Profitability and soil health impacts of cover crops and annual forages with integration of livestock into wheat-based systems

by

Zachariah Charles Carson

B.S., Fort Hays State University, 2023

A THESIS

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Agronomy
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2026

Approved by:

Co-Major Professor
Kraig L. Roozeboom

Approved by:

Co-Major Professor
Augustine K. Obour

Copyright

© Zachariah Carson 2026.

Abstract

Integrating annual forages and livestock into dryland cropping systems can increase profitability and improve soil health. A study was conducted from 2021-2025 at the Kansas State University Agricultural Research Center in Hays, KS, to investigate the soil health, production, and profitability effects of integrating ruminant livestock and forage sorghum (FS) (*Sorghum bicolor Moench*) into a no-till (NT) dryland winter wheat (*Triticum aestivum*)-grain sorghum-fallow (W-GS-F) rotation. Treatments included W-GS-F (control), W-GS-F with GS residues grazed (W-GSG-F), W/FS-FS-F with FS grazed (W/FSG-FSG-F), and W/FS-FS-F with FS hayed (W/FSH-FSH-F). The study was a randomized complete block design with four replications, with all phases of rotations present each year. Double-crop FS averaged 2,894 to 2,951 kg ha^{-1}, and was not harvested in 2 out of the 5 years due to limited moisture post-wheat and extreme drought conditions. Full-season FS forage dry matter averaged 6,933 to 7,338 kg ha^{-1}, and provided adequate production each year of the study, despite extreme drought conditions in 2022 and 2023. In 3 years of double-crop FS grazing, ~60% of forage biomass was retained as residue post-graze, while haying retained ~40% of forage biomass as residue. Grazing full-season FS retained ~50% of biomass as residue compared to ~30% when hayed. Wheat yields were collected in 2023-2025 after all rotations had made a complete cycle, and experienced extreme spring droughts in each growing season, resulting in low yields. Because of poor yields, no significant effect was observed across rotation. Grain sorghum yields were collected in 2024 and 2025, again, after all rotations had made a complete cycle. Similar to wheat yields, no significant rotation effect was observed in grain sorghum yield between W-GS-F and W-GSG-F. Averaged across the 0-15 cm sampling depth, no differences in bulk density, bulk SOC or particulate organic matter were observed among treatments. However, dry aggregate associated

SOC was greater in W-GSG-F and W/FSG-FSG-F than W-GS-F and W/FSH-FSH-F in nearly all aggregate sizes. No differences in mean weight diameter (MWD) of water stable aggregates were observed among treatments. Dry-aggregate MWD was similar for W-GS-F, W-GSG-F, and W/FSG-FSG-F treatments, but significantly less for W/FSH-FSH-F. Percent wind erodible fraction was consistently higher for W/FSH-FSH-F. Cropping system net returns varied by year but were consistently significantly higher for W-GSG-F. The second study was established on-farm in fall 2022 on a 20-hectare producer field in Russell County, KS to investigate the effects of cover crop (CC) biomass removal with cattle grazing on soil health parameters and grain crop yields in a no-till dryland cropping system. The study design was a randomized complete block with three treatments and four replications. The treatments included ungrazed CCs (UGR), "take-half-leave-half" (T-H-L-H, 50% biomass removal), and "graze-out" (G-O, 90% biomass removal). Averaged across 2023-2024, the T-H-L-H and G-O significantly reduced CC residue amount, height, and residue cover when compared to UGR. In 2023, T-H-L-H had 224 kg ha^{-1} more residue remaining and 15 cm taller residue than the G-O treatment. Though, in 2024, CC biomass parameters were not significantly different between T-H-L-H and G-O, because biomass removed from each grazing treatment was essentially the same. Cover crop management had no significant effect on concentrations of SOC and particulate organic matter. However, averaged across the 0-15 cm soil depth, phosphorus (P) concentration was reduced by T-H-L-H and G-O compared to UGR, likely due to purposefully avoiding sampling near manure pats on the grazed plots that may be high in P. Grazing CCs increased soil bulk density compared to UGR at the 0-5 cm soil depth. Take-half-leave-half also increased soil penetration resistance in one of two years. Percent wind-erodible fraction, MWD, time-to-runoff, and subsequent grain sorghum yield were unaffected by CC management. Nearly every measured soil property declined from initial

sampling to 2024 in all treatments including the UGR control, possibly because the study site was converted to crop production from Conservation Reserve Program grass prior to study implementation in 2021. In 2023, we were relatively close to our target T-H-L-H and G-O removal goals, but in 2024 there was no biomass removal difference between T-H-L-H and G-O due to limited biomass production. Grazing intensity effects on soil properties differed in the two-years of investigation, but overall soil health was maintained with grazing in both studies and even increased aggregate associated SOC concentrations within the Hays study, while haying annual forage diminished soil properties. Our findings from both studies showed no significant impact on subsequent grain production from addition of forage for haying and grazing while providing extra revenue, but the less intensive grazed system W-GSG-F was the most profitable in the Hays study.

Table of Contents

List of Figures ix
List of Tables x
Acknowledgements xi
Dedication xii
Chapter 1 - Introduction and Literature Review 1
Introduction 1
Dryland Agricultural Production of the Central Great Plains 2
Usefulness of Intensified Crop Rotation 6
Cover Crop Benefits for Soil Properties 8
Cover Crops as Weed Suppressants 11
Cover Crop Water Use and Yield Impact 13
Grazing Cover Crops 15
Grazing Enhances Nutrient Cycling 18
Utilizing Annual Forages 20
Annual Forage Production vs. Grain Production 22
Hypothesis and Objectives 23
References 24
Chapter 2 - Diversifying wheat-based Cropping Systems with Forages and Livestock 34
Abstract 34
Introduction 37
Materials and Methods 41
Site Description and Experiment Layout 41
Crop Management 42
Forage Biomass and Grazing Management 43
Residue Cover and Soil Properties 44
Economic Analysis 47
Statistical Analysis 48
Results 48
Weather Patterns 48

Winter Wheat and Grain Sorghum Yields 50
Forage mass 50
Residue Cover 51
Aggregate Stability 51
Bulk Density and Penetration Resistance 52
Soil Organic Carbon and Particulate Organic Matter 53
Aggregate Associated Carbon 53
Nitrogen, Phosphorus and pH 54
Costs and Net Returns 55
Discussion 56
Conclusion 61
References 62
Tables 70
Figures 76
Chapter 3 - Cover Crop Biomass Removal Rates to Optimize Livestock Production and Soil Properties in Dryland Cropping Systems 82
Abstract 82
Introduction 85
Materials and Methods 87
Site Description and Experiment Layout 87
Crop Management 88
Grazing Management and Biomass Parameters 89
Soil Properties and Time-to-Runoff 90
Statistical Analysis 93
Results 93
Precipitation 93
Cover Crop Biomass Parameters 94
Aggregate Stability 95
Bulk Density and Penetration Resistance 96
Soil Organic Carbon and Particulate Organic Matter 97
Nitrogen, Phosphorus and pH 98

Time-to-Runoff 99
Grain Sorghum Yield 99
Discussion 99
Conclusion 102
References 103
Tables 109
Figures 113

List of Figures

Figure 2.1. Daily precipitation and temperature averages in 2023 (a.), 2024 (b.), and 2025 (c.) near Hays, KS. 76
Figure 2.2. Effect of harvest type on forage sorghum remaining on the soil surface in 2021 (a.), 2024 (b.), and 2025 (c.) near Hays, KS. 77
Figure 2.3. Effect of rotation intensification on soil surface residue cover in 2023 (a.), 2024 (b.), and 2025 (c.) near Hays, KS. 78
Figure 2.4. Effect of rotation intensification on wind erodible fraction in 2023 (a.), 2024 (b.), and 2025 (c.) near Hays, KS. 79
Figure 2.5. Soil organic carbon as affected by rotation intensification and sampling depth within 2023 (a.), 2024 (b.), and 2025 (c.) near Hays, KS. Error bars represent standard error of means. 80
Figure 2.6. Effect of rotation intensification on dry-aggregate SOC (DASOC) at <0.25mm size fraction 2023 (a.), 2024 (b.), and 2025 (c.) near Hays, KS. 81
Figure 3.1. Effect of grazing intensity on soil bulk density at the 0-5cm and 5-15 cm soil depth in Russell County, KS. UGR = Ungrazed; T-H-L-H = Take-half-leave-half; G-O = Graze out. 113
Figure 3.2. Effect of grazing intensity on penetration resistance within 2023 and 2024 averaged across the 0-15cm soil depth in Russell County, KS. UGR = Ungrazed; T-H-L-H = Take-half-leave=half; G-O = Graze Out. 114
Figure 3.3. Effect of cover crop from initial implementation, to 2023 and 2024 on time-to-runoff in Russell County, KS. 114

List of Tables

Table 2.1. Effect of rotation intensification and haying and grazing on winter wheat and grain sorghum yield averages near Hays, KS. 70
Table 2.2. Available forage sorghum yields in full-season and post-wheat production, and percent of forage remaining after haying and grazing forage sorghum near Hays, KS. 71
Table 2.3. Average cropping system intensification effects on soil chemical, bio-chemical, and physical properties measured in 2023 through 2025 near Hays, KS. 72
Table 2.4. Cropping system intensification effects on dry aggregate soil organic carbon (DASOC) and wet aggregate soil organic carbon (WASOC) measured in 2023 to 2025 near Hays, KS. 73
Table 2.5. Cropping system intensification effects on total production costs averaged over 2024 and 2025 growing seasons near Hays, KS. 74
Table 2.6. Cropping system intensification effects on net returns between 2024 and 2025 growing seasons near Hays, KS. Grazed systems were calculated as alternative to grazing rangeland and an alternative to confined hay feeding lease values. 75
Table 3.1. Total monthly and 30-year average precipitation for Russell County, KS over the study period. 109
Table 3.2. Cover crop residue remaining, residue height, and residue cover averages and ANOVA table as effected by grazing intensities and year in Russell County, KS. 110
Table 3.3. Initial and 2-year averages and ANOVA table for effect of grazing intensity on soil chemical, bio-chemical, and physical properties in Russell County, KS. 111
Table 3.4. Effects of grazing intensity of cover crops on grain sorghum yield near Russell County, KS. 112

Acknowledgements

I sincerely thank my committee members: Dr. Augustine Obour, Dr. Kraig Roozeboom, and Dr. John Holman for their guidance, wealth of knowledge, and mentorship throughout this process. Joining the program in 2021 as an undergraduate while attending Fort Hays State University, I would have never imagined the life time knowledge and memories I would make with my time at the Kansas State University Agricultural Research Center in Hays, KS. My project and laboratory co-workers (Dr. Logan Simon, Payton Mauler, Mikaela Lawrence, Jena Schwartze, Priscilla Akporsoe, Benjamin Garcia, and Joseph Kimzey) have been a tremendous help with processing data and taking care of seasonal plot duties. I would also like to thank all of my family members, and beautiful fiancée for all of the moral support throughout the years. If it wasn't for my dad instilling the love of agriculture at an early age, none of this would be possible. I look forward to continued years at the university, and uncovering groundbreaking advancements in the field of agriculture.

Dedication

I want to dedicate my work to the four generations of Carson farmers who came before me. My great-great grandfather laid the foundation for my family's farm, and has passed the green thumb trait throughout generations. During the dustbowl, my grandfather built sod houses for incoming settlers and fed his cattle with yucca roots to make ends meet. When many others left the area during the harsh conditions, he survived, and built something that has now lasted over 100 years. In later years, his son even won the award of Corn King of Scott, County! Those who came before me laid the foundation for what my family and I continue to do today. Without it, I certainly would not be in this position and will forever be grateful for the sacrifices that they've made.

Chapter 1 - Introduction and Literature Review

Introduction

Current dryland cropping systems in the Great Plains are highly vulnerable to wind and water soil erosion (Carr et al., 2020). The primary reasons for this vulnerability are lack of precipitation and extended periods of exposed soil from fallow fields. Soils are exposed to erosion for extended periods of time due to the 11-15-month fallow period that is necessary for building soil moisture in the profile for the next grain crop. Although the fallow period is essential for the grain crop, moisture retention during that period is inefficient. Depending on tillage practice and residue cover, fallow retains only 20-35% of precipitation received as soil moisture (Holman et al., 2018). In addition, the Great Plains is prone to occasional high precipitation events that can cause soil erosion and water runoff, reducing storage efficiency (Anderson, 2005a). The inefficiency of precipitation storage and soil exposure leaves many to wonder if there is a way to make fallow more efficient or utilize the soil moisture in a more efficient manner.

Growing cover crops (CCs) or annual forages could help improve fallow efficiency. Greater water retention and infiltration can be accomplished through increased amount of residue cover and soil aggregation provided by CCs (Burke et al., 2022). An increase in residue cover and soil aggregation also reduces soil erosion. Soil chemical properties can be improved by CCs as well by increasing soil organic carbon and nutrient availability near the soil surface (Blanco-Canqui et al., 2013; Mahama et al., 2016; Hallama et al., 2019). Additionally, CCs can suppress herbicide-resistant weeds through smothering emerging weeds with residue competition and allelopathy (Osipitan et al., 2018; Mirsky et al., 2013; Hutchinson and McGiffin, 2000; Kunz et al., 2016). With all the advantages of CCs, there is still a hesitancy by producers to adopt this

practice. Cover crops use water, and that can lead to a negative impact on subsequent grain crop yields (Nielsen et al., 2016a; Unger, 1998; Burke et al., 2022; Holman et al., 2018; Holman et al., 2018; 2020; 2021; Obour et al., 2022a). A way to negate the economic impacts of reduced grain production is to utilize cover crops as annual forages. Annual forages can maintain many of the positive soil health benefits of a CC, while also being used for haying or grazing of livestock (Holman et al., 2022; 2023a; Obour et al., 2021a; 2023). Growing annual forages in place of a fallow system or in place of a grain crop may even be superior to grain-based systems. Forages require less water, and can be more productive in drought years than grain crops (Holman et al., 2022; Nielsen et al., 2005; 2016b), providing better yield stability and financial return (Holman et al., 2021; 2022) for producers in a highly variable precipitation environment.

Dryland Agricultural Production of the Central Great Plains

The U.S. Great Plains is home to one of the vastest agricultural production regions in the world. Stretching north-south from North Dakota to Texas, and east-west from Missouri to the Rocky Mountains (Nielsen et al., 2018). The central Great Plains (CGP) was formerly an immense grassland but is now a region dominated by annual crop production. The primary soil texture of this area is silt loam, but silty clays and loamy sands are also present in the region (Cano et al., 2018). Soils with deep silt and clay textures can efficiently store water, allowing for dryland crop production in this semi-arid climate. Shallow soil with predominately sandy texture is often left as rangeland in this region if irrigation is not present.

Annually, the semi-arid CGP region receives between 350-500 mm of rainfall (Anderson, 2005a). On the east side of the region rainfall is significantly higher than the west (Nielsen et al., 2018). This is due to the Rocky Mountain's rain shadow effect over the western portion of the CGP. Additionally, from northeast to southwest, there is an increase in evaporative

loss due to escalating temperatures. The moisture flow from the Gulf of Mexico under the influence of the Great Plains Low Level Jet stream, is a major influence on weather patterns in the High Plains region as well. The Great Plains Low Level Jet stream is a fast-moving air flow that transports moisture and warm weather from the Gulf coast throughout the Great Plains region (Nielsen et al., 2018). With low precipitation levels in the west and high evaporative loss, continuous cropping is a challenge, thus making a fallow period necessary to meet grain yield goals. A fallow period is a part of the cropping cycle designed for areas of limited precipitation in the Great Plains, intended to store water and mitigate risk of crop failure for the next growing season (Holman et al., 2021).

Historically, much of CGP dryland agriculture depended on a two-year, winter wheat (*Triticum aestivum* L)-fallow rotation (Peterson and Westfall et al., 2004). This region has a mesic temperature regime, which favors winter wheat over spring wheat production (Carr et al., 2020). The warmer climate allows for wheat to overwinter, form tillers, and mature before high summer temperatures cause heat stress, creating higher yield potential. Spring wheat tillering and grain fill is often shortened by high temperatures in this climate. Growing winter wheat in the winter during a lower evaporative demand period, enables it to avoid a time of the year when moisture stress is greatest. Winter wheat growth period, drought tolerance, and production of residue cover, makes it a desired base crop for CGP rotations. Typically, after winter wheat is harvested, fields enter a 12 to 14-month fallow period (Peterson and Westfall et al., 2004).

Approximately 75% of annual precipitation occurs between April and September, during high temperatures and low relative humidity. Potential evaporative loss exceeds precipitation in most months of the year (Peterson and Westfall et al., 2004). In studies conducted by Peterson et al., (1993, 2001) in eastern Colorado, annual rainfall ranged between 400-450 mm, while

evapotranspiration ranged between 1600-1975 mm during the cropping season. The intention of the fallow period is to accumulate water in the soil profile for the following grain crop, but due to climate conditions in the CGP water storage is inefficient. Depending on how much crop residue cover is retained on the top soil and which tillage practice is implemented, fallow moisture retention efficiency ranges between 20-35% of total precipitation received. When analyzing a 14-month fallow period in a winter wheat-fallow system at a monthly level, fallow begins to have a negative impact on precipitation storage at the 10-month mark (Peterson and Westfall et al., 2004). The first 10-months of the fallow period has substantially more residue cover, moderate temperatures, and dry soil creating desirable conditions for precipitation storage. In the additional 4 months of the fallow period, there is not as much residue cover, temperatures are very high, and the soil profile is at field capacity, creating undesirable conditions for precipitation storage. In a Colorado study, mean precipitation storage efficiency during a 14-month fallow in a wheat-fallow system was 20% for conventional tillage and 35% for no-tillage (Nielsen and Vigil, 2010).

The traditional method of weed control when managing fallow in the CGP has been by conventional tillage methods (Peterson and Westfall et al., 2004). Conventional tillage leaves essentially no crop residue on the surface of the soil. With little to no surface cover, water evaporation is drastically accelerated, and less moisture is retained during the fallow period. During tillage, soil macro pores are reduced, therefore reducing water infiltration as well (Kirkham, 2023). When infiltration is reduced, the potential for soil runoff is increased. Fracturing soil capillaries also makes crops less resilient to freezing temperatures. The heat from ground water rises through soil capillaries, and can prevent a crop from freezing, but if they are fractured that heat cannot reach the plant (Kirkham, 2023). Fracturing of capillaries is not the

only physical property of soil that is disturbed during tillage. Tillage also reduces aggregate size, mean weight diameter of water stable aggregates and increases wind erodible soil fraction. (Obour et al., 2021b).

The reduction in soil aggregate size, reduced infiltration, and the lack of crop residue on the field after tillage has the potential to increase soil erosion rates, decrease grain yields, and increase fertilizer loss (Veresoglou et al., 2023). The Dust Bowl exposed how detrimental reducing soil particle size can be for erosion. The Dust Bowl was a decade of rainfall deficits, and high temperatures, coupled with extreme dust storms during the 1930s (Schubert et al., 2004). Extreme dust storms from the Dust Bowl resulted in one of the most severe environmental catastrophes in the history of the United States. Soil particles were reduced because of intensive deep tillage, which also reduced soil cover, leaving the soil surface exposed to wind erosion. This period exposed how fragile dryland ecosystems are and is the reason why much of the soil-based research done in the CGP region includes building resilience to extreme climate related shifts and reducing soil's vulnerability to wind and water erosion (Farooq and Siddique, 2016).

Although intensive tillage has a negative impact on soil physical properties and processes, reducing tillage with occasional tillage (OT), strategic tillage (ST), or no-till can help maintain soil properties when compared to intensive tillage (Schlegel et al., 2020; Obour et al., 2021b; Holman et al., 2023b). Occasional tillage is a single tillage pass every three years during the fallow phase prior to wheat, while ST is a single tillage pass prior to wheat only when there is a population of weeds that cannot be eliminated with an herbicide pass. Reducing tillage passes with only one pass every three years, or only tilling when weeds are out of control can also help maintain desired grain yields and available soil water (ASW) for the following crop. Obour et al. (2021b), Schlegel et al. (2020), and Holman et al. (2023b) observed no significant ASW losses at

time of wheat planting, or wheat grain yield losses when ST or OT systems were compared to no-till. While a more intensive tillage system, three passes every three years, during the fallow phase did reduce ASW and grain yields when compared to ST and no-till systems. No-till ASW averaged 336 mm of water across rotations, while the more intensive tillage system averaged 306 mm of ASW across the same rotations (Obour et al., 2021b). The extra soil water storage due to conservation tillage allows the potential to intensify cropping systems with an additional crop.

Usefulness of Intensified Crop Rotation

The winter wheat-fallow (W-F) rotation leaves minimal soil cover on the surface, and allows for an extended period of exposed soil. The limited residue inputs from W-F results in low soil organic matter content, when compared to more intensive cropping systems. Regardless of tillage practice, limited organic matter has the potential for numerous negative effects on soil health (Peterson and Halvorson et al., 1998). Not only is the two-year cropping system inefficient in maintaining soil health, it is also inefficient in managing weeds. In a study done by Nikolic et al. (2018), looking at rotation intensity effect on weed density in wheat-based systems, the two-year WF rotation had the highest weed density. This two-year rotation had 2963 weeds per m^{-2}; compared to just 40 weeds m^{-2} in a three-year crop rotation. In the same study, the authors reported that the WF rotation had the lowest diversity of weed species. According to Nikolic et al. (2018), annual weed species align to specific annual crop growing seasons. Growing solely winter wheat will promote winter annual weeds, such as downy brome (*Bromus tectorum L.*) or jointed goat grass (*Aegilops cylindrica*). With minimal species continuously present at an abundance, there is also risk of creating herbicide resistance in a no-till system through heavy reliance on specific herbicides. Creating resistance within the weed species causes herbicide costs to rise, and may necessitate implementing mechanical weed control methods.

