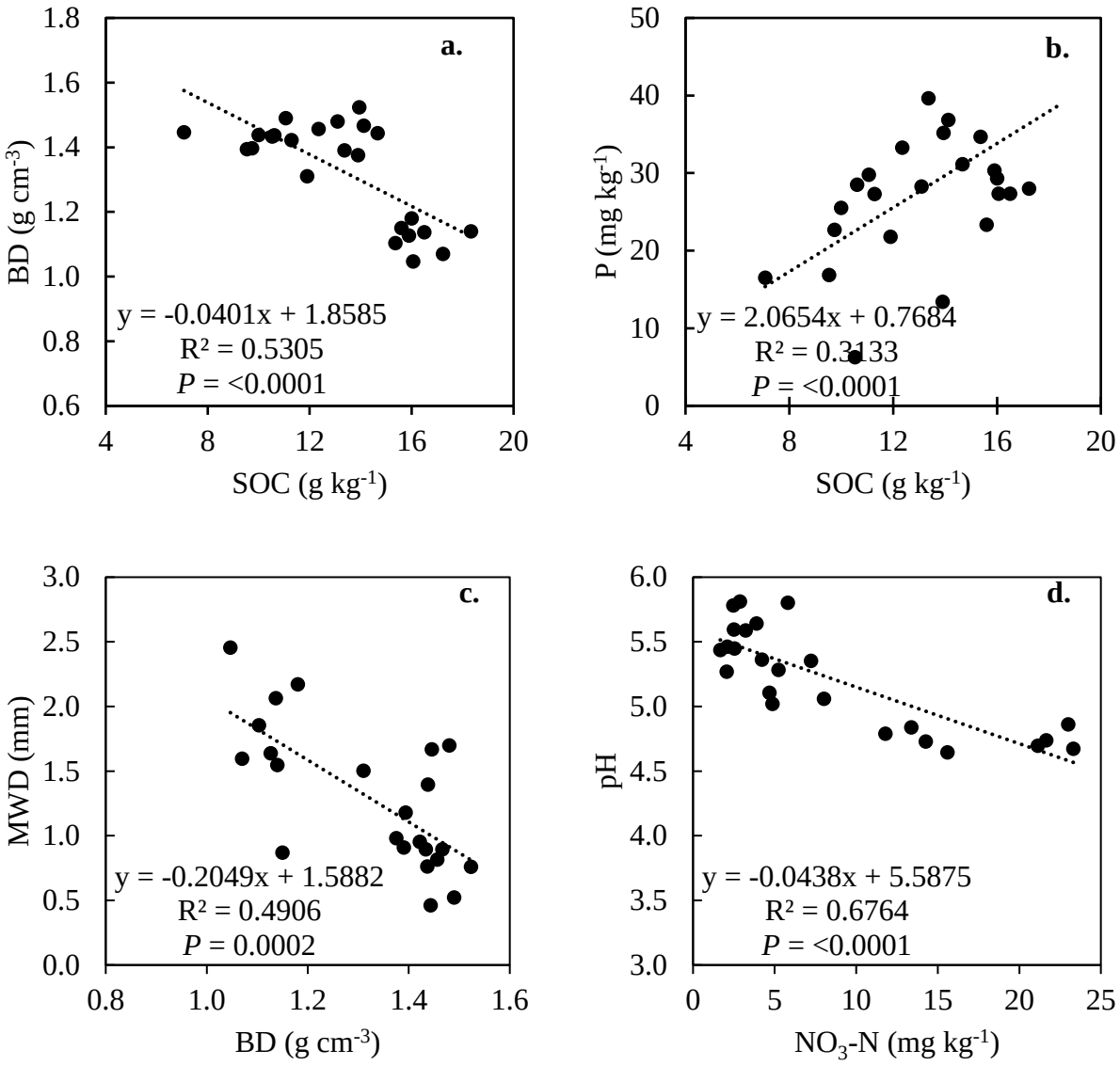


Figure 5.4. Relationships of soil organic carbon concentration (SOC) and bulk density (BD, a.), SOC and phosphorus (P, b.), BD and mean weight diameter (MWD, c.), as well as nitrate-nitrogen (NO_3-N) concentration and pH (d.) in the surface 0-15 cm soil depth across three on-farm sites in central and western Kansas.