Within the last thirty years, the majority of producers in the CGP region have shifted away from WF towards a more intensified wheat-based system. Conserved water from no-till and reduced tillage (RT) systems has made it possible for more intensive cropping rotations (Holman et al., 2018; 2022; Peterson and Halvorson et al., 1998). The most common three-year rotation utilized in the region is W-summer crop-F (WSF). This rotation allows for a crop to be planted annually on 67-100% of production acres (Dhuyvetter et al., 1996). The primary summer grain crops grown in the region are grain sorghum (*Sorghum bicolor Moench*) and corn (*Zea mays L.*) (Assefa et al., 2014; Holman et al., 2022; Schlegal et al., 2016). The WSF rotation has shifted fallow so a crop is in place more often during high precipitation months, and has reduced the fallow period from 15 to 11 months (Holman et al., 2018). The WSF rotation has increased residue input, efficient water use, and improved soil properties when compared to WF (Baumhardt et al., 2015; Holman et al., 2022). Intensive crop rotations coupled with no-till can build carbon reserves in the top 5 cm of the soil within 10 years when compared to less intensive systems that utilize intensive tillage (Halverson et al., 2002). Within the semi-arid portion of the Great Plains, grain sorghum is typically preferred over corn production in dryland conditions. Grain sorghum has a vast root system that penetrates the soil 2.5-3 m, almost twice the depth of a corn root (1.5 m) (Assefa et al., 2014). Extended root exploration in soil allows grain sorghum to reach soil moisture that corn cannot. Grain sorghum also has much shorter above-ground stature than corn, requiring less water for biomass production and saving more soil water for grain fill. Collectively, these characteristics contribute to greater productivity of grain sorghum compared with corn in three-year rotations in the region (Assefa et al., 2014).

Not only is a more intensified system better for weed management and soil health, but there is also an increase in profitability. According to Dhuyvetter et al. (1996), seven of eight

studies reported that net returns were greater from a more intensive crop rotation than from WF when no-till or reduced tillage systems were used following wheat harvest and prior to the summer crop planting. Schlegel et al. (2002) reported the most profitable three-year rotation utilizing grain crops in the CGP was W-GS-F. Although, in that same study, the rotation with the highest return overall was actually a four-year W-GS-GS-F rotation. The W-GS-GS-F rotation yielded a net return of $95 per hectare, while the three-year W-GS-F rotation yielded a net return of $92 per hectare without crop insurance consideration. Holman et al. (2022) conducted a similar study that compared W-GS-F to more intensified systems that replaced the summer grain crop with summer forage sorghum (FS). A rotation of W/FS-FS-fallow was the highest-yielding rotation. These findings showed opportunity exists to potentially intensify CGP dryland systems even further. With the intensified cropping systems, there is still a 11-15-month fallow period in which 35% of precipitation is maintained in best case scenarios. An additional way to reduce the fallow period and improve soil properties in the CGP might be to add a cover crop into the rotation during fallow.

Cover Crop Benefits for Soil Properties

Cover crops have the potential to improve soil properties in semi-arid soils. The adoption of CCs can increase carbon storage, soil aggregation, reduce soil's susceptibility to wind and water erosion, reduce compaction, and improve nutrient cycling (Burke et al., 2022). However, in drought conditions when cover crop biomass is severely limited, soil properties may not differ when compared to fallow (Simon et al., 2022). Common CCs grown within the CGP region are oat (*Avena sativa L.*), rapeseed (*Brassica napus L.*), pea (*Pisum sativum* ssp. *arvense L.* Poir), foxtail millet (*Setaria Italica*), medic (*Medicago*), rye (*Secale cereale*), turnip (*Brassica rapa*), barley (*Hordeum vulgare L.*), hairy vetch (*Vicia villosa Roth*), radish (*Raphanus sativus*), forage

sorghum (*Sorghum bicolor*), sorghum x sudan (*Sorghum* × *drummondii*), and triticale (×*Triticosecale Wittm.*) (Nielsen et al., 2015; Holman et al., 2018).

In a five-year study conducted in the CGP, five different cover crops of hairy vetch, winter triticale, winter lentil, spring lentil, winter pea, spring pea, and spring triticale were planted during the fallow period to compare to a W-F and continuous wheat crop rotations under no-till management (Blanco-Canqui et al., 2013; Holman et al., 2018). Winter and spring triticale increased SOC levels by 2.8 Mg ha^{-1}, and spring lentil increased SOC levels by 2.4 Mg ha^{-1} in the top 7.5 cm of soil compared to fallow. Spring triticale as well as spring lentil increased soil aggregate size distribution. Both species increased the MWD of water stable aggregates by 1.6 times compared to fallow. Spring lentil also reduced wind erodible fraction by 1.8 times compared to fallow. This information indicates that cover crops have the ability to reduce the soil's susceptibility to wind erosion. Increases in SOC relate to formations of aggregates, therefore reducing erodibility. Although there were positive effects on soil properties by cover crops, those effects were short lived. Just nine months after termination of the cover crops, there were no effects observed across treatments.

Cover crops are also a player in eliminating compaction. Compaction has occurred due to decades of heavy equipment and tillage implements passing over soil, creating compaction layers. Compaction can reduce plant growth, yield, and reduce water and nutrient movement throughout the soil. At a bulk density of 1.60 g cm^3 root growth is limited in silt-loam soils (USDA-NRCS, 2022). In a term called "bio-drilling" actively growing plant root systems have the potential to ameliorate subsoil in poor physical condition (Cresswell and Kirkegaard, 1995). Tap rooted CC species can alleviate compacted soils better than fibrous root species (Chen and Weil, 2009). A study by Chen and Weil (2009) showed that the increased diameter of taproot

species penetrated compacted layers better than thin diameter fibrous root species. Tap root species were twice as long as species with fibrous roots in highly compacted soils, with a bulk density ranging from 1.5-1.75 g/cm^3 in the top 45 cm of the soil. In medium compacted layers, taproots were 1.5 times as long, and in non-compacted areas, tap root length was similar to fibrous root covers. Tap rooted CCs can provide low-resistance pathways for subsequent crops in highly compacted soils. The effect of CC root channels on soil compaction in a soybean crop were analyzed, and in dry highly compacted soils, a CC mixture of forage radish and rye resulted in a significantly greater soybean yield (Williams and Weil, 2004). The increase in yield was primarily due to soybean plants' ability to fill root channels left by the CC and reach soil moisture and nutrients the crop would not have been able to access otherwise.

Improving soil physical properties with CCs can lead to improved nutrient cycling. Increasing soil aggregate size and improving soil structure reduces total nutrient loss through wind and water erosion (Blanco-Canqui et al., 2013). According to the Blanco-Canqui et al. (2013) study, the total loss of phosphorus (P) and NO_3-N in runoff are 3.4- 4.2 times greater in fallow compared to winter triticale and spring pea CCs after termination. The enhanced soil microbial community typically associated with a healthy soil accelerates the breakdown of CC plant biomass back into crop-available nutrients (Acosta-Martínez et al., 2007). Leguminous CCs have the potential to reduce nitrogen fertilizer requirements and improve nitrogen availability compared to fallow for the succeeding grain crops (Mahama et al., 2016). The addition of nitrogen through leguminous CCs might also reduce nitrogen fertilizer expense.

Cover crops can also act as nutrient miners. In a study done by Hallama et al. (2019), total P was increased in systems that were previously low in P. This was accomplished by the cover crop's ability to access previously unavailable P pools within the soil. Many have also

found conflicting results for CC effects of P levels. Although CCs reduced P losses by reducing erosion, they were not shown to be consistent in their ability to replace sound P fertilizer stewardship and sub-surface P replacement (Nelson et al., 2022; Bourns et al., 2023; Carver et al., 2022). Each study highlighted the importance of cover crop's ability to reduce P losses through run-off, but in years with limited erosion rates, CCs increased P losses when compared to fallow. Making CCs an effective site-specific management tool that can help reduce P losses. Outside of CCs ability to be beneficial for soil properties and processes, they can also serve as an additional weed suppressant.

Cover Crops as Weed Suppressants

Improving soil properties and reducing soil erosion is a major advantage of CC use, but CCs can be beneficial in weed management as well. As herbicide resistant weeds become more prevalent and effective herbicide options becomes fewer, the more alternative weed control methods, such as CCs, will gain importance. If producers can no longer effectively control weeds within their no-till systems, then the increased water storage efficiency of no-till is obsolete. Without effective herbicides, the only other options to control weeds are to use tillage, or utilize a more intensified cropping system to compete with weeds (Schlegel et al., 2020; Obour et al., 2021b; Holman et al., 2023b).

Cover crops can reduce weeds by utilizing an ecologically based weed management system. Ecological weed control emphasizes cultural tactics that enhance natural loss of weed seeds in soil with reduced use of herbicides (Anderson, 2005b). Typically, the most impactful time to grow a CC for weed suppression is during the 11-15-month fallow period, because weeds are the most prevalent, there is no crop competition with weeds, and herbicide cost is the highest during this time period. Herbicide cost is highest at this time because of the frequent passes

required to keep fallow clean. Cover crops not only reduce weed density, but can help save cost during the fallow period by reducing the number of herbicide applications. Determining which growing season to implement CCs might be determined by what season the most troublesome weeds are in. For example, if palmer amaranth (*Amaranthus palmeri*) (summer annual) is most challenging, then planting a summer cover crop during the fallow period could improve weed control. If downy brome (winter annual) is most challenging, then planting a winter cover crop could help improve weed control. Growing a cover crop must also consider impact on soil water, subsequent grain crops, and profitability in addition to weed control.

Methods of weed control by cover crops can either be through competition, smothering, and potential allelopathic activity (Petrosino et al., 2015; Osipitan et al., 2018; Mirsky et al., 2013; Hutchinson and McGiffin, 2000; Kunz et al., 2016). With competition, the cover crop competes with weeds for nutrients, light, and water, smothering is the ability of cover crop residues to shade out weed seeds/seedlings, and allelopathic activity is cover crop influence on a plant's biochemical communications that influence its ability to grow and develop.

In a cover crop weed suppression study conducted in south-western Kansas in a W-F system, fall sown cover crops Austrian winter pea, hairy vetch, and winter triticale were compared to a chemical fallow system. Among those species, triticale alone and specie mixtures that included triticale reduced kochia density by 78-94% and kochia biomass by 98% when compared to chemical fallow (Petrosino et al., 2015). Austrian winter pea and hairy vetch also reduced kochia populations when compared to chemical fallow. Spring-sown cover crops spring lentil, spring pea, and spring triticale had little to no effect on kochia density, because of similar emergence timing. The Fall-sown cover crops produced significantly more biomass before kochia emergence, leading to greater suppression.

Cover crop mixes with predominantly grass species can have a greater impact on suppressing weed density. The attributes that grass species possess make them more competitive for resources. Total biomass is generally increased when grass species are utilized within cover crop mixtures (Holman et al., 2018). In a review paper by Silva and Bagavathiannan (2023), analyzing rye cover crop studies throughout the United States, rye cover crops produced between 0.9-20-ton ha^{-1} depending on precipitation under which it was grown (Silva and Bagavathiannan, 2023). On the higher end of rye biomass production, 100% weed suppression can be achieved during the growing season and for a period after termination. To the contrary, in a study conducted in three different counties in Kansas looking at a wheat cover crop's effect on pigweed density and biomass, the cover crop treatment had greater or equal amount of pigweed biomass and density at two out of the three locations when compared to herbicide treatments (Hay et al., 2019). Regardless, amounts of residue left over can be beneficial to soil properties, water storage, and weed suppression, but in semi-arid conditions the water usage from producing greater cover crop biomass can be a detrimental to the subsequent grain yield.

Cover Crop Water Use and Yield Impact

In semi-arid dryland environments like the CGP, producers are hesitant to adopt cover crops into their rotations. The cause of this hesitancy is due to limited and highly variable precipitation, and the effect of cover crop water use on available plant water for subsequent grain crops. With herbicide-resistant weeds becoming more prevalent and using soil water during the fallow phase, producers should consider cover crops and their water use.

In a study by Burke et al. (2022) in the Texas High Plains, no-till with a single species rye cover and a no-till multi-species cover were compared to fallow. The cover crops depleted soil water content in the soil before cotton planting, but precipitation interception and water

storage were improved post cover crop. The residue cover provided by the cover crop shaded the soil surface, therefore retaining more soil moisture and reducing evaporation. As a result, cotton lint yields were unaffected by the cover crop treatments. In western Kansas, Holman et al. (2020) evaluated available soil water at planting, performance, management, post-cover crop fallow efficiency, and available soil water at wheat planting of 12 short season cover crops (hairy vetch, lentil, Austrian winter pea, triticale, hairy vetch–triticale, winter lentil–triticale, and winter pea–triticale, lentil, field pea, triticale, spring lentil–triticale, and spring pea–triticale) and the effect in Garden City, KS. Spring planted species had more plant available water at planting, but post-cover crop fallow efficiency, water use, and productivity were greater for sole winter triticale and legume-triticale mixtures. The authors concluded that cover crops left standing stored 4-27% more soil water when compared to hayed cover crops, but hayed cover crops could provide a dual-purpose and economic benefit to the overall system. In that study, cover crop biomass produced had a negative linear relationship with available soil water at wheat planting. Indicating that wheat yields are likely reduced when cover crop biomass is increased.

Other studies indicate that cover crops reduce plant available water for subsequent grain crops when compared to no-till fallow in the CGP and decrease succeeding grain yield. A study conducted by Nielsen et al. (2016a) in Colorado and Nebraska showed a 10% decrease in wheat yield after cover crop compared to no-till fallow. Available water was greater in fallow compared to cover crop treatments. A similar study by Obour et al. (2022a), conducted in western Kansas, found an 18% reduction in wheat yields following spring planted cover crops when compared to no-till fallow. A meta-analysis suggested that cover crops are more suited for humid and sub-humid regions where precipitation is more reliable than semi-arid climates (Unger et al., 1998). The same study indicates that the effect on subsequent crop yield far

outweighs the potential benefits that cover crops provide in semi-arid climates. When cover crops are not utilized as a forage, similar conclusions can be made for much of the CGP (Holman et al., 2018; Holman et al., 2020; Holman et al., 2021; Obour et al., 2022a).

With some studies showing positive and some negative effects on grain yield, farmers remain hesitant. One way to mitigate hesitancy is to plant a cover crop in years that have adequate soil moisture, and a favorable climate outlook. This method is known as flex-cover cropping. Flex-cover cropping might help mitigate negative effects to grain yield in dry conditions. However, the unpredictability of long-range weather forecasting limits the accuracy of flex-cover cropping (Holman et al., 2018). Determining the correct time for termination is also useful in saving soil moisture, thus preserving subsequent crop yield (Nielsen et al., 2015; Sivoma and Gantzer, 2016; Holman et al., 2018; Holman et al., 2020; Holman et al., 2021; Obour et al., 2022a). If the cover crop reaches maturity more soil moisture will be used compared to when termination occurs during vegetative stages or at heading. Utilizing these vegetative stages as forage for livestock is also a path forward. Making use of cover crops as forage can mitigate cost of the cover crop, as well as economic loss associated with the subsequent grain crop.

Grazing Cover Crops

Many producers in the CGP were once diversified as both crop and livestock producers. Within the last 60 years, the majority of producers are now specialized as producing either crops or livestock (Russelle et al., 2021). This specialization is primarily driven by economies of scale and enabling technologies such as no-till farming and chemical fertilizers (Macdonald and McBride et al., 2009). The increase in specialization has caused an increase in conversion of grassland to cropland that raises concerns of degradation and pollution of natural resources

(Anderson et al., 2021; Russelle et al., 2007; Sulc and Tracy, 2007). A way to combat this would be to re-integrate livestock into cropland through cover crop grazing.

Cover crop grazing may allow for grasslands to receive needed rest, particularly in extreme drought years, provide high nutritive value feed and additional forage for revenue (Obour et al., 2021a). Many of the species promoted and utilized as cover crops can serve as excellent forage for livestock grazing (Sulc and Franzluebbers, 2013). Producers have shown hesitancy towards grazing cover crops primarily because of the high cost to acquire livestock, and water and fence infrastructure. Many also fear the effect grazing may have on soil properties such as compaction and residue cover.

A way to mitigate negative effects on soil properties would be to manage grazing intensity and duration. Managing grazing intensity is important because high grazing intensity may increase the potential for soil roughness in wet conditions, compaction, and soil erosion (Blanco-Canqui et al., 2021). When grazing grasslands, a conservative general rule of thumb is to graze 31-50% of available forage (Holechek and Galt, 2000). Leaving at-least 50% of cover crop residue remaining after grazing helps conserve croplands (Simon et al, 2021; 2022). The total amount of forage produced from cover crops is highly variable from year to year, so having a flexible herd size where animals can be added or subtracted is important to maintaining adequate residue cover (Obour et al., 2021a).

Determining the right cover crop species to plant for grazing is important. Producers should choose species that will benefit soil health, while also being palatable and safe as a forage for livestock (Johnson et al., 2020). Some cover crops such as hairy vetch (*Vicia villosa*) and lupin (*Lupinus perennis L*) species have poisonous traits that can be toxic to livestock, so avoiding high rates of hairy vetch in forage mixtures is important for maintaining animal health.

A two-year study conducted on ten producer fields in Colorado, western Kansas, and western Nebraska where cover crops were grazed found that grazing had no negative effect on soil properties (Kelly et al., 2021). Cover crops un-grazed and grazed had the same diminishment to wheat yield (20%) compared to no-till fallow. The researchers concluded that carefully managed grazing of cover crops may provide a potential avenue to diversify farm economics (Kelly et al., 2021) and offset the cost of growing the cover crop.

Similarly, research conducted in Watkinsville, Georgia within a cotton no-till system, showed grazing a rye cover crop with beef cattle (*Bos taurus*) offset the cost of planting the rye cover crop (Schomberg et al., 2014). The authors reported that the un-grazed treatment left 6.7 Mg ha^{-1} of rye residue remaining at cotton planting annually compared to 1.7 Mg ha^{-1} after grazing. Despite the differences in forage biomass, there were no differences in soil properties observed until the final year, where compaction was higher among grazed treatments. Differences between grazed and non-grazed returns ranged from \$-26 to \$355 ha^{-1}, respectively (Schomberg et al., 2014).

Net returns of four different scenarios utilizing cover crops as forage either as harvested hay or grazing were analyzed by Higgins (2017). The four scenarios were: 1) a mixed crop and livestock producer who owns a herd of cattle and has both cows and calves available to graze corn stover and cover crops; 2) a crop grower purchases stocker cattle to graze corn stover and cover crops; 3) a crop grower leases out corn stover and cover crop field to livestock producer (and provides value added services for a fee); and 4) an integrated operation with crops and cattle where cover crops are not grown, but harvested as hay and fed to cattle during the winter months. Utilizing stocking rates of 75-100 animals per 100-acre field, scenario 3 had the greatest potential for economic return. Scenario 3 had the least amount of risk for the crop farmer. In this

scenario, crop residue was rented for $9.00 an acre, a livestock management fee was charged at $0.875 per head/day, and all services provided for grazing were paid for. If scenario 3 was implemented on a 100-acre field with 75 head for 30 days, that would have generated a revenue of $2,934. This dollar amount could potentially cover costs of growing the cover crop, and offset potential grain yield loss of the succeeding crop. Not only may grazing cover crops reduce economic risk to grain production, but it can reduce fertilizer costs through the ability of ruminant animals to accelerate the breakdown of cover crop residue. This makes essential crop nutrients more plant available for the succeeding grain crop in the rotation.

Grazing Enhances Nutrient Cycling

Grazing cover crops with ruminant livestock can accelerate nutrient cycling. Manure (excrement of ruminant livestock) has the ability to decrease the carbon to nitrogen (C:N) ratio in the soil (Sommerfeldt et al., 1988). The lower the C:N ratio the more plant available nitrogen becomes. Plant material passing through the rumen of livestock may accelerate the breakdown of plant material and make nutrients plant available quicker than the microbial residue decomposition (Singer and Schoenecker, 2003). Nutrient cycling is not only important for N, but is vital for P. Though there is an extreme energy cost, we can fix N from the air using the Haber Bosch process in order to create ammonia fertilizers, but P is a limited resource (Dawson and Hilton, 2011). Phosphorus fertilizer is mined from phosphate rock, and is then processed into fertilizer (Drangert, 2012). In plants, P is a non-substitutable nutrient, so reusing and recycling P is important to sustaining agriculture. Fortunately, plants are efficient in their P use, and when P is properly reused and recycled it can become essentially limitless (Drangert, 2012). The manure from grazing with ruminant livestock is a great source of reused/recycled P. Grazing can also accelerate residue break down by trampling of plant material. When cattle graze, much of the

plant material available is trampled, and pressed into the soil surface. When the residue is pressed into the surface of the soil the process of breaking down that plant residue is accelerated. because the natural process of residue falling to the soil surface, which may take months, is sped up.

Although grazing has the potential to accelerate the breakdown of plant material, nutrients are still lost with grazing. Every nutrient in the plant will not be returned to the soil. Virgona et al. (2006), showed that when crop residue is grazed compared to non-grazed, the non-grazed soils have a higher concentration of nitrogen. Simon et al. (2021; 2022) found that soil nutrients were not decreased in grazed CCs when compared to ungrazed. The animal utilizes a portion of the nutrients within the plant to build muscle, and for other metabolic functions. Nutrients are also lost through detachment of residue from the soil surface, causing it to blow or wash away. Cattle also return a portion of leaf material nutrients that would have blown away during decomposition back to the soil through grazing and manure deposition.

Grazing at a later stage in the cover crop's life cycle could accelerate the loss of residue as well, because regrowth is less of a possibility later in the crop's life cycle. This conflicts with the primary goal of planting a cover crop to maintain a layer of residue cover over the soil surface. Implementing livestock grazing at a vegetative stage where regrowth is still a possibility is important to maintaining adequate residue cover. Annual forages can be used for grazing or for haying. Grazing as previously mentioned helps accelerate nutrient cycling and allows for vital nutrients to be reused and recycled, while haying leaves limited plant residue. The removal of plant residue also removes nutrients from the soil, but haying annual forages at vegetative stages where regrowth is possible can help mitigate those negative effects.

Utilizing Annual Forages

The difference between an annual forage and a cover crop comes down to the intended purpose of the crop. If the intended purpose of intensifying a system with a crop is for environmental stability, then a producer is utilizing cover crops. If the intended purpose of intensifying a system with a cultivar is to boost production and profitability, then you are utilizing an annual forage. Annual forages can provide similar soil health benefits that cover cropping provides, while not using the water that grain crops use. Intensifying systems with annual forages can shorten the 11-15-month fallow window, increase water use efficiency, improve soil properties, and provide additional income through haying or grazing (Anderson et al., 2021). Adding annual forages into grain-based systems makes cropping systems more dynamic by improving crop production resilience and providing protection against climate extremes (Simon et al., 2021; 2022; Holman et al., 2022). The unpredictive climate of the CGP makes grain crops very risky. With grain crops, plant maturity is required. This leads to short planting and harvesting times. Because annual forages are harvested for biomass, planting and harvesting dates can be more subjective. This allows for the producer to choose the most optimum time to plant and harvest. With forages not requiring the entire growing season for production, water in the soil water profile is saved for the following grain crop.

Annual forages can be utilized in the spring or summer months. Significant forage producers in the CGP in the spring months would be spring triticale, and spring oat. In a study by Schomberg et al. (2014), rye produced 9.1 Mg ha^{-1} in a no-till cotton system in Watkinsville, Georgia. The primary summer forage in the CGP is forage sorghum or sorghum x sudan. In a study by Holman et al. (2019), forage sorghum produced a maximum yield of 6.5 Mg ha^{-1} in western Kansas. With such significant production it makes annual forages a viable option to

increase revenue and diversify current rotations in the CGP (Holman et al., 2022). With the majority of precipitation occurring during the summer months, a summer annual forage may be the most stable production option. Rye may have potential to produce a lot of biomass, but dry winters can limit the ability of a winter and spring forage to establish and produce.

Haying is the most common way to harvest annual forages. With haying there is concern that removing residue will negatively impact soil properties. Haying can remove up to 73% of available forage (Simon et al., 2021). Removing residue may negate the positive soil impacts of intensifying cropping systems, and could possibly increase soil erosion and soil compaction. However, a 5-year study in western Kansas showed that haying forages had no impact on bulk density or penetration resistance when compared to forages that were grazed or left as cover (Simon et al., 2021). In the same study, aggregate MWD was increased in hayed forage treatments compared to fallow treatments. Grazing annual forages also showed an increase in MWD when compared to fallow. The results of this study indicate that haying and grazing annual forages may not have the negative soil property impacts that were previously thought. Compared to fallow, grazing and haying even enhanced the soils ability to resist erosion.

In wet years, annual forages can significantly increase a system's production and profitability. In dry years, adding annual forages may significantly reduce grain production. Utilizing annual forages in CGP systems can be treated much like the flex-cover cropping method (Holman et al., 2023a). Sampling soils using a Paul Brown soil water probe ensuring at least 30 cm of available soil water in the top 180 cm (Brown, 1960; Obour et al., 2022b), as well as utilizing the National Weather Service Seasonal Outlook for the fallow period (NOAA, 2024) before planting can help determine if the conditions are favorable enough to support an annual forage in that year. When moisture is greater than 30 cm in the profile, annual forages have little

to no impact on the succeeding grain crop. Some producers in the CGP have totally abandoned the use of summer grain crops, and have moved to producing summer annual forages in a winter wheat-based system. In years when the demand for forage is high, growing a summer forage instead of a summer grain crop may boost system profitability and preserve soil water for winter wheat production.

Annual Forage Production vs. Grain Production

The growing season for annual forages is significantly shorter than that of grain crops. Winter wheat growing season from planting to maturity is approximately 9 months, with planting occurring in late September to early October, and harvest occurring in late June to early July in Kansas. Grain crops grown during the summer season from planting to maturity is approximately 5-6 months, with planting occurring in early April-June and harvest occurring in October. An annual forage growing season can be as short as 3 months. A summer forage sorghum can be planted in May-June and harvested in August, and with adequate regrowth, a second harvest in October. The short growing season of an annual forage allows for early summer rains to have more of an impact on total forage production, than early season rains would have on total grain yield for a summer grain crop. Inclusion of forages could potentially stabilize yields under variable precipitation conditions. Nielsen et al. (2010) showed that dry conditions have less of an effect on biomass production than they do on grain production.

Utilizing forage crops instead of grain crops can potentially boost profitability. In a study by Nielsen et al. (2005), continuous forage rotation (14.5 kg ha^{-1} mm^{-1}) far out produced continuous grain rotation (2.8 kg ha^{-1} mm^{-1}) for each mm of precipitation. On a price-received basis, forage production (\$1.20 ha^{-1} mm^{-1}) was greater than grain production (\$0.30 ha^{-1} mm^{-1}). In another study conducted by Nielsen et al. (2016b), utilizing a summer forage crop instead of a

summer grain crop in a three-year winter wheat-summer crop-fallow rotation was seen as more profitable. Flexing the fallow period with an additional forage crop in the rotation was also seen as a potential way to boost profitability. The downside to producing an abundance of forage is that the market can easily become saturated, and pricing is highly variable compared to grain production. The best approach a producer can take is to be flexible, and willing to substitute grain for forage or vice versa when soil moisture is adequate, weather outlook is favorable, and potential return is adequate.

Hypothesis and Objectives

Our hypothesis is that intensifying rotations with annual forages (by grazing or haying) will have neutral or positive impacts on soil residue cover, soil organic carbon, aggregate mean weight diameter, compaction indicators, nutrient cycling, available nitrogen and phosphorus, water use efficiency, system production, and profitability when compared to less intensive cropping systems. Furthermore, we hypothesize that increasing grazing intensity of forages will increase system productivity by increasing amount of biomass removed, while having a minimal impact on soil health indicators (penetration resistance and bulk density, wet and dry-aggregate mean weight diameter, soil organic carbon, particulate organic matter, nitrogen, phosphorus, pH, and soil time-to-runoff) as well as subsequent grain yields.

The objectives of this research are to:

(i) evaluate soil health impacts of intensifying the traditional winter wheat-sorghum-fallow rotation with annual forages and cover crops;

(ii) asses the effects of grazing and haying cover crops, annual forages, and grain-sorghum stalks on soil health; and

(iii) estimate the economic returns of producing an annual forage compared to a grain crop in an intensified crop rotation.

References

Acosta-Martínez, V., Mikha, M. M., and Vigil, M. F. (2007). Microbial communities and enzyme activities in soils under alternative crop rotations compared to wheat–fallow for the Central Great Plains. Applied Soil Ecology, 37(1–2), 41–52. https://doi.org/10.1016/j.apsoil.2007.03.009

Anderson, R. L. (2005a). Improving Sustainability of Cropping Systems in the Central Great Plains. Journal of Sustainable Agriculture, 26:97-114. doi: 10.1300/J064v26n01_08

Anderson R. L. (2005b). A multi-tactic approach to manage weed population dynamics in crop rotations. Agronomy Journal, 97:1579-1583. doi: 10.2134/agronj2005.0194

Anderson, L. K., Blanco-Canqui, H., Drewnoski, M. E., MacDonald, J. C., Carlson, Z., Hansen, B. H., Brinton, M. M., Ulmer, K. M., and Calus, K. J. (2021). Cover crop grazing impacts on soil properties and crop yields under irrigated no-till corn-soybean management. Soil Science Society of America, 86:118-133. doi: 10.1002/saj2.20358

Assefa, Y., Roozeboom, K., Thompson, C., Schlegel, A., Stone, L., and Lingenfelser, J. (2014). Rotation effect of corn and sorghum in cropping systems. In Corn and grain sorghum comparison: All things considered. Academic Press, New York. pp. 87-101.

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

Blanco-Canqui, H., Holman, J.D., Schlegel, A.J., Tatarko, J., Shaver, T.M. (2013). Replacing Fallow with Cover Crops in a Semiarid Soil: Effects on Soil Properties. Soil Science Society of America, 77:1026-1034. https://doi-org.er.lib.k-state.edu/10.2136/sssaj2013.01.0006

Blanco-Canqui, H., Drewnoski, M.E., MacDonald, J.C., Redfearn, D.D., Parsons, J., Lesoing, G.W., Williams, T. (2021). Does cover crops grazing damage soils and reduce crop yields? Agrosystems, Geosciences & Environment, 3(1), 1–11. https://doi.org/10.1002/agg2.20102

Brown, P. L. (1960). You can predict yields, plan fertilizer applications by use of a soil moisture probe. Montana Farmer-Stockman, 47:9.

Burke, J. A., Lewis, K. L., DeLaune, P. B., Cobos, C. J., and Keeling, J. W. (2022). Soil water dynamics and cotton production following cover crop use in semi-arid ecoregion. Agronomy Journal, 12:1306. https://doi.org/10.3390/agronomy12061306

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

Carr, P. M., Bell, J. M., Boss, D. L., DeLaune, P., Eberly, J. O., Edwards, L., Fryer, H., Graham, C., Holman, J., Islam, M. A., Liebig, M., Miller, P. R., Obour, A., Xue, Q. (2020). Annual forage impacts on dryland wheat farming in the Great Plains. Agronomy Journal, 113:1-25. doi: 10.1002/agj2.20513

Chen, G., and Weil, R. R. (2009). Penetration of cover crop roots through compacted soils. Springer Link, 331:31-43. https://doi.org/10.1007/s11104-009-0223-7

Cresswell, H.P., and Kirkegaard, J.A. (1995). Subsoil amelioration by plant-roots – the process and the evidence. Agronomy Journal of Soil Research, 33:221-239. https://doi.org/10.1071/SR9950221

Dawson, C. J., and Hilton, J. (2011). Fertilizer availability in a resource-limited world: Production and recycling of nitrogen and phosphorus. Food Policy, 36:S14-S-22. https://doi.org/10.1016/j.foodpol.2010.11.012

Dhuyvetter, K. C., Thompson, C. R., Norwood, C. A., and Halvorson, A. D. (1996). Economics of dryland cropping systems in the great plains: a review. Journal of Production Agriculture. https://doi-org.er.lib.k-state.edu/10.2134/jpa1996.0216

Drangert, J. O. (2012). Phosphorus – a limited resource that could be made limitless. Science Direct, 46:228-233. doi: 10.1016/j.proeng.2012.09.469

Farooq, M., K. and Siddique, H. M. (2016). Innovations in dryland agriculture. Springer. doi: 10.1007/978-3-319-47928-6

Hallama, M., Pekrun, C., Lambers, H., and Kandeler, E. (2019). Hidden miners – the roles of cover crops and soil microorganisms in phosphorus cycling through agroecosystems. Plant Soil, 434:7-45. https://doi.org/10.1007/s11104-018-3810-7

Hay, M. M., Dille, J. A., Peterson, D. E. (2019). Integrated pigweed (Amaranthus spp.) management in glufosinate-resistant soybean with a cover crop, narrow row widths, row-crop cultivation, and herbicide program. Weed Technology, 33:710-719. https://doi.org/10.1017/wet.2019.62

Higgins, T. R. (2017). An economic analysis of the value of grazing winter cover crops

(Master's Thesis, Kansas State University).

Holechek, J. L., and Galt, D. (2000). Grazing intensity guidelines. Rangelands Archives, 22:11-14.

Holman, J.D., Arnet, K., Dille, J., Maxwell, S., Obour, A. (2018). Can cover or forage crops replace fallow in the semiarid central great plains? Crop Science, 58:932–944. doi: 10.2135/cropsci2017.05.0324.

Holman, J. D., Obour A. K., and Mengel D. B. (2019). Nitrogen application effects on forage sorghum production and nitrate concentration. Journal of Plant Nutrition, 42:2794-2804. https://doi.org/10.1080/01904167.2019.1659321

Holman, J. D., Obour, A. K., and Assefa, Y. (2021). Productivity and profitability with fallow replacement forage, grain, and cover crops in W-S-F rotation. Crop Science Society of America, 62: 913–927. doi: 10.1002/csc2.20670

Holman, J. D., Obour, A. K., and Assefa, Y. (2022). Forage sorghum grown in a conventional wheat-grain sorghum-fallow rotation increased cropping system productivity and profitability. Canadian Journal of Plant Science, 103:61-72. http://dx.doi.org/10.1139/CJPS-2022-0171

Holman, J., Obour, A., Johnson, S., and Assefa, Y. (2023a). Nutritive value and net return of forage crop rotations in the central great plains. Agronomy Journal, 115:1399-1414. https://doi.org/10.1002/agj2.21316

Holman, J. D., Obour, A. K., Haag, L. A., and Lawrence, M. A. (2023b) Occasional Tillage in a Wheat-Sorghum-Fallow Rotation: 2022 Growing Season. Kansas Agricultural Experiment Station Research Reports, Vol. 9: Iss. 6. https://doi.org/10.4148/2378-5977.8488

Hutchinson, C.M., and McGiffen, M. E. (2000). Cowpea cover crop mulch for weed control in desert pepper production. HortScience, 35:196-198.

Johnson, S., Brummer, J., Obour, A., Moore, A., Holman, J., Schipanski, M. (2020). Cover crops grown post-wheat for forage under dryland conditions in the high plains. K-State Research and Extension.

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

Kirkham, M. B. (2023). Principles of soil and plant water relations: Third edition. Academic Press. ISBN: 978-0-323-95641-3

Kunz, C., Sturm, D. J., Sökefeld, M., and Gerhards, R. (2016). Weed suppression and early sugar beet development under different cover crop mulches. Plant Prot. Science, 52:1–7. doi:10.17221/109/2016-PPS

MacDonald, J. M., and McBride, W. D. (2009). The Transformation of U.S. Livestock Agriculture Scale, Efficiency, and Risks. Economic Information Bulletin No. 43. https://dx.doi.org/10.2139/ssrn.1354028

Mahama, G. Y., Prasad, P. V., Roozeboom, K.L., Nippert, J.B., and Rice, C. W. (2016). Cover crops, fertilizer nitrogen rates, and economic return for grain sorghum. Agronomy Journal, 108:1-16. doi: 10. 2134/agronj15.0135

Mirsky, S.B., Ryan, M. R., Teasdale, J. R., Curran, W.S., Reberg-Horton, C. S., Spargo, J. T., Wells, M.S., Keene, C. L., and Moyer, J. W. (2013). Over-coming weed management

challenges in cover crop–based organic rotational no-till soybean production in the eastern United States. Weed Technology, 27:193–203. doi:10.1614/WT-D-12-00078.1

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

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

Nielsen, D. C., Lyon, D. J., Hergert, G. W., Higgins, R. K., Holman, J. D. (2015). Cover Crop Biomass Production and Water Use in the Central Great Plains. Agronomy Journal, 107:2047-2058. https://doi.org/10.2134/agronj15.0186

Nielsen, D.C., Higgins, R. K., Hergert, G. W., Holman, J. D., Lyon, D. J. (2016a). Cover Crop effect on subsequent wheat yield in the central Great Plains. Agronomy Journal 108:243. doi: 10.2134/agronj2015.0372.

Nielsen, D. C., Vigil, M. F., and Hansen, N. C. (2016b). Evaluating potential dryland cropping systems adapted to climate change in the central great plains. Agronomy Journal, 108: 2391-2405. doi: 10.2134/agronj2016.07.0406

Nielsen, D. C. (2018). Influence of Latitude on the US Great Plains East–West Precipitation Gradient. Agricultural and Environmental Letters, 3:1-5. https://doi/10.2134/ael2017.11.0040

Nikolic, L., Seremesic, S., Milosev, D., Dalovic, I., Latkovic, D. (2018). Weed infestation and biodiversity of winter wheat under the effect of long-term crop rotation. Applied Ecology and Environmental Research, 16:1413-1426.

NOAA. (2024). National Weather Service seasonal outlook. Available from: https://www.cpc.ncep.noaa.gov/products/predictions/multi_season/13_seasonal_outlooks/color/p.gif.

Obour, A. K., Simon, L. M., Holman, J. D., and Johnson, S. K. (2021a). Does grazing Cover crops impact soil properties? K-State Research and Extension vol. 7: Iss. 5. https://doi.org/ 10.4148/2378-5977.8078

Obour, A. K., Holman, J. D., Simon, L. M., Schlegel, A. J. (2021b). Strategic Tillage Effects on Crop Yields, Soil Properties, and Weeds in Dryland No-Tillage Systems. Agronomy, 11, 662. https://doi.org/10.3390/agronomy11040662

Obour, A. K., Dille, J., Holman, J. D., Simon, L. M., Sancewich, B., Kumar, V. (2022a). Spring-planted cover crop effects on weed suppression, crop yield, and net returns in no-tillage dryland crop production. Crop Science Society of America, 62:1981-1996. https://doi.org/10.1002/csc2.20801

Obour, A. K., Holman, J. D., and Assefa, Y. (2022b). Grain sorghum productivity as affected by nitrogen rates and available soil water. Crop Science Society of America, 62:965-1404. doi: 10.1002/csc2.20731

Obour, A. K., Holman, J. D., Simon, L. M. (2023). Grazing cover crops improved soil health in dryland cropping systems. Kansas Agricultural Experiment Station Research Reports: Vol. 9: Iss. 6. https://doi.org/10.4148/2378-5977.8486

Osipitan, O. A., Dille, J. A., Assefa, Y., Knezevic, S. Z. (2018). Cover Crop for Early Season Weed Suppression in Crops: Systematic Review and Meta-Analysis. Agronomy Journal, 110:2211-2221. doi: 10.2134/agronj2017.12.0752

Peterson, G. A., Westfall, D. G., Cole, C. V. (1993). Agroecosystem approach to soil and crop management research. Soil Science Society of America Journal, 57:1354-1360.

Peterson, G. A., Halvorson, A. D., Havlin, J. L., Jones, O. R., Lyon, D. J., and Tanaka, D. L. (1998). Reduced tillage and increasing cropping intensity in the Great Plains conserves soil C. Soil and Tillage Research, 47:207-218. https://doi-org.er.lib.k-state.edu/10.1016/S0167-1987(98)00107-X

Peterson, G. A., Westfall, D. G., Peairs, F. B., Sherrod, L., Poss D., Gangloff, W., Larson, K., Thompson, D. L., Ahuja L. R., Koch, M.D., Walker, C. B. (2001). Sustainable dryland agroecosystem management. Technical Bulletin TB01-2. Fort Collins, CO: Agricultural Experiment Station Colorado State University.

Peterson, G. A., and Westfall, D. G. (2004). Managing precipitation use in sustainable dryland agroecosystems. Annals of Applied Biology, 114:127-138. https://doi.org/10.1111/j.1744-7348.2004.tb00326.x

Petrosino, J. S., Dille, J. A., Holman, J. D., Roozeboom, K. L. (2015). Kochia suppression with cover crops in southwestern Kansas. Crop, Forage and Turfgrass Management, 1:1-8. https://doi.org/10.2134/cftm2014.0078

Russelle, M. P., Entz, M. H., and Franzluebbers, A. J. (2007). Reconsidering Integrated crop-livestock systems in North America. Agronomy Journal 99:325-344. doi:10.2134/agronj2006.0139

Schlegel, A. J., Dumler, T. J., Thompson, C. R. (2002). Feasibility of Four-Year Crop Rotations in the Central High Plains. Agronomy Journal, 94:509-517. https://doi/10.2134/agronj2002.5090

Schlegel, A. J., Holman, J. D., Assefa, Y. (2020). A single tillage in a long term no-till system on dryland crop performance. Agronomy Journal, 112:3174-3187. https://doi.org/10.1002/agj2.20284

Schomberg, H. H., Fisher, D. S., Reeves, D. W., Endale, D. M., Raper, R. L., Jayaratne, K. S. U., Gamble, G. R., and Jenkins, M. B. (2014). Grazing winter rye cover crop in a cotton no-till system: Yield and Economics. Agronomy Journal, 106:1041-1050. doi: 10.2134/agronj13.0434

Schubert, S. D., Suarez, M. J., Pegion, P. J., Koster, R. D., Bacmeister, J. T. (2004). On the cause of the 1930s Dust Bowl. Science, 303:1855-1859. https://doi.org/10.1126/science.1095048

Silva, G.C., and Bagavathiannan, M. (2023). Mechanisms of weed suppression by cereal rye cover crop: A review. Agronomy Journal, 115:1571-1585. doi: 10.1002/agj2.21347

Simon, L. M., Obour, A. K., Holman, J. D., Johnson, S. K., and Roozeboom, K. L. (2021). Forage productivity and soil properties in dual-purpose cover crop systems. Agronomy Journal, 113:5569-5583. doi: 10.1002/agj2.20877

Simon, L. M., Obour, A. K., Holman, J. D., Roozeboom, K. L. (2022). Long-term cover crop management effects on soil properties in dryland cropping systems. Agriculture, Ecosystems and Environment, 328. https://doi.org/10.1016/j.agee.2022.107852

Singer, F. J., and Schoenecker, K. A. (2003). Do ungulates accelerate or decelerate nitrogen cycling? Forest Ecology and Management, 181:189-204. https://doi.org/10.1016/S0378-1127(03)00133-6

Sommerfeldt, T. G., Chang, C., and Entz, T. (1988). Long-term annual manure applications increase soil organic matter and nitrogen, and decrease carbon to nitrogen ratio. Soil Science Society of America Journal 52:1668-1672. https://doi.org/10.2136/sssaj1988.03615995005200060030x

Sulc, R. M., Tracy, B. F. (2007). Integrated crop livestock systems in the U.S. corn belt. Agronomy Journal, 99:335-345. doi: 10.2134/agronj2006.0086

Sulc, R. M., Franzluebbers, A. J. (2013). Exploring integrated crop-livestock systems in different ecoregions of the United States. European Journal of Agronomy, 57:21-30. http://dx.doi.org/10.1016/j.eja.2013.10.007

Unger, P. (1998). Cover crop effects on soil water relationships. Journal of Soil and Water Conservation, 53:200–207. http://dx.doi.org/10.15666/aeer/1602_14131426

USDA-NRCS (2022). Soil Health-Bulk Density, from: https://www.nrcs.usda.gov/sites/default/files/2022-11/Bulk%20Density%20-%20Soil%20Health%20Guide_0.pdf

Veresoglou, S. D., Chen, J., Du, X., Fu, Q., Huang, C., et al. (2023). No tillage outperforms conventional tillage under arid conditions and following fertilization. Soil Ecology Letters, 5:137-141. https://doi.org/10.1007/s42832-022-0145-3

Virgona, J.M., Gummer, F. A. J., and Angus, J. F. (2006). Effects of grazing on wheat growth, yield, development, water use, and nitrogen use. Australian Journal of Agricultural Research 57:1307-1319. https://doi.org/10.1071/AR06085

Williams, S. M., and Weil, R. R. (2004). Cover crop root channels may alleviate soil compaction effects on soybean crop. Soil Science Society of America Journal 68:1403-1409. https://doi-org.er.lib.k-state.edu/10.2136/sssaj2004.1403

Chapter 2 - Diversifying wheat-based Cropping Systems with Forages and Livestock

Abstract

Integrating annual forages and livestock into dryland cropping systems can increase profitability and improve soil health. This study determined crop yield and soil property impacts of integrating annual forages and livestock in a dryland winter wheat (*Triticum aestivum L.*)-grain sorghum (*Sorghum bicolor Moench*)-fallow rotation (W-GS-F). Treatments included W-GS-F (control), W-GS-F with GS residues grazed (W-GSG-F), wheat/forage sorghum-forage sorghum-fallow (W/FS-FS-F) with FS grazed (W/FSG-FSG-F), or FS hayed (W/FSH-FSH-F) in a randomized complete block design with four replications. The study was conducted from 2021 through 2025, and all phases of rotations were present each year. Results showed full-season FS forage dry matter averaged 6,933 to 7,338 kg ha^{-1}, while double-crop FS averaged 2,894 to 2,951 kg ha^{-1}. Grazing full-season FS retained ~50% of biomass as residue compared to ~30% when hayed. Double-crop FS was grazed in 3 out of 5 years because of limited yield, with ~60% of forage biomass remaining as residue after grazing or ~40% after haying. Wheat and grain sorghum yields did not differ across treatments. Soil measurements taken in August 2023 to 2025 immediately preceding wheat planting showed W/FSG-FSG-F had the most residue cover and least penetration resistance. Averaged across the 0-15 cm sampling depth, no differences in bulk density, bulk SOC or particulate organic matter were observed among treatments. However, dry aggregate-associated SOC was greater in W-GSG-F and W/FSG-FSG-F than W-GS-F and W/FSH-FSH-F in nearly all aggregate sizes. No differences in mean weight diameter (MWD) of water stable aggregates were observed among treatments. Dry-aggregate MWD was similar for W-GS-F, W-GSG-F, and W/FSG-FSG-F treatments, but significantly less for W/FSH-FSH-F.