Tables

Table 5.1. Cropping history and field management of no-till cover crop experiments at three producer fields in west central Kansas.

Description/activity	Alexander, KS 2019-2021	Hays, KS 2019-2021	Marquette, KS 2018-2021
Coordinates	38°22'20.5"N, 99°31'27.4"W	38°49'57.4"N, 99°17'24.4"W	38°35'54.1"N, 97°56'14.1"W
Field size (ha)	32	20	37
Crop rotation	wheat-corn-fallow	triticale (forage)-sorghum-fallow	wheat-wheat-soybean
First cover crop mixture†	Oats Triticale Barley Pea Rapeseed Sunflower	Sorghum-sudangrass Millet Sunn hemp Sunflower Radish	Triticale Rapeseed Radish
Planting time	March 2019	June 2019	August 2018
Grazing dates	5/14/19 to 6/14/19	08/24/19 to 10/10/19	12/17/18 to 2/10/19
Livestock breed and class	Crossbred Angus/Hereford yearling steers and heifers	Angus cow-calf pairs	Angus yearling steers and heifers
Stocking rate (AUM‡ ha^{-1})	0.9	3.2	2.5
Termination time††	June 2019	October 2019	May 2019
Second cover crop mixture†	Sorghum-sudangrass Millet Sunn hemp Sunflower Radish	Oats Triticale Barley Pea Rapeseed Sunflower	Triticale Rapeseed Radish
Planting time	June 2020	March 2021	August 2020
Grazing dates	8/7/20 to 9/18/20	6/30/21 to 7/20/21	1/9/2021 to 2/17/2021
Livestock breed and class	Crossbred Angus/Hereford yearling steers and heifers	Angus yearling steers and heifers	Angus yearling steers and heifers
Stocking rate (AUM‡ ha^{-1})	1.9	1.3	2.0
Termination time††	October 2020	July 2021	May 2021
Soil sampling time	May 2021	August 2021	May 2021

†Seeding rates at Alexander and Hays were 16.8 kg ha^{-1} oats, 11.2 kg ha^{-1} triticale, 16.8 kg ha^{-1} barley, 5.6 kg ha^{-1} pea, 1.1 kg ha^{-1} rapeseed, and 1.1 kg ha^{-1} sunflower or 8.4 kg ha^{-1} sorghum-sudangrass, 5.6 kg ha^{-1} millet, 1.1 kg ha^{-1} sunn hemp, 1.1 kg ha^{-1} sunflower, and 1.1 kg ha^{-1} radish. Seeding rates at Marquette were 45.0 kg ha^{-1} triticale, 2.2 kg ha^{-1} radish, and 2.2 kg ha^{-1} rapeseed.
‡Animal unit month.
††Triticale/rapeseed/radish cover crops at Marquette, KS and oat/triticale/barley/pea/rapeseed/sunflower cover crops at Alexander and Hays, KS were terminated with glyphosate (N-[phosphonomethyl] glycine), and 2,4-D (2,4-dichlorophenoxy-acetic acid). Sorghum-sudangrass/millet/sunn hemp/sunflower/radish cover crops at Alexander and Hays, KS were frost-killed.

Table 5.2. Soil physical and chemical properties measured at study initiation in the 0-5 and 5-15 cm soil depths across on-farm study sites in central and western Kansas.