Percent wind erodible fraction was consistently higher for W/FSH-FSH-F than all other rotations. Cropping system net returns varied by year but were consistently greater for W-GSG-F than all other treatments. Overall, integrating annual forages and livestock maintained or improved soil health, and was more profitable than haying forages.

Core Ideas

- Wheat and grain sorghum production was limited by below-average precipitation, but full-season forage sorghum had greater than 7,000 kg ha^{-1} of productivity on average over the study period.
- Double-crop forage sorghum was grazed and hayed only three out of the five years due to limited soil moisture and precipitation post-wheat crop.
- Grazing had a neutral or positive effect on nearly every soil health parameter measured in the study.
- Wheat-grain sorghum (grazed stalks)-fallow rotation had the highest net returns, followed by the forage intensive grazing treatment, wheat-grain sorghum-fallow, and least in the forage hayed treatment.

Introduction

Due to the semi-arid climate, winter wheat (*Triticum aestivum L.*)-fallow (W-F) had been the predominant two-year rotation in the Central Great Plains (CGP) throughout the 1900s, but an extended fallow period leaves minimal soil cover on the soil surface (Carr et al., 2020; Nielsen and Vigil, 2010; Peterson and Westfall, 2004). Limited residue inputs from W-F results in low soil organic matter content with consequent negative impact on numerous soil physical and chemical properties regardless of the tillage practice, such as wind and water erosion due to degraded soil structure, and decreased nutrient and water retention (Carr et al., 2020; Peterson et al., 2020; Peterson and Halvorson et al., 1998; Simon et al., 2021; 2022). At best, the W-F rotation retains about 35% of total precipitation during the fallow period as stored soil water (Holman et al., 2021; Peterson and Westfall et al., 2004).

Through adoption of reduced tillage practices such as no-till (NT), producers are now capable of intensifying their crop rotations. Currently, the most widely adopted rotation in the CGP is the three-year rotation of wheat-summer crop-fallow (WSF) (Holman et al., 2022; Simon et al., 2021; 2022). The 3-year rotation allows for a crop to be planted annually on 67-100% of production acres (Dhuyvetter et al., 1996). The primary summer grain crops grown in the region are grain sorghum (*Sorghum bicolor Moench*) and corn (*Zea mays L.*) (Assefa et al., 2014; Holman et al., 2022; Schlegal et al., 2016). The WSF rotation has shifted fallow so a crop is in place more often during high precipitation months and has reduced the fallow period from 15 to 11 months (Holman et al., 2018). The WSF rotation has increased residue input, efficient water use, and improved soil properties when compared to W-F (Baumhardt et al., 2015; Holman et al., 2022). Intensive crop rotations coupled with NT can build carbon reserves in the top 5 cm of the

soil within 10 years when compared to less intensive systems that utilize intensive tillage (Halverson et al., 2002).

Not only is a more intensified system better for soil health, it also improves profitability. Dhuyvetter et al. (1996) in seven of eight studies reported greater net returns from a more intensive crop rotations than WF when NT or reduced tillage systems were used following wheat harvest and prior to the summer crop planting. Grain sorghum is the primary summer crop grown in the semi-arid portions of the CGP due to a vast and extended root system that penetrates the soil 2.5-3 m, almost twice the rooting depth of a corn root (1.5 m) (Assefa et al., 2014). Grain sorghum also has much shorter above ground stature than corn, requiring less water for biomass production and saving more soil water for grain fill. Collectively, these characteristics contribute to greater productivity of grain sorghum compared with corn in three-year rotations in the region (Assefa et al., 2014). Even though the three-year rotation has benefitted the region, there are still 23 months in 3-years without a growing crop within the rotation (Baumhardt et al., 2015). Therefore, the opportunity exists to further intensify the three-year rotation system with short-season crops such as forages between or in place of grain crops.

Intensifying current three-year rotations in the CGP with forages could benefit overall soil health, as well as total system profitability (Holman et al., 2022; Nielsen et al., 2016). The growing season for annual forages is shorter, requiring substantially less water compared to grain crops. For example, season length for grain crops grown during the summer from planting to maturity is approximately 5-6 months, with planting occurring in early April-June and harvesting in October. An annual forage growing season can be as short as 3 months with adequate moisture conditions (Holman et al., 2020a). A summer forage sorghum can be planted in May-June and harvested in August, and with adequate moisture and regrowth, a second harvest can occur in

October. The relatively short growing season of annual forages allows them to capture and efficiently utilize early season precipitation, resulting in greater precipitation use efficiency than summer grain crops within the region (Holman et al., 2020b). Inclusion of forages could potentially stabilize total system yields under variable precipitation conditions. Nielsen et al. (2010) showed that dry conditions have less of an effect on forage biomass production than they do on grain production. A recent study in southwest Kansas that evaluated six alternate three-year wheat-based cropping systems compared to the common W-GS-F rotation showed that inclusion of forage sorghum within any of the conventional rotations increased overall economic profitability (Holman et al., 2022). In that study, the more intensified forage system, double-cropping forage sorghum after winter wheat, had no significant impact on subsequent winter wheat yields, but rotations utilizing double-cropped forage sorghum significantly reduced grain sorghum yields compared to W-GS-F rotation. Despite the decrease in grain sorghum yield, the overall profitability was greater for the more intensified grain sorghum cropping system that had double-cropped forage sorghum as part of the rotation.

These previous findings in the CGP indicate that utilizing forages within wheat-based rotations can have a significant positive impact on production economics. Haying and/or grazing are the primary forms of utilizing a forage as an economic resource and could provide a balance between positive economic outcome and system sustainability that cover crops cannot provide. Grazing annual forages can also provide needed rest for grasslands (Obour et al., 2021a), particularly in prolonged dry periods that reduce productivity of native pastures in the CGP. Annual forages can provide high nutritive feed value at times of the year native pasture is dormant or low in productivity. Notwithstanding the economic and agronomic benefits, many producers have concerns with the negative impacts haying and grazing could potentially have on

soil organic carbon (SOC) reserves, water stable aggregates, and wind erodible fraction due to removal of essential crop residue. Haying is the most common form of harvesting forages within the region, but haying removes significantly more residue when compared to grazing forages. Haying can remove up to 73% of available forage, while grazing may remove less than 50% of forage (Simon et al., 2021). Among grain crop producers, grazing is often seen negatively because it could increase soil compaction, which can impact water infiltration and root growth (Blanco-Canqui et al., 2021). Though in western Kansas, Simon et al. (2021, 2022) and Obour et al. (2023) found that grazing has a neutral or positive effect on most soil health parameters because of forage biomass residue left post-grazing. If soil conditions are favorable, and stocking intensity and grazing duration is managed properly, an increase in soil compaction indicators and a decline in soil chemical properties is seldom observed. Another challenge of grazing is the high overhead cost that may be incurred by producers who don't currently own livestock. This includes the costs to acquire livestock, watering, and fence infrastructure. A way to negate high costs of grazing would be to lease croplands with a growing forage to ranchers who have the resources necessary for grazing. This can be done by using methods described by Hofstrand and Edwards (2015), which shift the cost of acquiring cattle and infrastructure to ranchers leasing the crop field. Haying of forages is not inexpensive either; current estimated cost of producing a 682 kg large round bale is $27.94 per bale (Kansas State University Ag-manager, 2024). This suggests that if lease rates are used for grazing forages on cropland, haying may be a substantially more expensive harvesting method than grazing.

To our knowledge, few studies have compared productivity and economic return of grazing or haying forage sorghums in dryland WSF systems in the CGP. Therefore, we hypothesized that intensifying rotations with annual forages (by grazing or haying) will have

neutral or positive impacts on soil residue cover, SOC, aggregate mean weight diameter (MWD), compaction indicators, nutrient cycling, available nitrogen (N) and phosphorus (P), water use efficiency, system production, and profitability when compared to less intensive cropping systems. Thus, the objectives of this study were to evaluate how cropping system intensification with annual forages, including haying and grazing management, affects soil physical and chemical properties, crop yields and overall system profitability.

Materials and Methods

Site Description and Experiment Layout

This study was conducted from 2021 to 2025 at the Kansas State University Agricultural Research Center-Hays near Hays, KS (38.84826, -99.3448) to investigate effects of intensifying current dryland cropping rotations with haying and grazing of crop residues and annual forages. The study area was on a Harney silt loam soil series formed from loess material and slopes ranging from 1 to 3 percent. The 147-year average annual precipitation at Hays is 580 mm with an open-pan evaporation (April-June) of 1741 mm (Figure 2.1). The study design was a randomized complete block with four replications in a W-GS-F base rotation system, with all phases of the rotations present each year. The study treatments compared the base rotation of W-GS-F with grazing of GS stalks (W-GSG-F), an intensified forage system with forage sorghum (FS) planted directly after wheat harvest and in place of GS the following year with available biomass grazed (W/FSG-FSG-F), and an intensified FS system with available forage hayed (W/FSH-FSH-F). Forage sorghum grown directly after wheat and planted in late June would be considered double-crop FS, while forage sorghum grown in place of grain sorghum and planted at the beginning of June in the second year of the rotation would be considered full-season FS. The individual grazing treatments plots were 18.3 m × 37 m and W-GS-F and hayed treatment

plots were 9 m × 37 m. The wider grazed treatment plots compared to W-GS-F and W/FSH-FSH-F was intentionally done for ease of grazing.

Crop Management

Each year, winter wheat was planted at the end of September at a rate of 67 kg ha^{-1} on 19-cm row spacing using a Great Plains NT drill (Model 3p1006NT, Great Plains Manufacturing, Salina, KS). With the seed at planting, each plot received 20 kg ha^{-1} P_2O_5 as monoammonium phosphate (11-52-0). At spring green up, (approximately late March), an additional application of 84 kg N ha^{-1} as urea (46-0-0) was broadcast on each plot. Around the same time, winter-annual weed control in wheat was accomplished with an application of dicamba (3,6-dichloro-2-methoxybenzoic acid) at 0.58 L ha^{-1}. Winter wheat was harvested in late June to early July using an 8XP small plot combine harvester (Massy Ferguson, Duluth, GA, USA). Directly after wheat harvest, the double-crop FS was planted in W/FSG-FSGF and W/FSH-FSH-F plots at a rate of 16.82 kg ha^{-1} on 19-cm rows with the same NT drill. Double-crop FS was grazed with yearling heifers approximately 454 kg each (*Bos taurus*) and hayed with a small plot Carter forage harvester (Carter Manufacturing Company, Inc., Brookston, IN) at a 15-cm cutting height shortly after heading, which corresponds to Zadoks growth stages 45-60 (Zadoks et al., 1974) or at first freeze, whichever occurred first. The non-double-crop treatments, W-GS-F and W-GSG-F received one or two applications of glyphosate (N-(phosphonomethyl) glycine) at 1.73 L ha^{-1} to control annual weeds and volunteer wheat through late summer. An additional application of glyphosate at 1.73 L ha^{-1}, 2, 4-D (2,4-dichlorophenoxyacetic acid) at 1.16 L ha^{-1}, and atrazine (2-chloro-4-ethylamino-6-isopropylamino-s-triazine) at 2.32 L ha^{-1} was made in the spring to control weeds prior to GS and full-season FS planting for all treatments. After an 11-month fallow period, grain sorghum was planted at the beginning of June at a rate of 86,450 seeds ha^{-1}

on 38-cm rows with the same NT drill as wheat. Within the same time period, full-season FS was planted at a rate of 16.82 kg ha^{-1} on 19-cm rows with the same NT drill, and received P_2O_5 applications similar to that applied to wheat, however full-season FS received only 56 kg N ha^{-1}. Grain sorghum received similar N and P_2O_5 applications to wheat. Grain sorghum was harvested in late October, using the same small plot combine harvester as used for wheat. Full-season FS was grazed with yearling heifers and hayed with the same small plot forage harvester as double-crop FS, coinciding with the same Zadoks growth stages. One or more sequential applications of glyphosate at 1.73 L ha^{-1}, 2, 4-D at 1.16 L ha^{-1}, saflufenacil (N'-[2-chloro-4-fluoro-5-(3-methyl-2,6-dioxo-4-(trifluoromethyl)-3, 6-dihydro-1(2H)-pyrimidinyl)benzoyl]-N-isopropyl-N-methylsulfamide) at 73.04 mL ha^{-1}, and s-metolachlor ((S)-2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl)acetamide) at 0.94 L ha^{-1} were applied during the fallow period to control weeds prior to wheat planting.

Forage Biomass and Grazing Management

Each year before grazing and haying, available FS and GS stalk biomass was determined by hand clipping, to 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. This information was used to determine available forage mass and stocking rates for the grazed treatments. Typically, plots were grazed with ~3 (grain sorghum stalks) to 16 (forage sorghum) 454-kg heifers ha^{-1} that were contained with movable fencing panels. Cattle were removed from each plot when ~50% of the forage mass had been removed, determined by pre-graze biomass sampling and visual assessment. After grazing, each grazed plot was resampled as previously described to determine forage biomass remaining. Hayed plots were harvested with a small-plot forage harvester from a strip measuring 0.9 m by 37 m. Whole-plot

fresh weights were recorded, subsamples collected and weighed, then oven-dried to determine FS hay yield. Following the cutting of a sample strip, the remaining plot area in the hayed plots were harvested with the same equipment. Residue remaining in hayed plots was determined by subtracting biomass removed with the small plot harvester from the total available biomass measured in each hayed plot from the hand clippings before haying.

Residue Cover and Soil Properties

Residue cover measurements and soil sampling first occurred in fall of 2023, and then again in the fall 2024 and 2025 during the fallow period after all treatments had completed a full rotation cycle. Residue cover was determined by the line-transect method (USDA-NRCS, 2002). Briefly, a 3.05 m long PVC pipe with marks at every 0.305-m interval was randomly placed at two separate points diagonally across crop rows, and marks directly above residue were counted. The percentage of residue cover on the soil surface was calculated by dividing the total number of counted residue cover points by 10 and multiplying by 100. The two measurements per plot were averaged to obtain one value for each plot.

At each soil sampling, ten soil cores (2.5-cm diameter) were taken from 0-5 cm and 5-15 cm depths for determination of soil chemical and biochemical properties. After the samples were taken from the plots, they were air dried and then ground to pass through a 2-mm sieve. Soil chemical properties analyzed were soil organic carbon (SOC), nitrate-N (NO_3-N), phosphorus (P) (M3-P), and pH. The soil biochemical property analyzed was particulate organic matter (POM). Sub-samples used for total SOC were ground into fine particles with a mortar and pestle, then analyzed using a high-temperature combustion method on an Elementar UNICUBE® CN analyzer (Elementar Americas Inc., Ronkonkoma, NY) after pretreating samples with 10% (v/v) HCl to remove carbonates (Nelson and Sommers, 1996). Nitrate concentrations were determined

colorimetrically after samples were extracted with 2 M KCl. Soil available P was determined after extracting samples with Mehlich-3 solution (Mehlich, 1984). After extraction, the M3-P concentration was measured using inductively coupled plasma-optical emission spectrometry (ICP-OES). Soil pH was determined by mixing 20 grams of each sample with 20 mL of double deionized water, and allowing to sit for 30 minutes. After 30 minutes, measurements were made using the Oakton® PC 700 Benchtop pH/mV/Conductivity/°C/°F Electrode Meter (Environmental Express, Charleston, SC). The meter was calibrated using pH buffers of 4.01, 7.00, and 10.01 (Thomas, 1996). Particulate organic matter was analyzed by using a sub-sample of approximately 25 grams of the 2-mm sieved samples and mixing 100 mL of 5g/L hexametaphosphate sodium and placing on an orbital shaker at 200 rotations per minute for 4 hours (Cambardella and Elliott, 1992). Samples were then poured over a 53-um sieve, and the material remaining on the sieve was dried at 105°C. The remaining material was burned at 450°C in a muffle furnace (Lindberg Blue M, Ashville, NC) and used to calculate POM.

Soil compaction indicators of bulk density (BD) and penetration resistance (PR) were measured at the 0-5 cm and 5-15 cm depths. Two soil cores per plot were sampled for BD using an AMS BD sampler (AMS, Inc., American Falls, ID). The samples were then dried at 105°C until a constant weight was reached to determine BD as mass of oven-dried soil divided by volume of the core (Grossman and Reinsch, 2002). Penetration resistance was measured with an Eijkelkamp Hand Penetrometer (Eijkelkamp Soil and Water, Morrisville, NC). The penetrometer was uniformly pressed into the soil at ten random locations within a plot. Readings were divided by the area of the cone (2 cm^2). Gravimetric water content measurement was taken at the time of penetration resistance readings and used to adjust penetration resistance values (Simon et al.,

2021) to a standard field capacity gravimetric water content (GWC) of 0.30 (g g^{-1}) for silt loam soils (Ratliff et al., 1983) to account for potential differences in GWC across plots.

Additional soil samples used for indicating erosion potential were taken from the 0-5 cm depth. For wet and dry aggregate stability, about 1 to 2.5 kg of intact soil was sampled from three random locations within each plot using a flat shovel. After air drying, the samples were split into two, and half of each sample was passed through an 8 mm sieve. The portion of the sample passed through the 8 mm sieve was used to determine water stable aggregates (WSA) and mean weight diameter (MWD) of WSA using the wet sieving method (Nimmo and Perkins, 2002). Prior to calculating WSA and MWD, sand corrections were conducted for each aggregate fraction to remove sand particles. The remaining portion of each sample was used to determine dry aggregate stability and wind erodible fraction (WEF). The air-dried sample was placed on a system of 5 nested rotary sieves with 19, 6.3, 2-, 0.84-, and 0.25-mm square openings. All samples were shaken for 5 minutes using a portable shaker (W.S. Tyler Model RX-812, Mentor, OH) (Chepil, 1962). After shaking, the soil particles remaining on each sieve were weighed and used to compute dry aggregate mean weight diameter (DAMWD) and WEF (aggregates < 0.84 mm) using equation 2.1.

Calculation of mean weight diameter

$$\text{MWD} = \sum_{i=1}^{n} (x_i \, w_i) \qquad \text{Equation 2.1}$$

where n equals the number of size fractions, x_i equals the mean weight diameter of the size fraction, and w_i equals the fraction of the total sample weight on the sieve.

After wet and dry aggregate samples were processed, a portion of the sample from each aggregate size fraction was analyzed for SOC concentrations within each size fraction using an Elementar UNICUBE® CN analyzer (Elementar Americas Inc., Ronkonkoma, NY).

Economic Analysis

A partial budget approach was used to estimate cropping system net returns. Net returns were calculated using revenue accrued from each rotation system minus associated production costs after each treatment was completely in phase in 2024 and 2025. Estimates for current field operations and input costs used 5-year average custom rate values published by Kansas State University Land Use Survey Program and the Kansas Department of Agriculture (AgManager, 2024). Winter wheat price was set at \$0.24 kg^{-1}, grain sorghum at \$0.21 kg^{-1}, and forage sorghum hay (15% moisture) at \$0.10 kg^{-1} representing 5-year averages generated from values within the United States Department of Agriculture Economic Research Services market reports (USDA ERS, 2025). Revenue generated from grazed forages were estimated from two grazing lease rate scenarios, where the alternative to grazing forages is grazing native rangeland (\$42.11 Animal Unit Month $(AUM)^{-1}$) or the alternative to grazing forages is confined feeding of hay (\$55.82 AUM^{-1}).

To estimate the economic value of grazed forages, a methodology described by Simon et al. (2024) was used to calculate rangeland and confined feeding lease rates. The rangeland lease rates of \$42.11 AUM^{-1} were obtained by multiplying the 20-year average pasture yield of 2242 kg ha^{-1} (Rangeland Analysis Platform, 2026) by 25% cattle intake of dry pasture biomass produced and dividing that value by the monthly dry biomass demand (408 kg ha^{-1}) of cattle weighing 454 kg to get AUM ha^{-1}; and then dividing pasture rental rates of \$57.80 ha^{-1} averaged from reported pasture lease rates in central Kansas for 2025 (USDA, 2025) by the AUM ha^{-1} calculated in the previous step. For the confined feeding of hay scenario, lease rates were calculated using the previously mentioned hay price of \$0.10 kg^{-1} multiplied by the monthly hay amount required to feed cattle per month plus an estimated yardage cost of \$0.50 $head^{-1}$ day^{-1}

multiplied by 30 days. Carrying capacity of the forage was determined by dividing available forage by the monthly forage demand of 454 kg ha^{-1} cattle with a daily consumption of 2.5% of their body weight. The leasing rates were then multiplied by the carrying capacity estimated for each grazing treatment. Total costs were calculated using the sum of fertilizer and application costs, herbicide and application, seed and planting, and total haying cost to produce large round bales (approximately 682 kg^{-1}), which included swathing, conditioning, raking, baling, hauling, and stacking (Ag Manager, 2024). All production costs and revenues were calculated on a ha^{-1} basis.

Statistical Analysis

Analyses of forage mass, grain yields, rotation net returns, and soil chemical and physical properties were performed using the PROC GLIMMIX procedure in SAS ver. 9.4 (SAS Institute, 2012). First, forage mass, grain yields, rotation net returns, RC, MWD, WEF, and aggregate associated carbon were analyzed with year, rotation, and their interactions as fixed effects in the model, and replication as random. The soil BD, PR, SOC, POM, extractable nutrient concentrations, and pH were modeled with rotation, year, sampling depth, and their interactions as fixed effects, while replication and its interaction with fixed effects were considered random. Interaction and treatment effects were considered significant when *P*-values were ≤ 0.10. The LSMEANS procedure in SAS was used to compute and compare fixed effect means.

Results

Weather Patterns

Average annual precipitation from 2021 to 2025 was 510 mm, which was 88% of the average long-term (1868-2016) annual precipitation for the site (580 mm). Full-season forage sorghum was harvested every year of the study, and cumulative precipitation from June-August

during the growing season averaged 198 mm across the five years of production, which is 80% of the average long-term precipitation for the same months (247 mm). Double-crop forage sorghum was harvested three of the five years (2021, 2024, 2025) of the study. In the three years double-crop forage sorghum was harvested, precipitation during the growing season (July-October) averaged 262 mm, which is 104% of the long-term average. In the years (2022, 2023) when double-crop forage sorghum did not produce enough biomass to be harvested, growing season precipitation (163 mm) was only 64% of the long-term average. Winter wheat was harvested in 2023-2025 after all treatments completed a full cycle, with the growing season spanning from October to June. Although the growing season received near average precipitation, the critical months of March and April received well below average precipitation in 2023 and 2024. In 2023, cumulative March-April precipitation was 28% of the long-term average for the same months (Figure 2.1a). Similarly, 2024 cumulative March-April precipitation was 29% of the long-term average (Figure 2.1b). Cumulative March-April precipitation in 2025 exceeded long-term averages and provided favorable conditions for wheat grain production (Figure 2.1c). Grain sorghum was harvested in 2024-2025 after all treatments completed a full cycle, with the growing season spanning from June to October. In 2024, lack of precipitation from January-May provided minimal soil moisture at the time of grain sorghum planting (Figure 2.1b). Furthermore, limited precipitation and high daily air temperature from July through October led to unfavorable flowering and grain fill conditions for the 2024 grain sorghum crop. In 2025, May received adequate precipitation and favorable soil moisture conditions for grain sorghum planting (Figure 2.1c). From July to October, precipitation was 133% of the long-term average, minimizing potential negative effects of high air temperatures during flowering and grain fill stages, leading to adequate grain production.

Winter Wheat and Grain Sorghum Yields

Winter wheat yield was not different among treatments, with an average of 1540 kg ha^{-1} over the three years (Table 2.1). Yields were significantly different across years, 2025 had the most wheat yield (2541 kg ha^{-1}) compared to 2023 (1028 kg ha^{-1}) and 2024 (1052 kg ha^{-1}). Likewise, grain sorghum yields were not significantly different between treatments, with an average of 4564 kg ha^{-1} across treatments for the 2-years (Table 2.1). Again, 2025 had significantly higher sorghum yields (5935 kg ha^{-1}) than 2024 (3194 kg ha^{-1}).

Forage mass

Available forage mass was not statistically different for harvest type (grazing and haying) in full-season or double-crop production (Table 2.2). However, available forage mass varied yearly regardless of planting time. Double-crop forage production was highest in 2024 and lowest in 2022, due to below average precipitation and limited soil moisture post-wheat. Full-season FS production was highest in 2025 and lowest in 2022 again due to below-average precipitation (Table 2.2). On average, full-season FS forage productivity (7135 kg ha^{-1}) was approximately 2.5 times the amount of double-crop forage (2924 kg ha^{-1}) FS produced.

Forage mass remaining as residue was significantly impacted by harvest type in both double-crop and full season forage production (Table 2.2). Double-crop forage mass remaining was analyzed only in 2021, 2024, and 2025, because treatments were not grazed or hayed in 2022 and 2023 due to limited production. The grazed treatment had 1.5 times the amount of residue remaining on the soil surface than the hayed treatment on average, despite a significant harvest type × year effect due to no significant difference between harvest types in 2025 (Figure 2.2). Averaged across the 5-years, grazing full-season FS left approximately 3466 kg ha^{-1} of biomass on the soil surface, which represented 50% of the total aboveground biomass produced.

The residue remaining after haying of full-season FS was 2201 kg ha^{-1}, about 30% of the total biomass produced (Table 2.2).

Residue Cover

Crop rotation, year, and rotation × year interaction all had significant effect on residue cover measured at winter wheat planting (Table 2.3). In 2023, W/FSG-FSG-F had significantly more residue cover than all other treatments followed by W-GS-F, W/FSH-FSH-F, W-GSG-F (Figure 2.3a). However, residue cover in 2024 did not differ among treatments, but the W/FSG-FSG-F treatment trended higher, while W/FSH-FSH-F tended to have the least residue cover (Figure 2.3b). In 2025, residue cover in W-GS-F, W-GSG-F, and W/FSG-FSG-F were not significantly different from one another but had significantly more residue cover than the W/FSH-FSH-F treatment (Figure 2.3c). Averaged across the 3-years, the W/FSG-FSG-F had the most residue cover, followed by W-GS-F, W-GSG-F, and least in W/FSH-FSH-F (Table 2.3). Averaged across crop rotation treatments, residue cover in 2025 (74%) and 2024 (72%) were significantly higher than residue cover measured in 2023 (59%).

Aggregate Stability

Wet-aggregate MWD was not different among treatments. However, dry-aggregate MWD was significantly less for W/FSH-FSH-F compared to the other treatments (Table 2.3). In 2023, W/FSH-FSH-F had significantly higher percent WEF fraction than all other treatments, and the grazed treatments (W-GSG-F and W/FSG-FSG-F) remaining similar to W-GS-F prior to wheat planting (Figure 2.4a). In 2024, all treatments were similar in percent WEF prior to wheat planting, but in 2025, the more intensive forage treatments, W/FSG-FSG-F and W/FSH-FSH-F had significantly higher percent WEF, than the less intensive grain-based treatments W-GSG-F

and W-GS-F (Figure 2.4b; c). Overall, the WEF measured under W/FSH-FSH-F ranked highest in each sampling year.

Bulk Density and Penetration Resistance

Rotation had no effect on soil bulk density (Table 2.3). Year, depth, and the two-way interaction of year × sampling depth had a significant effect on bulk density. The likely explanation for the two-way interaction is that bulk density sampling occurred in different plot locations each year, therefore year x sampling depth has little to do with treatment effect. At the 5-15 cm sampling depth, bulk density was significantly higher in 2025 (1.50 g cm^{-3}) than in 2024 (1.45 g cm^{-3}) and 2023 (1.43 g cm^{-3}). The bulk density at the 0-5 cm sampling depth in 2024 (1.25 g cm^{-3}) and 2025 (1.23 g cm^{-3}) was significantly higher than 2023 (1.14 g cm^{-3}). Although there was an overall increase across depths in 2025, the increase in bulk density was still less than the root limiting threshold of 1.60 g cm^{-1} for silt-loam soils (USDA-NRCS, 2022).

Penetration resistance was significantly affected by rotation and sampling depth. Interestingly, the less intensive rotations W-GS-F and W-GSG-F had significantly higher penetration resistance than W/FSG-FSG-F and W/FSH-FSH-F treatments (Table 2.3). The decrease in penetration resistance in the more intensive cropping rotations was likely due to the increased root biomass provided by the additional double-crop forage. As expected, the 5-15 cm (0.85 MPa) depth had significantly greater penetration resistance than the 0-5cm depth (0.51 MPa) across years. Even though the less intensive rotations and deeper sampling depth had significantly greater penetration resistance, values were still far from the root limiting value of 2.00 MPa for silt-loam soils (Banco-Canqui et al., 2021).

Soil Organic Carbon and Particulate Organic Matter

Soil organic carbon was significantly affected by crop rotation × year × depth (Table 2.3). The significant three-way interaction indicated that crop rotation effects on SOC varied across years and soil depths. In general, SOC concentrations were highest in the 0-5 cm sampling depth, with no significant difference among rotation at the 0-5 cm depth. At the 5-15 cm sampling depth, no significant difference was observed among rotation in 2023 and 2024 (Figure 2.5a; b). In 2025, the W-GS-F had significantly more SOC than W-GSG-F, likely due to grain sorghum stalk biomass removal with grazing (Figure 2.5c).

Particulate organic matter concentrations were not significantly affected by crop rotations, but differences were seen among years, depths, and the year × depth interactions (Table 2.3). The POM concentrations were significantly higher in 2024, followed by 2025 and 2024 averaged across treatments. Across treatments, the 0-5 cm (0.54%) sampling depth had significantly more POM than the 5-15 cm (0.19%) depth.

Aggregate Associated Carbon

Because of the limited rotation effect on SOC and POM, aggregate associated SOC was analyzed to see if rotations differed within individual aggregate size classifications, which can indicate if total SOC will increase in further iterations of rotation cycles. Dry-aggregate associated carbon was not significantly different in the >2 mm size fraction among crop rotation treatments. However, aggregate SOC differed among years with 2024 having the highest SOC concentrations. Again, even though there was not a significant effect, the grazed treatments trended higher than the un-grazed. Dry-aggregate SOC within the 2-0.25 mm and <0.25 mm size classes significantly differed among rotation treatment and year. Interestingly, when averaged across the three sampling years, SOC concentrations within the 2-0.25 mm aggregate size

classification were significantly higher for the less intensive W-GSG-F when compared to W/FSG-FSG-F, W/FSH-FSH-F, and W-GS-F. Which is the opposite of 2025 total SOC concentrations analyzed at the 5-15 cm sampling depth. Because of a significant rotation × year interaction within the <0.25 mm aggregate size class, SOC concentrations were presented for each sampling year. In 2023, W-GS-F had significantly less dry-aggregate associated SOC than W-GSG-F, W/FSG-FSG-F, and W/FSH-FSH-F (Figure 2.6a). In 2024, there was no significant difference between treatments, but the grazed treatments had slightly higher dry-aggregate SOC (Figure 2.6b). Similar to 2023, W-GS-F had significantly less dry-aggregate SOC in 2025 when compared to W-GSG-F, W/FSG-FSG-F, and W/FSH-FSH-F (Figure 2.6c).

Wet-aggregate SOC did not have a significant rotation effect (Table 2.4). Although there was no significant rotation effect, the wet-aggregate SOC measured in the grazed (W-GSG-F, W/FSG-FSG-F) treatments trended higher in each size fraction. Within year, SOC concentrations across aggerate size classes were greater in 2023 (2.92%) than 2025 (2.24%), or 2024 (1.55%), which may be differences in plot areas sampled in each year of the study. Overall, aggregate-associated carbon was either significantly higher or trended higher in the grazed treatments.

Nitrogen, Phosphorus and pH

The two-way interaction of treatment × depth, year, and depth affected soil pH, N and P concentrations. The difference in nutrient concentrations and pH between sampling depth had little to do with rotation treatment effect, and more to do with nutrient and pH stratification in no-tillage soil between soil depths. As expected, the surface 0-5 cm depth (25.38 kg ha^{-1}) had higher N concentrations than the sub-surface 5-15 cm depth (15.60 kg ha^{-1}) across treatments. Available soil P concentrations at the 0-5 cm depth (40.49 kg ha^{-1}) were significantly higher than the sub-surface 5-15 cm depth (25.72 kg ha^{-1}) when averaged across treatments. Soil pH was

significantly different between the two sampling depths, with an average pH of 6.0 in the sub-soil and 5.5 near the surface in the 0-5 cm depth.

Costs and Net Returns

Costs were averaged across the two years of economic analyses, because there was not a significant year effect. Average cost of production was least for the W/FSG-FSG-F treatment. The W-GS-F and W-GSG-F treatments did not have a significant cost difference from one another, but both had significantly less cost of production than the hayed treatment W/FSH-FSH-F (Table 2.5). The W/FSH-FSH-F costs were \$442.00 ha^{-1} more than W/FSG-FSG-F.

Net return was significantly affected by rotation × year interaction, so net return and profitability for all treatments were determined for both 2024 and 2025 (Table 2.6). In both years, treatments were compared to grazing alternative lease values of rangeland and confined hay feeding. In 2024, within the rangeland lease alternative, W-GS-F had significantly lower net returns than all other treatments and was the only treatment that had negative net returns (Table 2.6). In the same year, within the confined hay feeding lease alternative, the two grazing treatments (W-GSG-F, W/FSG-FSG-F) had significantly higher net returns, ~\$229 ha^{-1} more than W/FSH-FSH-F and ~\$401 ha^{-1} more than W-GS-F. In 2025, within the rangeland leasing alternative, again, the less intensive grazed treatment (W-GSG-F) had the highest net return, followed by W-GS-F>W/FSG-FSG-F>W/FSH-FSGH-F. The alternative confined hay feeding lease scenario in 2025 mimicked what was seen within the rangeland lease alternative, with the less intensive cropping rotations (W-GSG-F>W-GS-F) providing higher net returns than W/FSG-FSG-F and W/FSH-FSGH-F. Overall, W-GSG-F consistently provided greater net returns than all other treatments within each year and grazing lease scenario. In 2025, the less

intensive cropping systems provided greater net returns than W/FSG-FSG-F and W/FSH-FSH-F, due to higher grain production in 2025 than 2024.

Discussion

Intensifying or substituting grain sorghum in the rotation with annual forages that were grazed or hayed did not have a significant effect on average winter wheat yields. For this study, the lack of wheat yield differences between crop rotation treatments could be attributed to poor wheat yields (1,541 kg ha^{-1}) throughout the three years due to less than average growing season precipitation in January to May (Figure 2.1). This finding was similar to Holman et al (2022), who concluded that wheat yields are not impacted by cropping intensification in very low or high yielding environments. Similarly, average yields between the two grain sorghum treatments, W-GS-F and W-GSG-F were not significantly different, indicating that grazing sorghum stalks did not impact subsequent grain sorghum yields. The presence of fallow periods between grain sorghum growing seasons, combined with minimal soil disturbance from grazing likely buffered any potential effects seen from residue cover removal to subsequent grain sorghum yields.

Full-season forage sorghum production was relatively high for all five years of production, ranging from a low in 2022 to a high in 2025 (Table 2.2). Less than average long-term rainfall (2022, 2023, and 2024) had less of an impact on forage production than it did on grain sorghum production, which agrees with conclusions from previous research within the region (Holman et al., 2018; 2020c; 2021; 2022). This difference likely reflects the fact that forage yield depends on vegetative growth, while grain sorghum yield depends on successful reproductive development, which can be extremely sensitive to extreme temperatures and drought. Haying and grazing harvest methods also had limited impact on total forage production, despite the biomass removal difference between the two (Grazing removed 50% vs. 70% with

Haying) (Table 2.2). Double-crop forage sorghum production on the other hand was limited in years with less than average precipitation, especially in 2022 when biomass was not harvested. Limited double-crop forage biomass is not surprising, because available soil water is often depleted after wheat grain harvest, making it difficult to achieve adequate crop establishment (Obour et al., 2021b). Because of limited forage production in the double-crop forage growing season, less biomass was removed when harvested (Grazing 40%, Haying 62%) than what was removed in the full-season production period in order to maintain adequate soil surface cover for the fallow period. Within limited forage mass production scenarios, grazing of forage is recommended to maintain soil surface residue and soil properties (Kelly et al., 2021; Simon et al., 2021). This agrees with Holman et al. (2022), who proposed that forage should be grazed in dry years, and hayed or kept as silage in wet years to build up feed reserves and stabilize forage demand.

Soil surface residue cover measured at wheat planting was either significantly higher or trending higher for the more intensified grazing treatment (W/FSG-FSG-F), because of significant regrowth potential of forage sorghum and trampling of forage by grazing cattle, which retained more biomass on the soil surface. Soil residue cover left from grazing was similar to findings by Simon et al. (2021), where grazing of cool-season dual-purpose cover crops left 86% of the soil surface covered in a similar production system. Though, within Simon's findings, hayed forage treatments often maintained soil surface coverage compared to the grazed treatments.

With haying and grazing there is still concern that removing large amounts of biomass may negate the positive soil health benefits that adding an additional crop within the rotation provides (Franzluebbers and Studemann, 2008; 2014; 2015). The wet aggregate stability analysis

in this study contradicted previous findings, with no significant increase or decrease of water erosion potential observed within any of the rotations or harvest types compared to the W-GS-F control treatment. Where previous research showing soil degradation due to harvesting of forages aligned was within the dry-aggregate analysis. The intensified forage rotation with haying significantly reduced dry-aggregate MWD, and increased soil WEF in most years. These results double down on the term "residue is king", as the reduction in soil cover due to haying is likely the cause of the reduction in dry-aggregate MWD and increase in WEF within the hayed treatment. Though, in 2025 the W/FSG-FSG-F treatment had significantly higher WEF than the control and the less intensive grazed treatment. We believe the increase in 2025 can be attributed to wet grazing conditions in 2024, as cattle were unable to be removed from plots during a rainstorm, thus degrading soil aggregates and increasing soil WEF. This example of soil degradation due to wet grazing conditions further amplifies the importance of grazing in dry soil conditions, and/or having a paddock for grazing animals to be moved to during a rain event.

Another concern with grazing and haying of forages is the risk of root-limiting soil compaction that could diminish subsequent crop yields within the cropping system (Blanco-Canqui et al., 2021; Obour et al., 2021c; Schomberg et al., 2021). In NT systems, root-limiting layers may have to be alleviated by unwanted tillage operations, therefore diminishing positive soil health impacts of NT (Blanco-Canqui et al., 2021; Franzluebbers and Stuedemann, 2008; Schomberg et al., 2021). In this study, bulk density was not different among crop rotation treatments and averaged 1.34 g cm^{-3} across treatments and sampling depth over the 3-year study period. However, bulk density is not as accurate of a compaction indicator for root growth as penetration resistance. Penetration resistance is more accurate, because it simulates pressure that a root may encounter through soil layers. In this study, penetration resistance was significantly

different among treatments with W-GS-F and W-GSG-F requiring more force on average than W/FSG-FSG-F and W/FSH-FSH-F. The more intensified grazing and haying rotations likely had lower penetration resistance because of the inclusion of forage sorghum as part of cropping rotations. Forage sorghum is planted at a narrow row spacing, creating more root biomass with greater potential to break up compacted soil layers that the less intensive cropping systems were unable to alleviate. Although crop rotation treatments differed in their effect on penetration resistance, the measured values are still far below the root-limiting threshold of 2.00 Mpa that will negatively impact crop productivity (Banco-Canqui et al., 2021). Results from this study align with previous studies in CGP region that concluded that if grazing and haying is done responsibly, soil health will not be diminished when compared to un-grazed treatments (Blanco-Canqui et al., 2013; 2020; 2021; Kelly et al., 2021; Simon et al., 2021; 2022).

In this study, bulk SOC concentrations were not different among treatments in 2023 and 2024. But in 2025, the W-GSG-F had significantly smaller SOC concentrations than the W-GS-F control treatment at the 5-15 cm depth. The reduction was minimal, and frankly an anomaly compared to other sampling years because it was the only time any significance was seen within bulk SOC at either sampling depth. Wet-aggregate associated SOC was not different among treatments, but trended higher in grazed treatments (WGSG-F and W/FSG-FSG-F) compared to W-GS-F and W/FSH-FSH-F for each aggregate size class. The results seen within the wet-aggregate SOC mirrored results of the dry-aggregate SOC, but the dry aggregate fractions had significantly higher SOC within the grazed treatments. The cause of greater aggregate associated SOC concentration in grazed treatments likely has less to do with manure deposited, because during the sampling period cattle manure pats were intentionally missed to avoid skewing of results. The increase in aggregate associated SOC in the grazed treatments was more likely due

to cattle trampling available forage into the soil, therefore speeding up nutrient cycling and increasing SOC faster than un-grazed treatments.

In this study crop rotation had minimal impact on soil N, P, or pH. Most of observed differences were between soil sampling depth. The nutrient concentrations differences between depth had little to do with treatment effect, but mostly due to nutrient stratification. Nitrogen is a mobile soil nutrient and moves readily through the soil than immobile nutrients like P. With P being immobile, concentrations are consistently higher in the 0-5 cm soil depth. The inverse was true for pH, the soil surface (0-5 cm depth) had lower pH than the 5-15 cm sub-surface. This was possibly due to greater calcium carbonates concentration within the sub-surface that neutralize hydrogen ions, therefore increasing soil pH in the sub-surface 5-15 cm depth compared to the top 0-5 cm depth.

Net return results in 2024 somewhat agree with other studies done within the last ten years looking at profitability of intensifying dryland cropping systems with an additional forage crop (Holman et al., 2018; 2022; Nielsen et al., 2016; 2017). In the present study, grazing sorghum stalks (W-GSG-F) or incorporating FS as part of the cropping system had significantly higher net returns than W-GS-F, regardless of the two leasing alternatives. In 2025, which had above average precipitation, all cropping systems were profitable. Again, cropping system profitability increased with the less intensive grain-based rotations in each alternative leasing rate. These results indicate that in above average precipitation years, grain-based systems have higher net return potential than forage-based rotations. Overall, utilizing grain sorghum as a dual-purpose crop greatly influenced net returns for the W-GSG-F rotation. Outside of W-GSG-F consistently exhibiting higher net returns, and W-GSG-F and W-GS-F exhibiting higher net returns in 2025, net returns seen within the rotations were variable. In general, the grain-based

systems W-GS-F and W-GSG-F were ~$294 cheaper to produce than the intensively managed forage-based hayed production system. The W/FSG-FSG-F treatment had the lowest cost of production, approximately $377.13 cheaper than W/FSH-FSH-F and ~$83.63 cheaper than W-GS-F and W-GSG-F. The W/FSG-FSG-F treatment had the least cost of production because it did not incur high costs associated with grain harvest and forage haying. Also, due to leasing of forage to a rancher, costs such as water and fence infrastructure were left as a cost to the rancher rather than the forage producer, therefore leaving minimal cost of forage harvest. Further investigation is needed to analyze effects of increasing biomass removal beyond 50%, as increasing removal would have greatly increased net returns for the W/FSG-FSG-F rotation.

Conclusion

Intensifying the W-GS-F rotation with forage sorghum and integrating livestock and haying had no effect on subsequent wheat yields in 2023-2025. Integrating livestock also had no effect on grain sorghum yields. Harvest method had no impact on overall forage production, but grazing left significantly more biomass (50% biomass as residue retained) as residue cover than the haying (30% of biomass retained) treatments. Because of significantly more biomass remaining after grazing forage sorghum, soil cover was greater in each sampling period, with haying of forage sorghum having significantly less or trending less in each period except for 2023 where W-GSG-F had the least percent cover. In general, wet aggregate MWD was not different among treatments, but DAMWD was significantly less in the W/FSH-FSH-F treatment. This resulted in significantly higher WEF under W/FSH-FSH-F compared to the other remaining treatments. Bulk density was unaffected by crop rotation treatments, but penetration resistance was significantly less in both intensified forage sorghum systems. Bulk SOC and WASOC concentrations were minimally affected by treatments, while dry aggregate associated SOC

fractions were increased by the grazing treatments. Indicating that bulk SOC concentration within the grazing treatments may increase in future cycles of the rotations. Nitrogen, P, and pH was unaffected by crop rotation treatments. The W-GSG-F treatment had either the highest or second highest net returns than all other treatments within each alternative grazing lease, highlighting the value of a dual-purpose crop. However, W/FSG-FSG-F had the least associated costs making it more economical than W/FSH-FSH-F and W-GS-F in dry years such as 2024, but removing greater than 50% of available forage mass would significantly increase the rotation net return. Though, it is plausible that removing greater than 50% of available forage mass may negate positive soil health effects from the rotation. Overall, grazed treatments had a positive or neutral impact on soil health due to increased cycling of nutrients through grazing and leaving adequate surface residue cover, while having lower production costs and providing greater net returns compared to W-GS-F and W/FSH-FSH-F.