Site	Depth	Sand	Silt	Clay	BD	SOC	pH	NO_3	P	K
		g kg^{-1}			g cm^{-3}	g kg^{-1}		mg kg^{-1}		
Alexander	0-5 cm	168.8	566.5	264.8	1.01	11.90	5.07	1.38	38.80	514.00
		(21.3)†	(38.0)	(33.4)	(0.09)	(0.34)	(0.07)	(0.21)	(6.88)	(11.34)
	5-15 cm	154.9	530.4	314.8	1.29	9.05	5.56	1.05	12.98	357.25
		(19.9)	(38.3)	(30.2)	(0.05)	(0.44)	(0.15)	(0.25)	(4.43)	(28.47)
Hays	0-5 cm	205.9	552.1	242.0	1.24	14.10	5.36	3.20	45.90	488.50
		(8.4)	(3.5)	(11.2)	(0.05)	(0.16)	(0.23)	(0.32)	(1.10)	(8.45)
	5-15 cm	163.3	501.0	335.8	1.43	13.15	5.88	1.13	16.18	386.00
		(8.1)	(3.7)	(5.2)	(0.01)	(0.18)	(0.31)	(0.13)	(3.29)	(30.91)
Marquette	0-5 cm	251.8	514.8	233.5	1.12	15.63	5.60	1.38	87.05	440.55
		(31.7)	(21.6)	(15.6)	(0.07)	(0.13)	(0.11)	(0.08)	(3.51)	(26.63)
	5-15 cm	217.6	507.4	275.0	1.29	13.00	5.73	1.13	42.15	314.13
		(6.0)	(22.1)	(27.0)	(0.08)	(0.20)	(0.02)	(0.07)	(3.42)	(22.07)

†Values in parenthesis indicate one standard deviation of the mean.

Table 5.3. Ungrazed, pre-grazing, post-grazing cover crop biomass accumulation across six on-farm site-years in central and western Kansas.

			Management			Standard error	
Site	Year	Planting window	Ungrazed	Pre-Grazing	Post-Grazing		*P*-value
			kg ha^{-1}				
Alexander	2019	Spring	2385a[†]	1337b	918b	252	0.0154
	2020	Summer	5696a	3948b	3226b	666	0.0150
Hays	2019	Summer	6904ab	7744a	5318b	623	0.0637
	2021	Spring	1437a	1063b	429c	127	0.0011
Marquette	2019	Winter	2702a	1273b	1130b	160	0.0002
	2021	Winter	3101a	2136b	2207b	336	0.0783
Average of site-years			3704a	2893ab	2228b	446	0.0154

[†]Means followed by the same lower-case letter within the same row (site-year) are not significantly different ($\alpha = 0.10$) among cover crop management treatments.

Table 5.4. Mean effects of cover crop management, site, and sampling depth on bulk soil organic carbon (SOC) and particulate organic carbon (POC) concentrations across on-farm sites in central and western Kansas; and *P*-values of type III analyses of fixed effects and their interactions.

Treatments	SOC	POC
	g kg^{-1}	
Management		
Ungrazed	13.4a[†]	3.80a
Grazed	14.8a	4.16a
Standard error	0.50	0.24
Site		
Alexander	11.2c	2.57c
Hays	17.3a	5.15a
Marquette	13.9b	4.22b
Standard error	0.73	0.29
Depth		
0-5 cm	16.7a	6.21a
5-15 cm	11.6b	1.75b
Standard error	0.46	0.20
Type III analysis of fixed effects	*P*-values	
Management (M)	0.1449	0.3673
Site (S)	0.0005	0.0003
M × S	0.7697	0.5121
Depth (D)	0.0027	0.0003
M × D	0.9064	0.9140
S × D	0.3894	0.0075
M × S × D	0.6375	0.9350

[†]Means followed by the same lower-case letter within the same column are not significantly different ($\alpha = 0.10$) among treatments.

Table 5.5. Main effects of management, site, and sampling depth on soil pH, NO_3-N, P and K concentrations across on-farm sites in central and western Kansas; and *P*-values of type III analyses of fixed effects and their interactions.

Treatments	pH	NO_3-N	P	K
		mg kg^{-1}		
Management				
Ungrazed	5.15a[†]	11.48a	32.61a	416.6b
Grazed	5.13a	11.24a	34.89a	462.3a
Standard error	0.08	1.40	3.50	14.4
Site				
Alexander	5.23a	5.96b	24.78b	467.6a
Hays	5.45a	3.59b	37.25a	498.1a
Marquette	4.73b	24.53a	39.24a	352.6b
Standard error	0.10	1.74	4.28	22.0
Depth				
0-5 cm	4.92b	19.49a	50.60a	498.6a
5-15 cm	5.35a	3.23b	16.91b	380.3b
Standard error	0.08	1.43	3.91	14.7
Type III analysis of fixed effects		*P*-values		
Management (M)	0.8314	0.9018	0.5124	0.0269
Site (S)	0.0031	0.0002	0.0555	0.0069
M × S	0.6270	0.6609	0.3933	0.1073
Depth (D)	0.0063	0.0034	0.0054	0.0026
M × D	0.3162	0.8454	0.1020	0.0355
S × D	0.0148	0.0003	0.0202	0.0026
M × S × D	0.2785	0.7988	0.8018	0.7552

[†]Means followed by the same lower-case letter within the same column are not significantly different ($\alpha = 0.10$) among treatments.

Table 5.6. Main effects of management, site, and sampling depth on soil bulk density (BD), penetration resistance (PR), mean weight diameter (MWD) of water stable aggregates, and wind-erodible fraction (WEF) across on-farm sites in central and western Kansas; and *P*-values of type III analyses of fixed effects and their interactions.

Treatments	BD	PR	MWD	WEF
	g cm^{-3}	MPa	mm	%
Management				
Ungrazed	1.31a[†]	0.43a	1.30a	13.8a
Grazed	1.32a	0.44a	1.35a	12.1a
Standard error	0.01	0.02	0.17	1.3
Site				
Alexander	1.39a	0.52a	1.30b	13.9ab
Hays	1.11b		1.76a	15.6a
Marquette	1.44a	0.35b	0.92b	9.4b
Standard error	0.02	0.02	0.18	1.7
Depth				
0-5 cm	1.26b		1.45a	15.1a
5-15 cm	1.36a		1.21a	10.8a
Standard error	0.01		0.17	1.4
Type III analysis of fixed effects	———	*P*-values	———	
Management (M)	0.9018	0.7923	0.8109	0.3851
Site (S)	<0.0001	0.0111	0.0325	0.0986
M × S	0.6413	0.7361	0.3942	0.4575
Depth (D)	0.0055		0.3657	0.1097
M × D	0.3218		0.2797	0.7770
S × D	0.1369		0.2966	0.1490
M × S × D	0.3445		0.0109	0.4333

[†]Means followed by the same lower-case letter within the same column are not significantly different ($\alpha = 0.10$) among treatments.

Table 5.7. Mean weight diameter of water stable aggregates as affected by the interaction effects of management, site, and depth of sampling across on-farm sites in central and western Kansas.

		Management	
		Ungrazed	Grazed
Depth	Site	mm	
0-5 cm	Alexander	1.61a[†]A[‡]	1.41aA
	Hays	1.40aA	2.00aA
	Marquette	0.89aB	1.37aA
Standard error		0.29	0.29
5-15 cm	Alexander	1.16aA	1.02aB
	Hays	2.06aA	1.57aA
	Marquette	0.68aB	0.75aB
Standard error		0.29	0.29

[†]Means in the same row followed by the same lower-case letter are not significantly different ($\alpha = 0.10$) among cover crop management treatments in the same depth and site.
[‡]Means in the same column followed by the same upper-case letter are not significantly different ($\alpha = 0.10$) among sites within the same cover crop management treatment and depth.

Table 5.8. Correlation coefficients (*r*) and *P* values from correlation analysis among soil chemical and physical properties across sites and sampling depths.

Parameter	POC[†]	pH	NO_3-N	P	K
SOC					
r	0.72*****[‡]	0.24	-0.01	0.62*****	0.36**
POC					
r		-0.11	0.32**	0.85*****	0.24
pH					
r			-0.65*****	-0.15	0.55*****
NO_3-N					
r				0.35**	-0.40***
P					
r					0.25*

[†]POC, particulate organic carbon; SOC, soil organic carbo; NO_3-N, nitrate-nitrogen; P, phosphorus; K, potassium.
[‡]**P*≤0.10; ***P*≤0.05; ****P*≤0.01; *****P*≤0.001; ******P*≤0.0001

Table 5.9. Pearson correlation coefficients (*r*) from correlation analysis among soil chemical and physical properties across sites and sampling depths.