References

Agmanager (2024). Available online at: https://www.agmanager.info/machinery/papers/custom-rates-survey

Assefa, Y., Roozeboom, K., Thompson, C., Schlegel, A., Stone, L., and Lingenfelser, J. (2014). Rotation effect of corn and sorghum in cropping systems. In Corn and grain sorghum comparison: All things considered. Academic Press, New York. pp. 87-101.

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

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

Blanco-Canqui, H. and Ruiz, S.J. (2020). Cover crop impacts on soil physical properties: A review. Soil Science Society of America Journal, 84(2020), 1527–1576. https://doi.org/10.1002/saj2.20129

Blanco-Canqui, H., Drewnoski, M.E., MacDonald, J.C., Redfearn, D.D., Parsons, J., Lesoing, G.W., Williams, T. (2021). Does cover crops grazing damage soils and reduce crop yields? Agrosystems, Geosciences & Environment, 3(1), 1–11. https://doi.org/10.1002/agg2.20102

Cambardella, C.A., and Elliott, E. T. (1992). Particulate soil organic-matter changes across a grassland cultivation sequence. Soil Science Society, 56:777–783. https://doi.org/10.2136/sssaj1992.03615995005600030017x

Carr, P. M., Bell, J. M., Boss, D. L., DeLaune, P., Eberly, J. O., Edwards, L., Fryer, H., Graham, C., Holman, J., Islam, M. A., Liebig, M., Miller, P. R., Obour, A., Xue, Q. (2020). Annual forage impacts on dryland wheat farming in the Great Plains. Agronomy Journal, 113:1-25. doi: 10.1002/agj2.20513

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

Dhuyvetter, K. C., Thompson, C. R., Norwood, C. A., and Halvorson, A. D. (1996). Economics of dryland cropping systems in the great plains: a review. Journal of Production Agriculture. https://doi-org.er.lib.k-state.edu/10.2134/jpa1996.0216

Franzluebbers, A.J. and Stuedemann, J.A. (2008). Soil physical responses to cattle grazing cover crops under conventional and no tillage in the Southern Piedmont USA. Soil & Tillage Research, 100(2008), 141–153. https://doi.org/10.1016/j.still.2008.05.011

Franzluebbers, A.J. and Stuedemann, J.A. (2014). Temporal dynamics of total and particulate organic carbon and N in cover crop grazing cropping systems. Soil Science Society of America, 78, 1404–1413. https://doi.org/10.2136/sssaj2014.01.0042

Franzluebbers, A.J. and Stuedemann, J.A. (2015). Does grazing of cover crops impact biologically active carbon and nitrogen fractions under inversion or no tillage management? Journal of Soil and Water Conservation. 70(6), 365–373. https://doi.org/102489/jswc.70.6.365

Grossman, R.B., and Reinsch, T. G. (2002). Bulk density and linear extensibility. In: Dane J. H. and Topp G. C., editors, Methods of soil analysis. Part 4. SSSA Book Ser. 5. Soil Science Society of America, 201–225. https://doi.org/10.2136/sssabookser5.4.c9

Hofstrand, D. and Edwards, W. (2015). Computing a pasture rental rate. Ag Decision Maker. Iowa State University. https://www.extension.iastate.edu/agdm/wholefarm/pdf/c2-23.pdf

Holman, J.D., Arnet, K., Dille, J., Maxwell, S., Obour, A., et al. (2018). Can cover or forage crops replace fallow in the semiarid central great plains? Crop Science, 58:932–944. doi: 10.2135/cropsci2017.05.0324.

Holman, J., Obour, A., Schlegel, A., Roberts, T., and Maxwell, S. (2020a) Estimating Annual Forage Yields with Plant Available Water and Growing Season Precipitation, Kansas Agricultural Experiment Station Research Reports: Vol. 6: Iss. 8. https://doi.org/10.4148/2378-5977.7961

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

Holman, J. D., Assefa, Y., and Obour, A. K. (2020c). Cover-crop water use and productivity in the high plains wheat-fallow crop rotation. Crop Science Society of America, 61:1374-1385. https://doi.org/10.1002/csc2.20365

Holman, J. D., Obour, A. K., and Assefa, Y. (2021). Productivity and profitability with fallow replacement forage, grain, and cover crops in W-S-F rotation. Crop Science, 62, 913–927. **https://doi.org/10.1002/csc2.20670**

Holman, J. D., Obour, A. K., and Assefa, Y. (2022). Forage sorghum grown in a conventional wheat-grain sorghum-fallow rotation increased cropping system productivity and profitability. Canadian Journal of Plant Science, 103: 61-72. http://dx.doi.org/10.1139/CJPS-2022-0171

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

Mehlich, A. (1984). Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. Communications in Soil Science and Plant Analysis, 15:1409–1416. https://doi.org/10.1080/00103628409367568

Nelson, D.W. and Sommers, L. E. (1996). Total carbon, organic carbon, and organic matter. Soil Science Society of America, 961–1010. https://doi.org/10.2134/agronmonogr9.2.2ed.c29

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

Nielsen, D. C., Vigil, M. F., and Hansen, N. C. (2016). Evaluating potential dryland cropping systems adapted to climate change in the central great plains. Agronomy Journal, 108: 2391-2405. doi: 10.2134/agronj2016.07.0406

Nielsen, D.C. and Vigil, M.F. (2017). Intensifying a semi-arid dryland crop rotation by replacing fallow with pea. Agricultural Water Management, 127–138. https://dx.doi.org/10.1016/j.agwat.2017.03.003

Nimmo, J.R., and Perkins, K. (2002). Aggregate stability and size distribution. Methods of soil analysis, Part 4-Physical methods. Soil Science Society of America Book Series No. 5. https://doi.org/10.2136/sssabookser5.4.c14

Obour, A. K., Simon, L. M., Holman, J. D., and Johnson, S. K. (2021a). Does grazing Cover crops impact soil properties? K-State Research and Extension vol. 7: Iss. 5. https://doi.org/ 10.4148/2378-5977.8078

Obour, A. K., Simon, L. M., Holman, J. D., Carr, P. M., Schipanski, M., Fonte, S., Ghimire, R., Nleya, T., Blanco-Canqui, H. (2021b). Cover crops to improve soil health in North American Great Plains. Agronomy Journal, 113:4590-4604. https://doi.org/10.1002/agj2.20855

Obour, A.K., Holman, J.D., Simon, L.M., and Schlegel, A.J. (2021c). Strategic tillage effects on crop yields, soil properties, and weeds in dryland no-tillage systems. Agronomy, 11 (4), 662. https://doi.org/10.3390/agronomy11040662

Obour, A. K., Holman, J. D., Simon, L. M. (2023). Grazing cover crops improved soil health in dryland cropping systems. Kansas Agricultural Experiment Station

Research Reports: Vol. 9: Iss. 6. https://doi.org/10.4148/2378-5977.8486

Peterson, G. A., Halvorson, A. D., Havlin, J. L., Jones, O. R., Lyon, D. J., and Tanaka, D. L. (1998). Reduced tillage and increasing cropping intensity in the Great Plains conserves soil C. Soil and Tillage Research, 47:207-218. https://doi-org.er.lib.k-state.edu/10.1016/S0167-1987(98)00107-X

Peterson, G.A. and Westfall, D.G. (2004). Managing precipitation use in sustainable dryland agroecosystems. Annals of Applied Biology, 144(2), 127–138. https://doi.org/10.1111/j.1744-7348.2004.tb00326.x

Peterson, G.A., Westfall, D.G., Schipanski, M.E., and Fonte, S.J. (2020). Soil and crop management systems that ameliorate damage caused by decades of dryland agroecosystem mismanagement. Agronomy Journal, 112(5), 3227–3238. https://doi.org/10.1002/agj2.20257

Rangeland Analysis Platform. (2026). Cover and production data available online at https://rangelands.app

Ratliff, L.F., Ritchie, J.T., and Cassel, D.K. (1983). A survey of field measured limits of soil water availability and related laboratory-measured soil properties. Soil Science Society of America Journal, 47, 770 – 775. https://doi.org/10.2136/sssaj1983.03615995004700040032x

Schomberg, H.H., Endale, D.W., Balkcom, K.S., Raper, R.L., and Seman, D.H. (2021). Grazing winter rye cover crop in a cotton no-till system: Soil strength and runoff. Agronomy Journal, 113(2), 1271–1286. https://doi.org/10.1002/agj2.20612

Simon, L.M., Obour, A.K., Holman, J.D., Johnson, S.K., and Roozeboom, K.L. (2021). Forage productivity and soil properties in dual-purpose cover crop systems. Agronomy Journal, 113, 5569–5583. https://doi.org/10.1002/agj2.20877

Simon, L.M., Obour, A.K., Holman, J.D., and Roozeboom, K.L. (2022). Long-term cover crop management effects on soil properties in dryland cropping systems. Agriculture, Ecosystems & Environment, 328, 1–11. https://doi.org/10.1016/j.agee.2022.107852

Simon, L. M. (2024). Cover crops to regenerate soils and increase profitability in dryland crop production in the semi-arid central Great Plains. (Doctoral dissertation, Kansas State University).

Thomas, G. W. (1996). Soil pH and soil acidity. In D. L. Sparks (Ed.), Methods of soil analysis part 3: Chemical methods (pp. 475–490). SSSA.

USDA-NCRCS (2022). Soil Health-Bulk Density, from: https://www.nrcs.usda.gov/sites/default/files/2022-11/Bulk%20Density%20-%20Soil%20Health%20Guide_0.pdf

USDA ERS. (2025) Commodity cost and returns. Economic Research Service. Available online at https://www.ers.usda.gov/data-products/.

USDA-NRCS. (2002). National agronomy manual (3rd ed.). USDA Natural Resources Conservation Service.

USDA. (2025). Irrigated, non-irrigated, and pasture rental rates for Kansas counties. Available online at https://www.agmanager.info/farm-management/land-rental-rates/usda-nass-2025-rental-rates-kansas-data

Zadoks, J.C., Chang, T. T., and Konzak, C. F. (1974). A decimal code for the growth stages of cereals. Weed Research, 14, 415–421. https://doi.org/10.1111/j.1365-3180.1974.tb01084.x

Tables

Table 2.1. Effect of rotation intensification and haying and grazing on average winter wheat and grain sorghum yields near Hays, KS**.**

	Crop	
	Winter Wheat	Grain Sorghum
Treatment		
	——— kg ha^{-1} ———	
W-GS-F	1498a[†]	4375a
W-GSG-F	1514a	4753a
W/FSG-FSG-F	1523a	-
W/FSH-FSH-F	1627a	-
Test of fixed effects	P-values	
Treatment (T)	0.7859	0.3461
Year (Y)	**<.0001**	**<.0001**
T*Y	0.2553	0.3190

[†]Means within a column followed by the same lower-case number are not statistically different (α =0.1) among treatments within each crop.

Table 2.2. Available forage sorghum yields in full-season and double-crop production, and percent of forage remaining after haying and grazing forage sorghum near Hays, KS.

	Double-crop	Residue Remaining	Full-season	Residue Remaining
Treatment				
	– kg ha^{-1} –	– % –	– kg ha^{-1} –	– % –
Grazing	2951a[†]	60a	6933a	50a
Haying	2898a	38b	7338a	28b
Year				
2021	2997c	57a	7250ba	24d
2022	831e	-	5733b	44ba
2023	1527d	-	6123b	29dc
2024	5067a	47b	8254a	56a
2025	4201b	43b	8319a	41bc
Test of fixed effects		P-values		
Harvest Type (HT)	0.7477	**<0.0001**	0.556	**0.0005**
Year (Y)	**<.0001**	**0.0321**	**0.0701**	**0.0093**
HT*Y	0.1077	**0.0003**	0.3185	0.3446

[†]Means within a column followed by the same lower-case number are not statistically different (α =0.1) among harvest type and year.

Table 2.3. Average cropping system intensification effects on soil chemical, bio-chemical, and physical properties measured in 2023 through 2025 near Hays, KS.

Treatments	BD	PR	SOC	POM	N	P	pH	RC	WAMWD	DAMWD	WEF
	-g cm^{-3}-	-Mpa-	-%-	-%-	-kg ha^{-1}-	-kg ha^{-1}-	-pH-	-%-	-mm-	-mm-	-%-
W-GS-F	1.33a[†]	0.73a	1.16a	0.38a	21.1	38	5.8a	70.4b	0.95a	6.0a	28.0b
W-GSG-F	1.34a	0.73a	1.16a	0.34a	21.6	30.1	5.8a	64.2cb	0.97a	5.6a	27.6b
W/FSG-FSG-F	1.35a	0.63b	1.19a	0.37a	17.6	32.7	5.8a	80.4a	0.96a	5.6a	29.2b
W/FSH-FSH-F	1.32a	0.64b	1.17a	0.37a	21.6	31.6	5.7a	58.3c	1.05a	4.9b	33.2a
Test of fixed effects						P-values					
Treatment (T)	0.7736	**0.0327**	0.9571	0.5155	0.3275	0.2731	0.9006	**0.0006**	0.9139	**0.0226**	**0.0135**
Year (Y)	**0.002**	0.275	**<.0001**	**0.0001**	**<.0001**	**0.0008**	**<.0001**	**0.0021**	**0.0836**	**0.0022**	**0.043**
T*Y	0.1409	0.1865	0.8898	0.3905	0.1727	0.832	0.5166	**0.0903**	0.9291	0.5328	**0.0978**
Depth (D)	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	-	-	-	-
T*D	0.1179	0.7773	0.5837	0.1458	**0.0332**	**0.0946**	**0.0287**	-	-	-	-
Y*D	**0.0802**	0.1148	**0.0007**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	-	-	-	-
T*Y*D	0.1557	0.4762	**0.0285**	0.3674	0.2252	0.662	0.9454	-	-	-	-

[†]Means within a column followed by the same lower-case number are not different (α =0.1) across each treatment within each soil parameter. BD = bulk density; PR = penetration resistance; SOC = soil organic carbon; POM = particulate organic matter; N = nitrogen; P = phosphorus; RC = residue cover; WAMWD = wet aggregate mean weight diameter; DAMWD = dry aggregate mean weight diameter; WEF = wind erodible fraction.

Table 2.4. Cropping system intensification effects on dry aggregate soil organic carbon (DASOC) and wet aggregate soil organic carbon (WASOC) measured in 2023 to 2025 near Hays, KS.

	DASOC			WASOC		
	>2mm	2-0.25mm	>0.25mm	>2mm	2-0.25mm	>0.25mm
Treatment						
	%					
W-GS-F	1.03a[†]	1.26b	0.91b	2.33a	1.23a	0.92a
W-GSG-F	1.14a	1.46a	1.08a	2.64a	1.35a	1.03a
W/FSG-FSG-F	1.13a	1.30b	1.08a	2.10a	1.36a	1.01a
W/FSH-FSH-F	1.08a	1.28b	0.97b	1.88a	1.28a	0.99a
Test of fixed effects			P-values			
Treatment (T)	0.2003	**0.0494**	**0.0238**	0.2153	0.5956	0.5815
Year (Y)	**<.0001**	**<.0001**	**<.0001**	**0.0008**	**<.0001**	**<.0001**
T*Y	0.9917	0.1701	**0.0959**	0.4649	0.4951	0.9386

[†]Means within a column followed by the same lower-case number are not different ($\alpha = 0.1$) across each treatment within each soil parameter.

Table 2.5. Cropping system intensification effects on total production costs averaged over 2024 and 2025 growing seasons near Hays, KS.

Management	Unit	W-GS-F	W-GSG-F	W/FSG-FSG-F	W/FSH-FSH-F
Planting & Seeding					
Planting Cost	$/ha	91.47	91.47	120.30	120.30
Seeding Cost	$/ha	135.93	135.93	213.72	213.72
Total Cost	$/ha	227.4	227.4	334.02	334.02
Cost of bales	$/ha	-	-	-	441.51
Grain					
Harvesting	$/ha	148.97	148.97	72.05	72.05
Hauling Grain	$/ha	65.37	68.75	17.25	18.00
Total Cost	$/ha	214.34	217.72	89.30	90.05
Fertilizer					
Urea	$/ha	241.14	241.14	200.95	200.95
DAP	$/ha	70.14	70.14	70.14	70.14
Applications	No./yr	2	2	2	2
Cost Per Application	$/ha	18.74	18.74	18.74	18.74
Total Cost	$/ha	348.68	348.68	308.57	308.57
Herbicide					
Dicamba	$/ha	6.41	6.41	6.41	6.41
Glyphosate	$/ha	32.60	32.60	23.71	23.71
Sharpen	$/ha	20.25	20.25	20.25	20.25
2, 4-D	$/ha	23.56	23.56	23.56	23.56
Atrazine	$/ha	12.01	12.01	12.01	12.01
S-metolochlor	$/ha	18.54	18.54	18.54	18.54
Applications	No./yr	4	4	3	3
Cost Per Application	$/ha	14.80	14.80	14.80	14.80
Total Cost	$/ha	172.57	172.57	148.88	148.88
Total Expenses	$/ha	963.00b[†]	966.50b	880.88c	1322.88a

[†]Means within a row followed by the same lower-case number are not different ($\alpha = 0.1$) across each treatment.

Table 2.6. Cropping system intensification effects on net returns between 2024 and 2025 growing seasons near Hays, KS. Grazed systems were calculated as alternative to grazing rangeland and an alternative to confined hay feeding lease values.

		Net returns	
		Grazing as an alternative to:	
Year	Treatments	Grazing rangeland lease	Confined hay feeding lease
		——— US$ ha^{-1} ———	
2024	W-GS-F	†-85.75b	-85.75c
	W-GSG-F	183.00a	237.25ba
	W/FSG-FSG-F	169.67a	393.67a
	W/FSH-FSH-F	85.50ba	85.50bc
2025	W-GS-F	859.50b	859.50b
	W-GSG-F	1064.75a	1126.50a
	W/FSG-FSG-F	445.25c	699.25c
	W/FSH-FSH-F	317.75c	317.75d
Test of Fixed Effects		P-values	
Treatment (T)		**<.0001**	**<.0001**
Year (Y)		**<.0001**	**<.0001**
T*Y		**<.0001**	**<.0001**

†Means within a row followed by the same lower-case number are not different (α =0.1) across each treatment.

Figures

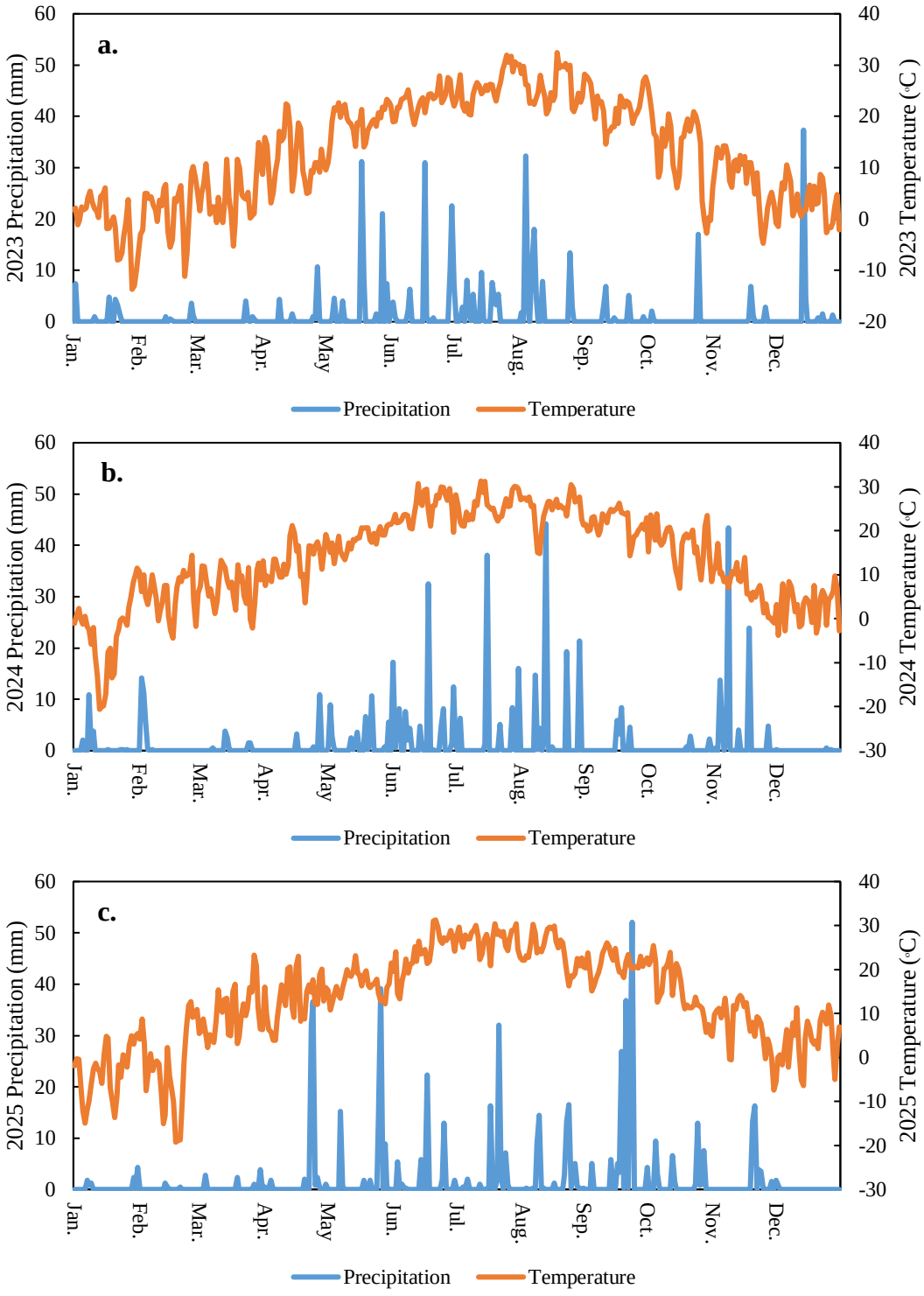

Figure 2.1. Daily precipitation and temperature averages in 2023 (a.), 2024 (b.), and 2025 (c.) near Hays, KS.