Parameter	POC[†]	BD	PR	MWD	WEF
SOC					
r	0.72*****[‡]	-0.71*****	-0.29	0.40***	0.21
POC					
r		-0.39***	-0.54**	0.12	0.12
BD					
r			-0.42	-0.68*****	-0.31**
PR					
r				0.37	0.64***
MWD					
r					0.09

[†]POC, particulate organic carbon; SOC soil organic carbon, PR, penetration resistance, MWD, mean weight diameter, WEF, wind-erodible fraction.
[‡]**P*≤0.10; ***P*≤0.05; ****P*≤0.01; *****P*≤0.001; ******P*≤0.0001

Appendix A - Additional supporting tables

Appendix Table A.1. Cover crop revenues and expenses, other fallow expenses, winter wheat revenues and expenses, and total revenues and expenses with fallow management and tillage treatments in a winter wheat-grain sorghum-fallow rotation from 2015 to 2023 near Brownell, KS.

Variable	Fallow		Standing cover crops		Hayed cover crops		Grazed cover crops	
	No-tillage	Occasional tillage	No-tillage	Occasional tillage	No-tillage	Occasional tillage	No-tillage	Occasional tillage
Cover crop revenues								
Available hay, kg ha^{-1}	0	0	0	0	2173	2173	0	0
Hay price, US$ kg^{-1}	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Hay revenue, US$ ha^{-1}	0.00	0.00	0.00	0.00	325.96	325.96	0.00	0.00
Available grazing, kg ha^{-1}	0	0	0	0	0	0	1552	1552
Carrying capacity, AUM ha^{-1}	0	0	0	0	0	0	1.78	1.78
Grazing lease price (1, rangeland alternative), US$ AUM^{-1}	0	0	0	0	0	0	73.40	73.40
Grazing lease price (2, hay alternative), US$ AUM^{-1}	0	0	0	0	0	0	145.79	145.79
Grazing revenue, US$ ha^{-1}	0	0	0	0	0	0	130.67 259.53	130.67 259.53
Winter wheat revenues								
Wheat yield, kg ha^{-1}	2928	2859	2656	2572	2710	2700	2577	2625
Wheat price, US$ kg^{-1}	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21

Wheat revenue, US$ ha^{-1}	617.81	603.19	560.51	542.88	571.99	569.61	543.80	553.93
Total revenue, US$ ha^{-1}	617.81	603.19	560.51	542.88	899.13	894.39	674.94 804.26	684.12 812.52
Cover crop expenses								
Cover crop seed, kg ha^{-1}	0	0	79	79	79	79	79	79
Cover crop seed price, US$ ha^{-1}	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64
Cover crop seed cost, US$ ha^{-1}	0.00	0.00	50.56	50.56	50.56	50.56	50.56	50.56
Planting cost, US$ ha^{-1}	0.00	0.00	15.95	15.95	15.95	15.95	15.95	15.95
Swathing expense US$ ha^{-1}	36.40	36.40	36.40	36.40	36.40	36.40	36.40	36.40
Bail and stack expense, US$ kg^{-1}	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Hay cost, US$ ha^{-1}	0.00	0.00	0.00	0.00	123.32	123.32	0.00	0.00
Other fallow expenses								
No. of herbicide applications	4	3	2	1	2	1	2	1
Herbicide application price, US$ ha^{-1}	11.60	11.60	11.60	11.60	11.60	11.60	11.60	11.60
Herbicide price, US$ ha^{-1}	26.79	26.79	26.79	26.79	26.79	26.79	26.79	26.79
Herbicide plus application cost, US$ ha^{-1}	153.56	115.17	76.78	38.39	76.78	38.39	76.78	38.39
No. of tillage passes	0	1	0	1	0	1	0	1
Sweep plow price,	27.20	27.20	27.20	27.20	27.20	27.20	27.20	27.20

US$ ha^{-1}								
Tillage cost, US$ ha^{-1}	0.00	27.20	0.00	27.20	0.00	27.20	0.00	27.20
Winter wheat expenses								
Wheat seed, kg ha^{-1}	67	67	67	67	67	67	67	67
Wheat seed price, US$ kg^{-1}	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
Wheat seed cost, US$ ha^{-1}	80.40	80.40	80.40	80.40	80.40	80.40	80.40	80.40
Planting cost, US$ ha^{-1}	15.95	15.95	15.95	15.95	15.95	15.95	15.95	15.95
N fertilizer amount, kg ha^{-1}	75	75	75	75	75	75	75	75
N fertilizer price, US$ kg^{-1}	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
P fertilizer amount, kg ha^{-1}	12	12	12	12	12	12	12	12
P fertilizer price, US$ kg^{-1}	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86
Fertilizer cost, US$ ha^{-1}	59.07	59.07	59.07	59.07	59.07	59.07	59.07	59.07
Harvest cost, US$ ha^{-1}	57.00	57.00	57.00	57.00	57.00	57.00	57.00	57.00
Hauling cost, US$ ha^{-1}	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.90
Total cost, US$ ha^{-1}	369.88	358.69	359.61	348.42	483.25	471.43	359.61	348.42
Net returns, US$ ha^{-1}	247.93	244.50	200.90	194.46	415.88	422.96	315.33 444.65	335.70 464.10

Appendix Table A.2. Cover crop revenues and expenses, other fallow expenses, grain sorghum revenues and expenses, winter wheat revenues and expenses, and total revenues and expenses with cover crop management treatments in a winter wheat-grain sorghum-fallow rotation from 2019 to 2022 near Brownell, KS.

Variable	Fallow	Standing cover crops	Hayed cover crops	Grazed cover crops
Cover crop revenues				
Available hay, kg ha^{-1}	0	0	1485	0
Hay price, US$ kg^{-1}	0.13	0.13	0.13	0.13
Hay revenue, US$ ha^{-1}	0.00	0.00	193.08	0.00
Available grazing, kg ha^{-1}	0	0	0	1061
Carrying capacity, AUM ha^{-1}	0	0	0	1.29
Grazing lease price (1, rangeland alternative), US$ AUM^{-1}	0	0	0	73.40
Grazing lease price (2, hay alternative), US$ AUM^{-1}	0	0	0	128.35
Grazing revenue, US$ ha^{-1}	0	0	0	161.83 282.97
Grain sorghum revenues				
Sorghum yield kg ha^{-1}	3360	2853	2900	2897
Sorghum price US$ kg^{-1}	0.20	0.20	0.20	0.20
Sorghum revenue US$ ha^{-1}	658.62	559.15	568.40	567.82
Total revenue, US$ ha^{-1}	658.62	559.15	761.48	657.13

				723.98
Cover crop expenses				
Cover crop seed, kg ha^{-1}		35	35	35
Cover crop seed price, US$ ha^{-1}	1.35	1.35	1.35	1.35
Cover crop seed cost, US$ ha^{-1}	0.00	47.25	47.25	47.25
Planting cost, US$ ha^{-1}	0.00	15.95	15.95	15.95
Swathing expense US$ ha^{-1}	36.40	36.40	36.40	36.40
Bail and stack expense, US$ kg^{-1}	0.04	0.04	0.04	0.04
Hay cost, US$ ha^{-1}	0.00	0.00	83.68	0.00
Other fallow expenses				
No. of herbicide applications	2	1	1	1
Application price, US$ ha^{-1}	11.60	11.60	11.60	11.60
Chemical price, US$ ha^{-1}	23.20	11.60	11.60	11.60
Herbicide cost, US$ ha^{-1}	53.58	26.79	26.79	26.79
Grain sorghum expenses				
Sorghum seed, kg ha^{-1}	4	4	4	4
Sorghum seed price, US$ kg^{-1}	7.93	7.93	7.93	7.93
Sorghum seed cost, US$ ha^{-1}	31.72	31.72	31.72	31.72
Planting cost,	15.95	15.95	15.95	15.95