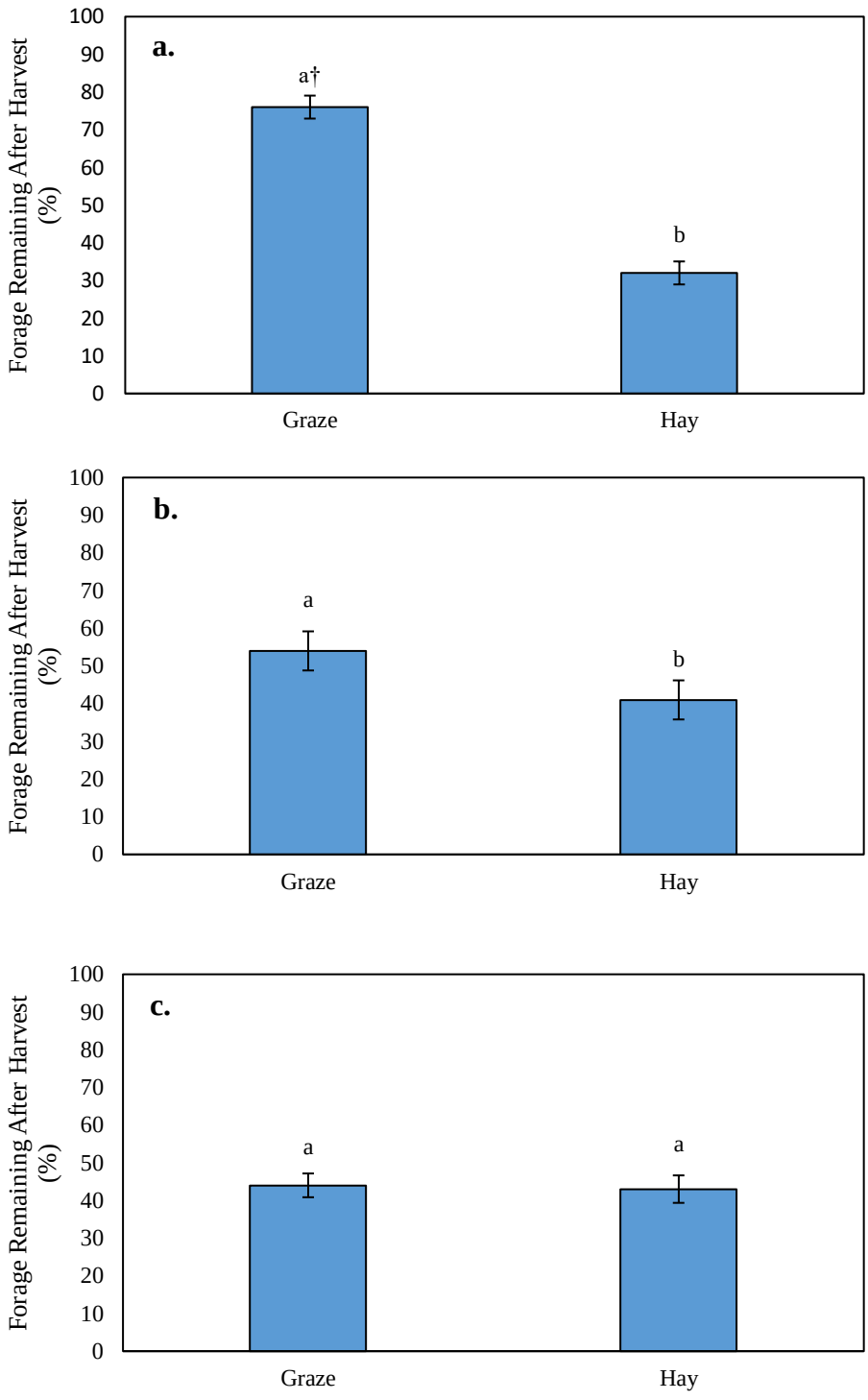

Figure 2.2. Effect of harvest type on forage sorghum remaining on the soil surface in 2021 (a.), 2024 (b.), and 2025 (c.) near Hays, KS.

†Means with the same letter are not significantly different ($\alpha = 0.1$) across treatments.

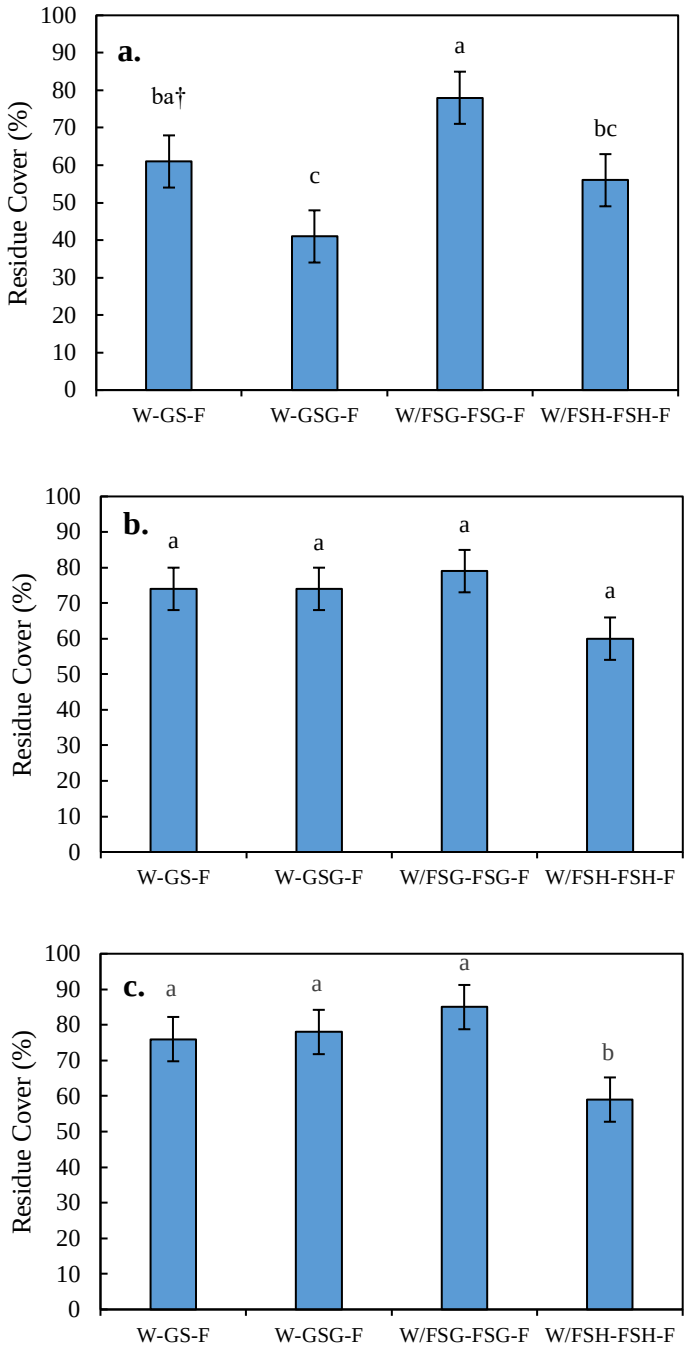

Figure 2.3. Effect of rotation intensification on soil surface residue cover in 2023 (a.), 2024 (b.), and 2025 (c.) near Hays, KS.

†Means with the same letter are not significantly different (α =0.1) across treatments.

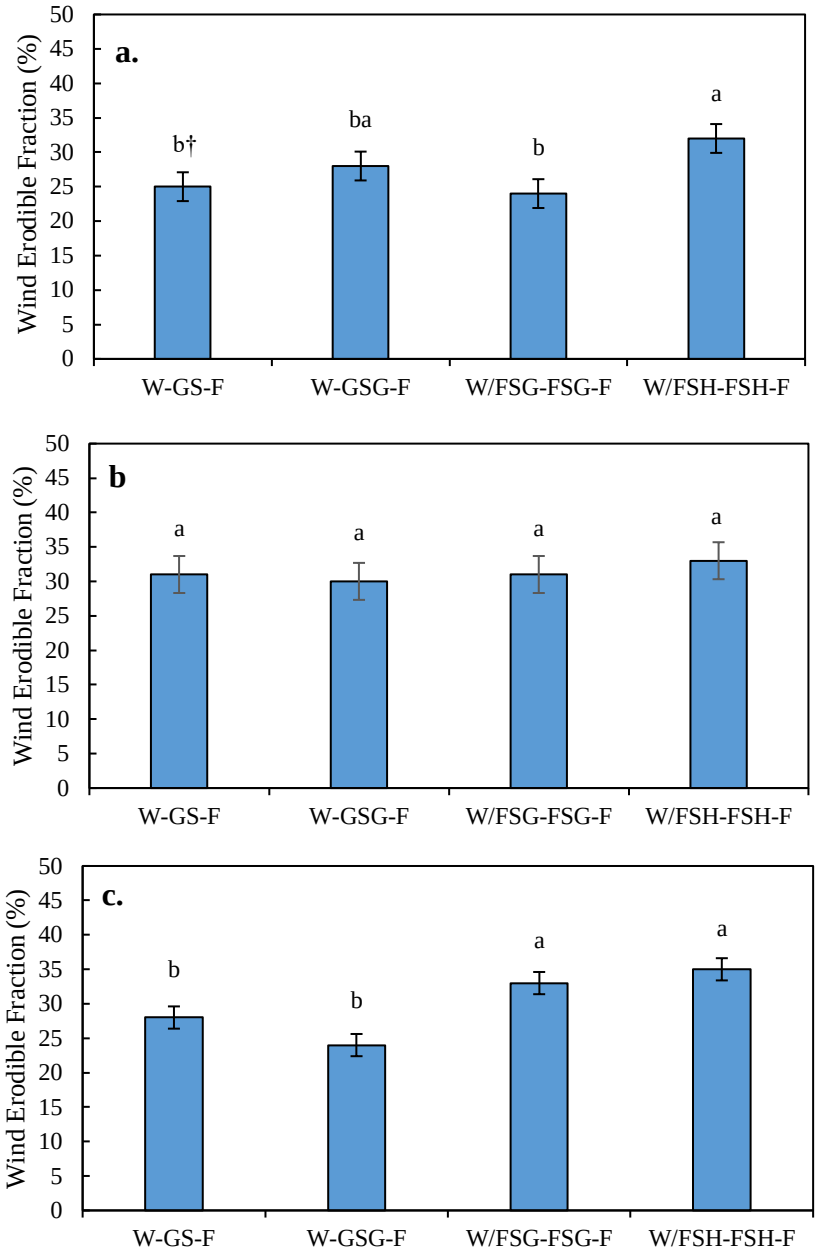

Figure 2.4. Effect of rotation intensification on wind erodible fraction in 2023 (a.), 2024 (b.), and 2025 (c.) near Hays, KS.

†Means with the same letter are not significantly different (α =0.1) across treatments.

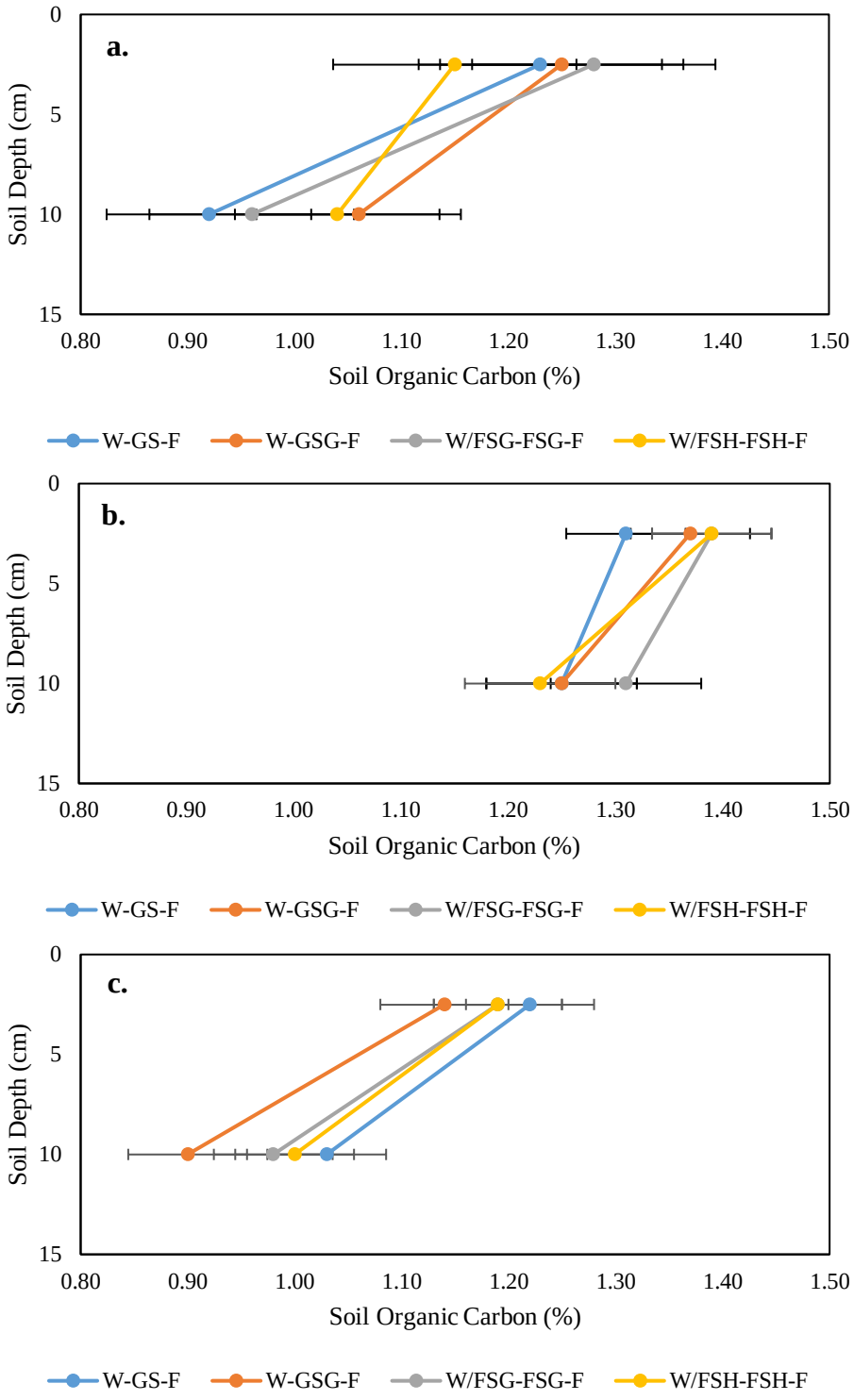

Figure 2.5. Soil organic carbon as affected by rotation intensification and sampling depth within 2023 (a.), 2024 (b.), and 2025 (c.) near Hays, KS. Error bars represent standard error of means.

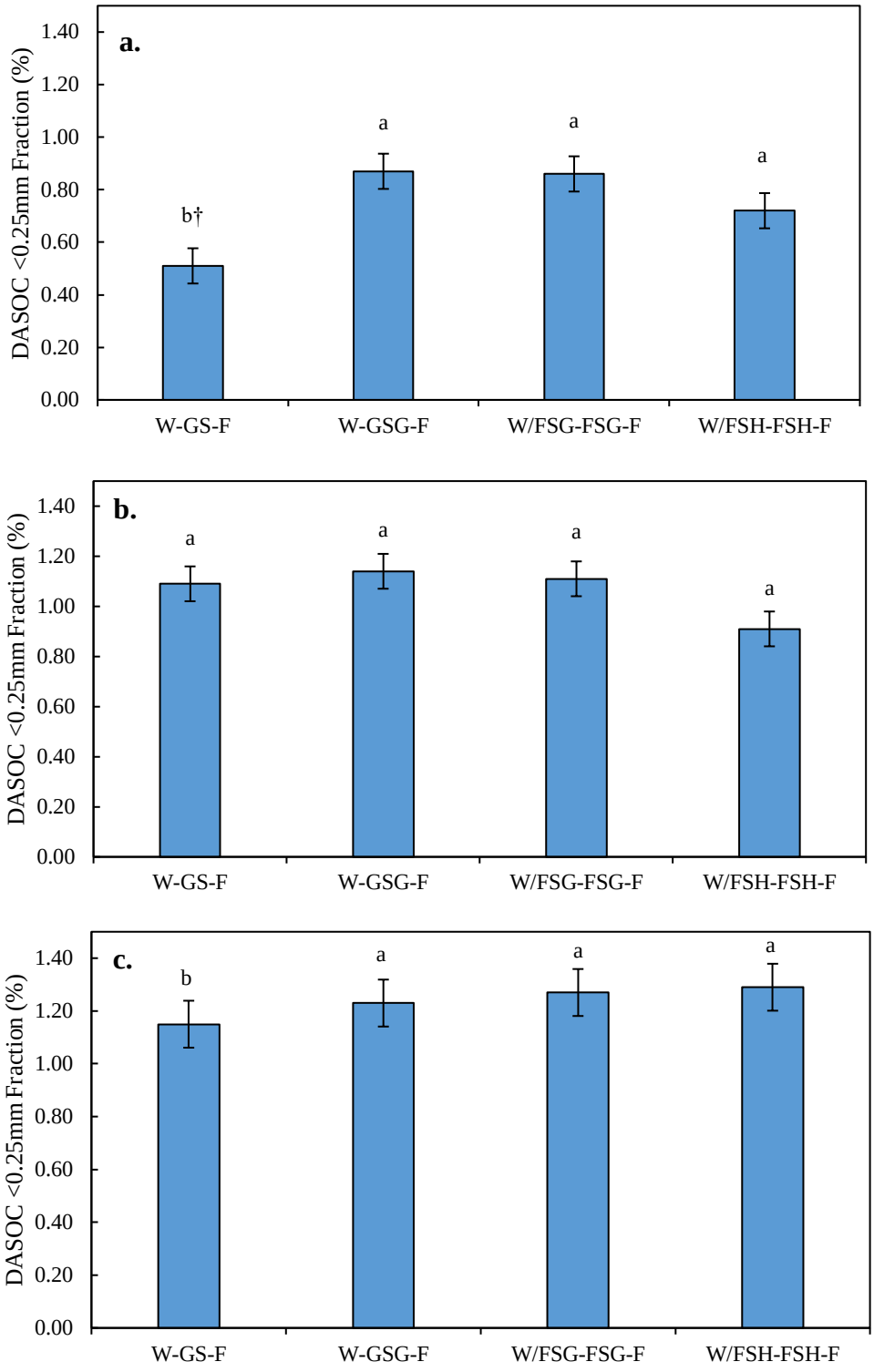

Figure 2.6. Effect of rotation intensification on dry-aggregate SOC (DASOC) at <0.25mm size fraction 2023 (a.), 2024 (b.), and 2025 (c.) near Hays, KS.

†Means with the same letter are not significantly different (α =0.1) across treatments.

Chapter 3 - Cover Crop Biomass Removal Rates to Optimize Livestock Production and Soil Properties in Dryland Cropping Systems

Abstract

Grazing cover crops (CCs) could increase cropping system profitability through offsetting reduced grain crop yields following a CC in moisture-limited environments or by increasing economic utility of CC. However, there is limited guidance on the optimum biomass removal rate of annual CCs that balances both soil health and grazing goals. An on-farm study was established in fall 2022 on a 20-hectare producer field in Russell County, KS to investigate the effects of CC biomass removal with cattle grazing on soil health parameters and grain crop yields in a no-till dryland cropping system. The study design was a randomized complete block with three treatments and four replications. The treatments included ungrazed CCs (UGR), "take-half-leave-half" (T-H-L-H, 50% biomass removal), and "graze-out" (G-O, 90% biomass removal). Averaged across 2023-2024, T-H-L-H and G-O significantly reduced CC residue amount, height, and residue cover when compared to UGR. In 2023, T-H-L-H had 224 kg ha^{-1} more residue remaining and had 15 cm taller residue than the G-O treatment. Though, in 2024 CC biomass parameters were not significantly different between T-H-L-H and G-O, because biomass removed from each grazing treatment was essentially the same. Cover crop management had no significant effect on concentrations of soil organic carbon and particulate organic matter. However, averaged across the 0-15 cm soil depth, phosphorus (P) concentration was reduced by ~8 kg ha^{-1} by T-H-L-H and G-O compared to UGR, likely due to purposefully avoiding sampling near manure pats in the grazed plots that may be high in P. Grazing CCs increased soil bulk

density compared to UGR at the 0-5 cm soil depth by 0.08 g cm^{-3}. Take-half-leave-half slightly increased soil penetration resistance in one of two years. Percent wind-erodible fraction, mean weight diameter, time-to-runoff, and subsequent grain sorghum yield were unaffected by CC management. In 2023, we were relatively close to our T-H-L-H and G-O removal goals, but in 2024 there was no biomass removal difference between T-H-L-H and G-O due to limited biomass production. Soil properties were largely unaffected by the grazing treatments except for slight increases in soil bulk density and penetration resistance. However, these observations were made in a 2-year study under exceptional drought conditions, so further investigation will be necessary under conditions of average or above average precipitation with adequate forage production so grazing intensities can be achieved.

Core Ideas

- Cover crop production was limited during both years of the study due to extreme drought conditions in the winter and early spring, providing limited forage for grazing in May of each year.
- Biomass removal between the two grazing intensities was not significantly different in 2024 due to limited biomass production, making residue remaining, residue height, and residue cover essentially the same in that year.
- Grazing had neutral effects on most soil properties when compared to the ungrazed treatment. Although bulk density at the 0-5 cm soil depth and penetration resistance averaged across the 0-15 cm soil depth in 2023 were slightly increased by the T-H-L-H grazing treatment, values were still far below root limiting thresholds.
- Grain sorghum yields were not significantly affected by increased grazing intensity in either year of the study.