US$ ha^{-1}				
N fertilizer amount, kg ha^{-1}	75	75	75	75
N fertilizer price, US$ kg^{-1}	0.65	0.65	0.65	0.65
P fertilizer amount, kg ha^{-1}	12	12	12	12
P fertilizer price, US$ kg^{-1}	0.86	0.86	0.86	0.86
Fertilizer cost, US$ ha^{-1}	59.07	59.07	59.07	59.07
Harvest cost, US$ ha^{-1}	57.00	57.00	57.00	57.00
Hauling cost, US$ ha^{-1}	3.90	3.90	3.90	3.90
Total cost, US$ ha^{-1}	244.42	282.03	365.70	282.03
Net returns, US$ ha^{-1}	414.20	277.12	395.77	375.10 454.75

Appendix Table A.3. Cover crop revenues and expenses, other fallow expenses, winter wheat revenues and expenses, and total revenues and expenses with fallow management treatments in a winter wheat-grain sorghum-fallow rotation from 2015 to 2023 near Brownell, KS.

Variable	Fallow	Standing cover crops	Hayed cover crops	Flex-hayed cover crops
Cover crop revenues				
Available hay, kg ha^{-1}	0	0	2083	1591
Hay price, US$ kg^{-1}	0.13	0.13	0.13	0.13
Hay revenue, US$ ha^{-1}	0.00	0.00	270.73	206.89
Winter wheat revenues				
Wheat yield, kg ha^{-1}	2859	2560	2706	2703
Wheat price, US$ kg^{-1}	0.21	0.21	0.21	0.21
Wheat revenue, US$ ha^{-1}	600.35	537.52	568.30	567.53
Total revenue, US$ ha^{-1}	600.35	537.52	839.03	774.42
Cover crop expenses				
Cover crop seed, kg ha^{-1}	0	79	79	79
Cover crop seed price, US$ ha^{-1}	0.64	0.64	0.64	0.64
Cover crop seed cost, US$ ha^{-1}	0.00	50.56	50.56	50.56
Planting cost, US$ ha^{-1}	0.00	15.95	15.95	15.95
Swathing expense US$ ha^{-1}	36.40	36.40	36.40	36.40
Bail and stack expense,	0.04	0.04	0.04	0.04

US$ kg^{-1}				
Hay cost, US$ ha^{-1}	0.00	0.00	119.70	90.99
Other fallow expenses				
No. of herbicide applications	4	3	3	3
Application price, US$ ha^{-1}	11.60	11.60	11.60	11.60
Chemical price, US$ ha^{-1}	26.79	26.57	26.57	26.57
Herbicide cost, US$ ha^{-1}	153.56	115.17	115.17	115.17
Winter wheat expenses				
Wheat seed, kg ha^{-1}	67	67	67	67
Wheat seed price, US$ kg^{-1}	1.20	1.20	1.20	1.20
Wheat seed cost, US$ ha^{-1}	80.40	80.40	80.40	80.40
Planting cost, US$ ha^{-1}	15.95	15.95	15.95	15.95
N fertilizer amount, kg ha^{-1}	75	75	75	75
N fertilizer price, US$ kg^{-1}	0.65	0.65	0.65	0.65
P fertilizer amount, kg ha^{-1}	12	12	12	12
P fertilizer price, US$ kg^{-1}	0.86	0.86	0.86	0.86
Fertilizer cost, US$ ha^{-1}	59.07	59.07	59.07	59.07
Harvest cost, US$ ha^{-1}	57.00	57.00	57.00	57.00

Hauling cost, US$ ha^{-1}	3.90	3.90	3.90	3.90
Total cost, US$ ha^{-1}	369.88	398.00	517.70	483.92
Net returns, US$ ha^{-1}	230.47	139.52	321.33	290.50