Introduction

Dryland cropping systems in the Great Plains are highly vulnerable to wind and water erosion. The primary causes of soil erodibility are low precipitation and extended fallow periods (11-14-month) within crop rotations where crops are not grown between grain crops (Peterson and Westfall, 2004). Fallow periods are also inefficient in retaining soil moisture due to low residue cover, retaining only 20-35 % of total precipitation received, even without tillage (Holman et al., 2021; Nielsen and Vigil, 2010; Peterson and Westfall, 2004). Although inefficient, moisture retained during the fallow period is essential for stabilizing subsequent grain crop production (Nielsen and Vigil, 2010; Peterson and Westfall, 2004). Through practices such as reduced tillage and intensifying cropping rotations, water use efficiency has increased but much of the rotation still remains without a growing crop (Baumhardt et al., 2015). The three-year wheat-summer crop-fallow (WSF) rotation has shifted fallow so a crop is in place more often during high precipitation months, and has reduced fallow by 4 months compared to the common two-year wheat-fallow rotation (Holman et al., 2018). Though reduced, the fallow period in WSF still has 11 months without a growing crop. No-tillage (NT) and cover crops (CCs) have been widely recommended to regenerate soils degraded after many years of conventionally-tilled, low-intensity crop production. Soil health benefits of CCs in NT cropping systems include increased soil organic carbon (SOC), enhanced nutrient cycling, reduced compaction, increased water infiltration, and reduced wind and water erosion (Burke et al., 2022; Blanco-Canqui et al., 2021; Simon et al., 2021; 2022). However, several barriers to adoption of CCs exist in water-limited regions including the costs of establishing CCs (seed, machinery, labor, and fuel) and the risk of CCs reducing subsequent grain crop yields due to reduced soil water at planting of the next crop (Nielsen et al., 2016; Unger, 1998; Burke et al., 2022; Holman

et al., 2018; 2020; 2021; 2022; Obour et al., 2022a). Some producers in the semi-arid Great Plains have sought to overcome these barriers by integrating livestock to graze CCs, which has been widely promoted for diversifying agricultural production systems in the region (Obour et al., 2021).

Dual use of CCs as forage can maintain many of the positive soil health benefits of a CC, while also being used as hay or grazing by livestock to reduce the negative economic impacts to grain production (Holman et al., 2022; Obour et al., 2021; Obour et al., 2023). Previous research has shown most CC species can provide high-quality forage for livestock (Holman et al., 2018; Landry et al., 2018), which can extend the grazing season and reduce the need for feeding costly stored forages in concentrated feeding sites for extended periods. Grazing CCs can delay grazing of native rangelands and allow for longer periods of rest or help in years with drought to take pressure off native rangeland (Obour et al., 2021). Previous research has demonstrated increased system profitability with integrated forage systems when compared to the three-year WSF rotation (Holman et al., 2022). However, in some instances when forages are harvested by grazing, subsequent grain yields have been variable with incidences of reduced yield often being attributed to soil compaction, aggregate destruction, and reduced water infiltration due to excessive animal hoof traffic (Blanco-Canqui et al., 2021). For long-term practitioners of NT, this is a major concern because yield-limiting soil compaction could require tillage for remediation.

At this time, there is limited guidance on the optimum CC biomass removal rate that balances soil health and grazing goals. The USDA-NRCS has made no provisions for grazing CCs, and current Kansas NRCS recommended stocking rates are based on those developed for native rangelands (take-half-leave-half (T-H-L-H), 50% biomass removal) (USDA-NRCS,

2022a). Previous research suggests that conservative stocking densities that remove 40-50% of CC biomass do not negatively affect soil properties compared to ungrazed CCs (Simon et al., 2021; 2022). This suggests that greater levels of biomass removal with grazing could be practical, especially when regrowth occurs after grazing, and would generate greater profit for farmers and ranchers. However, more intense grazing (70 to 90% forage removal) has occasionally resulted in compaction and reduced water infiltration in some studies (Blanco-Canqui et al., 2021).

These results leave producers questioning what the optimum grazing intensity, duration, and biomass removal rate is under dryland soil conditions. Should biomass removal be no greater than 50% to maintain soil properties, or is there a grazing intensity that can be reached to optimize both forage productivity and soil health? Therefore, the objective of this research was to determine effect of CC grazing intensity on farm productivity and soil health. Our hypothesis was that increasing grazing intensity of CCs will increase system productivity by increasing amount of biomass removed, while having a minimal impact on soil health indicators [penetration resistance (PR) and bulk density (BD), wet and dry-aggregate mean weight diameter (MWD), SOC, particulate organic matter (POM), nitrogen (N), phosphrous (P), pH, and soil time-to-runoff (TTR)] as well as subsequent grain sorghum yields.

Materials and Methods

Site Description and Experiment Layout

An on-farm study was established in fall 2022-2024 on a 20-hectare producer field in Russell Co., KS (38° 42' 2.2" N, 98° 37' 58.3" W). The study evaluated the effects of CC grazing intensity on soil health parameters and grain crop yields in a NT dryland cropping system. The study area has Crete silt loam (72%) and Harney silt loam (28%) soil series formed from loess

material and slopes ranging from 1 to 3 percent. Long-term average (30-yr) annual precipitation for the site is 648 mm (NOAA, 2026). The experimental design was a randomized complete block with four replications. Treatments included ungrazed CCs (UGR), "talk-half-leave-half" (T-H-L-H, 50% biomass removal), and "graze-out" (G-O, 90% biomass removal).
Each year CCs were planted in the fall and terminated the following spring immediately before planting the next sorghum crop. All plots were ~2-hectare in size. Crop Management

Prior to study initiation, the location of the field site had been in a USDA long-term Conservation Reserve Program (CRP) and was terminated using tillage and then planted to winter wheat in fall 2021. The crop rotation sequence from the beginning of the study in fall 2022 through the end of the study period in fall 2024 was as follows: CC established in October 2022; followed by grain sorghum planted in June 2023; a second CC was established in October 2023; and grain sorghum planted again in June of 2024. At study initiation in fall 2022, a three-species CC mixture of triticale, pea, and rapeseed was planted into the wheat stubble around the first week in October at 67, 16, and 2 kg ha^{-1} of each species, respectively, on 19 cm rows using a 1900 series John Deere NT drill (Deere and Company, Moline, IL). The CC mixture was planted again in fall 2023 after sorghum harvest. No fertilizer was applied to CCs in either year of the study. In May 2023 and 2024, CCs were grazed with cattle for approximately 1-2 weeks depending on biomass available at heading, which coincided with Zadoks growth stages 45-60 (Zadoks et al., 1974), then all CC treatments were terminated using an herbicide mixture of glyphosate (N-(phosphonomethyl)glycine,) at 0.94 L ha^{-1}, FulTime NXT (acetochlor (2-chloro-2'-methyl-6'-ethyl-N-ethoxymethylacetanilide) and atrazine (2-chloro-4-ethylamino-6-isopropylamino-s-triazine)) (Corteva Agriscience, Johnston, IA) at 1.6 L ha^{-1}, and Verdict (dimethenamid ((S)-2-chloro-N-[(1-methyl-2-methoxy)ethyl]-N-(2,4-dimethyl-thien-3-yl)-

acetamide) and saflufenacil (N'-[2-chloro-4-fluoro-5-(3-methyl-2,6-dioxo-4-(trifluoromethyl)-3,6-dihydro-1(2H)-pyrimidinyl)benzoyl]-N-isopropyl-N-methylsulfamide) (BASF, Florham Park, NJ) at 0.29 L ha^{-1}. Two weeks after CC termination (approximately June 1st), grain sorghum was planted at 86,500 seeds ha^{-1} on 76-cm rows using a 1700 series John Deere NT planter (Deere and Company, Moline, IL) both years of the study. Fertilizer applied to grain sorghum was based on the standard producer practice and kept consistent across treatments. Each treatment received 20 kg P_2O_5 ha^{-1} as monoammonium phosphate (11-52-0) with the seed and 84 kg N ha^{-1} urea (46-0-0) as a broadcast application after cover crop termination. Grain sorghum was harvested using a John Deere S760 combine with a 6-m-wide row head attachment (Deere and Company, Moline, IL) equipped with a calibrated yield monitor. Plot-level yield and moisture content data were extracted using QGIS 3.34 Prizren software (QGIS, Zurich, Switzerland), and yields were adjusted to 13.5% moisture content.

Grazing Management and Biomass Parameters

Each grazed plot was surrounded by fence posts attached to electric wire to contain the cattle. Take-half-leave-half and G-O treatments were grazed at 2-5 AUM ha^{-1} based off available forage with cattle yearlings beginning in the last week of April and moved plot-to-plot after a minimum of one day of grazing per plot. Biomass removal rates of 50% and 90% were achieved through visual estimation by the participating producer, when the producer felt T-H-L-H and G-O intensities had been met cattle were moved to the next grazing plot within the study. In 2023, each T-H-L-H treatment was grazed for one day, while G-O treatments were grazed for two days, in total grazing lasted about two weeks. In 2024, due to limited biomass production, one day of grazing resulted in > 70 % of total biomass removal for each grazing treatment. Therefore, skewing intended grazing intensity results for 2024, and removing essentially the same amount

of biomass in each grazing treatment. In total, grazing of grazed plots in 2024 lasted about a week. Post-grazing and prior to CC termination, CC biomass parameters were taken from all treatments. Biomass parameters measured were amount of CC biomass remaining, CC height, and total soil residue cover in each treatment. To estimate total CC biomass produced, samples were hand clipped to ground level within the UGR plots in two areas of 0.50 m^2 per plot. Estimation of the amount of CC biomass remaining in each grazed plot post-grazing followed the same sampling method. All biomass samples collected were dried at approximately 50˚C for a minimum of 48 h in a forced-air oven and weighed to determine dry matter content. Residue height was measured from ten random locations within each plot using a meter stick, measuring from the base of the plant to the tip of the plant to the nearest centimeter. The ten residue height measurements per plot were then averaged to determine an overall average height for each plot. Residue cover was determined by the line-transect method (USDA-NRCS, 2002). Briefly, a 3.05 m long PVC pipe with marks at every 0.305 m interval was randomly placed at two separate points diagonally across crop rows, and marks directly above residue were counted. The percentage of residue cover on the soil surface was calculated by dividing the total number of residue cover points by 10 and multiplying by 100. The two measurements for each plot were then averaged to obtain one residue cover value for each plot.

Soil Properties and Time-to-Runoff

Soil samples were taken at the initiation of the study in fall 2022 and in May 2023 and 2024, after grazing and before CC termination. At each sampling, 10 randomly distributed soil cores (2.5 cm diameter) were taken from 0-5 cm and 5-15 cm depths for determination of soil chemical and biochemical properties. While sampling, manure pats were avoided within the grazed plots to avoid skewing available nutrients in the treatments. The soil samples were air

dried and then ground to pass through a 2 mm sieve. Soil chemical properties analyzed were soil organic carbon (SOC), nitrate-N (NO_3-N), phosphorus (P) (M3-P), and pH. The soil biochemical property analyzed was particulate organic matter (POM). Sub-samples used for total SOC were ground into fine particles with a mortar and pestle, then analyzed using a high-temperature combustion method on an Elementar UNICUBE® CN analyzer (Elementar Americas Inc., Ronkonkoma, NY) after pretreating samples with 10% (v/v) HCl to remove carbonates (Nelson and Sommers, 1996). Nitrogen concentrations were determined colorimetrically once samples were extracted with 2 M KCl. Soil available P was determined after extracting samples with Mehlich-3 solution (Mehlich, 1984). After extraction, the M3-P concentration was measured using inductively coupled plasma-optical emission spectrometry (ICP-OES). Soil pH was determined by weighing out 25 grams of each sample and mixing with 20 mm of double deionized water, and allowed to sit for 30 minutes. After 30 minutes, measurements were made using the Oakton® PC 700 Benchtop pH/mV/Conductivity/°C/°F Electrode Meter (Environmental Express, Charleston, SC). The meter was calibrated using pH buffers of 4.01, 7.00, and 10.01 (Thomas, 1996). Particulate organic matter was analyzed by using a sub-sample of approximately 25 grams and mixing 100 mL of 5g/L hexametaphosphate sodium, and placing on an orbital shaker at 200 rotations per minute for 4 hours (Cambardella and Elliott, 1992). Samples were then poured over a 53-um sieve and the material remaining on top was dried at 105°C. This was burnt at 450°C in a muffle furnace (Lindberg Blue M, Ashville, NC) and used to calculate POM.

Soil compaction indicators of bulk density (BD) and penetration resistance (PR) were measured from samples taken at the 0-5 cm and 5-15 cm depths from each plot. Two soil cores per plot were obtained for BD using an AMS BD sampler (AMS, Inc., American Falls, ID). The

samples were then dried at 105°C until a constant weight was reached to determine BD as mass of oven-dried soil divided by volume of the core (Grossman and Reinsch, 2002). Penetration resistance was measured with an Eijkelkamp Hand Penetrometer (Eijkelkamp Soil and Water, Morrisville, NC). The penetrometer was uniformly pressed into the soil at ten random locations within a plot. Readings were divided by the area of the cone (2 cm^2). Gravimetric water content measurement was taken at the time of penetration resistance readings and used to adjust penetration resistance values (Simon et al., 2021) to a standard field capacity gravimetric water content (GWC) of 0.30 ($g\ g^{-1}$) for silt loam soils (Ratliff et al., 1983) to account for potential differences in GWC across plots.

Additional soil samples used for indicating erosion potential were taken from the 0-5 cm depth. For wet and dry aggregate stability, about 1 to 2.5 kg of intact soil was sampled from three random locations within each plot using a flat shovel. After air drying, the samples were split into two, and half of the samples were passed through an 8 mm sieve. The portion of the sample passed through the 8 mm sieve was used to determine water stable aggregates (WSA) and mean weight diameter (MWD) of WSA using the wet sieving method (Nimmo and Perkins, 2002). Prior to determining WSA and MWD, sand corrections were conducted for each aggregate fraction to remove sand particles. The remaining portion of the sample was used to determine dry aggregate stability and wind erodible fraction (WEF). The air-dried sample was placed on a system of 5 nested rotary sieves with 19, 6.3, 2-, 0.84-, and 0.25-mm square openings. All samples were shaken for 5 minutes using a portable shaker (W.S. Tyler Model RX-812, Mentor, OH) (Chepil, 1962). After shaking, the soil particles remaining on the sieve were weighed and used to compute dry aggregate mean weight diameter (DAMWD) and WEF (aggregates < 0.84 mm).

At each sampling time, the time-to-runoff (TTR) was measured using a Cornell Sprinkle Infiltrometer (Cornell University, Ithaca, NY) (Ogden et al., 1997). Time-to-runoff was measured in two separate locations per plot, by pounding a 12 cm diameter steel infiltration ring 7.62 cm into the soil surface with a rubber mallet, the infiltrometer was then placed on top of the ring after being filled with 30 cm of water. When infiltration began, a stop watch was started to capture the exact time it took for water to run out the ring hole of the infiltrometer. When runoff occurred, the stopwatch was stopped and the TTR was recorded. The two TTR measurements per plot were then averaged for each plot.

Statistical Analysis

Analyses of biomass parameters, grain yield, soil chemical and physical properties, and TTR were performed using the PROC GLIMMIX procedure in SAS ver. 9.4 (SAS Institute, 2012, Cary, NC). First, biomass remaining, residue height, residue cover, grain yield, RC, MWD, WEF, and TTR were analyzed with year, grazing management (biomass removal rate), and their interactions as fixed effects in the model, and replication as random. The soil BD, PR, SOC, POM, extractable nutrient concentrations, and pH were modeled with grazing management, year, sampling depth and their interactions as fixed effects, while replication and its interaction with fixed effects were considered random. Interaction and treatment effects were considered significant when *P*-values were ≤ 0.10. The LSMEANS procedure in SAS was used to compute and compare fixed effect means.

Results

Precipitation

Average annual precipitation in 2023-2024 was 75% of the average long-term (30-year) annual precipitation in Russell County, KS (Table 3.1). In the 2022-2023 CC growing season

(October-April), precipitation totaled 46 mm, which was 19% of the long-term average precipitation during that same time period. The CC growing season precipitation in 2023-2024 totaled 129 mm, which was 54% of the long-term average. Even though 2023-2024 CC growing season precipitation exceeded that of 2022-2023, the entirety of the precipitation came between October-December, which provided good CC establishment, but little moisture in January-April to impacted CC productivity. Although precipitation was low for CC growth, precipitation was much closer to the long-term average for the grain sorghum growing season (May-October). May is not technically a part of the grain sorghum growing season, but precipitation received during that time period is highly influential on crop establishment and known to impact sorghum grain yield in dryland environments (Obour et al., 2022b). In 2023, May-October received 446 mm of precipitation, which was 99% of the long-term precipitation for the same time period. In 2024, during the same months, precipitation totaled 361 mm, about 80% of the long-term precipitation. Precipitation received during both grain sorghum growing seasons provided sufficient moisture to produce relatively high grain yields, when compared to the 2023 and 2024 Russell County grain sorghum yield average of 3,830 kg ha^{-1} (Kansas Department of Agriculture, 2025).

Cover Crop Biomass Parameters

Cover crop biomass production in both years of the study was limited due to significant spring drought, but 2023 CC biomass was 976 kg ha^{-1} higher than in 2024 (Table 3.2). Due to a significant treatment × year effect, biomass remaining, residue height, and residue cover means were analyzed separately for 2023 and 2024. In 2023, the UGR CC treatment had ~1299 kg ha^{-1} more biomass than the T-H-L-H and G-O after grazing, and significantly greater residue height followed by T-H-L-H, then the G-O treatment. As expected, the less intensive grazing treatment (T-H-L-H) had significantly more biomass remaining than G-O. In 2024, again, the UGR

treatment had significantly more biomass remaining than the grazed treatments. However, due to difficulty of achieving targeted biomass removal rates with grazing in 2024 because of limited CC biomass production, no significant differences were observed between T-H-L-H and G-O biomass remaining, making the two grazing treatments essentially the same in 2024. Similar to 2023, UGR had significantly greater residue height than T-H-LH and G-O, and residue height did not differ between T-H-L-H and G-O due to similar grazing removal.

Total residue cover in 2023 was not significantly different between UGR and G-O treatments, but both treatments had significantly higher residue cover than the T-H-L-H treatment (Table 3.2). Much of the residue remaining in the G-O treatment was flat on the soil surface, therefore increasing total residue cover values. However, in 2024 the UGR CC treatment had significantly more residue cover than both grazed treatments. Again, similar to the biomass parameters above in 2024, the grazed treatments were not significantly different from one another due to no significant difference in biomass remaining. Biomass produced and residue cover results were variable year to year, likely due to inconsistent and limited CC production due to limited spring precipitation in both years.

Aggregate Stability

Residue removal had no significant effect on wet or dry aggregate stability (Table 3.3). Wet-aggregate stability was not different between years across treatments. In 2023, wet-aggregate MWD (1.81 mm) was significantly greater across treatments than in 2024 (1.13 mm). Compared to the initial wet-aggregate MWD analysis, 2023 values were 0.58 mm greater. In 2024 this trend flipped as wet-aggregate MWD values were 0.10 mm lower than initial values. No significant treatment effect was seen within dry-aggregate MWD, but the more intensive grazing system (G-O) MWD trended slightly larger than UGR and T-H-L-H treatments.

Therefore, WEF for G-O trended slightly less than UGR and T-H-L-H. Although there wasn't a significant year effect for dry-aggregate MWD, there was a significant year effect within WEF. The percent WEF in 2023 (31.89%) trended higher than the initial WEF. The trend of increasing WEF continued across years with 2024 (34.98%) having significantly higher WEF than 2023. The gradual increase in WEF was likely due to effects from returning CRP grass to conventional farming practices and dry conditions that limited CC biomass produced.

Bulk Density and Penetration Resistance

Bulk density was significantly affected by the two-way interaction of treatment × depth and by year (Table 3.3). At the 0-5 cm depth, T-H-L-H had significantly (0.08 g cm^{-3}) greater BD than the UGR treatment, and surprisingly, trended higher than the more intensive grazing treatment (G-O) (Figure 3.1). No significant effect between treatments was observed at the 5-15 cm depth. Within the year effect, 2024 (1.39 g cm^{-3}) had significantly higher BD averaged across the 0-15 cm depth than 2023 (1.30 g cm^{-3}). The bulk density measured in both years trended higher than initial BD measured at the same sampling depth. Despite T-H-L-H having significantly higher BD than UGR, and BD gradually increasing across years, values were far below the root limiting threshold BD of 1.60 g cm^{-3} for silt-loam soils (USDA-NRCS, 2022b).

Penetration resistance, which is a more accurate indicator of soil compaction because it simulates actual force required by a root to break through soil layers, was significantly affected by the two-way interactions of treatment × year and year × sampling depth (Table 3.3). In 2023, averaged across the 0-15 cm soil depth, the grazing treatment T-H-L-H had significantly higher PR than the G-O treatment, with UGR also trending higher than G-O (Figure 3.2). Differences in 2023 were short lived because 2024 measurements showed no significant difference among treatments, although UGR trended higher than the grazed treatments. At the 0-5 cm depth, there

was no significant difference between years, but at the 5-15cm depth in 2023 had significantly higher PR than 2024. Which is the exact opposite of what was observed in BD in 2023 and 2024. As with BD, the T-H-L-H treatment increased PR in 2023 across treatments, and 2023 had significantly higher PR at the 5-15 cm depth than 2024, likely due to greater CC biomass leading to longer grazing duration in 2023 within the G-O plots. Values are still far below the root limiting threshold of 2.00 Mpa for silt loam soils (Blanco-Canqui et al., 2021).

Soil Organic Carbon and Particulate Organic Matter

Soil organic carbon and POM were unaffected by CC biomass removal treatments (Table 3.3). Differences observed were caused by year and soil sampling depth. In 2023, SOC averaged 1.86%, which was significantly higher than the 1.70% measured in 2024. Compared to initial sampling analysis of SOC, 2023 averages trended 11 % higher, while 2024 average SOC concentrations trended 5 % lower than initial. By depth, the 0-5 cm SOC concentrations (2.14%) were significantly higher than 5-15 cm concentrations (1.42%), likely, due to higher amount of residue deposition and root concentration within the 0-5 cm soil depth. Similarly, POM concentrations were significantly higher in 2023 (1.03%), than in 2024 (0.85%). Particulate organic matter concentrations in 2023 trended 3 % higher than initial POM analyses, while 2024 POM concentrations trended 15 % lower than initial POM concentrations. Again, by depth, the 0-5 cm POM concentrations (1.47%) were significantly higher than the 5-15 cm concentrations (0.41%). Although there was not a significant treatment effect, both SOC and POM concentrations trended in the following order by grazing intensity: UGR>G-O>T-H-L-H, reflecting results seen from the residue cover analyses.

Nitrogen, Phosphorus and pH

Nitrogen concentration was not significantly affected by treatment, but differed by year and sampling depth (Table 3.3). Soil N concentrations measured in 2023 (7.78 kg ha^{-1}) were significantly higher than 2024 (4.93 kg ha^{-1}) averaged across the top 15 cm of the soil. Initial N concentrations averaged ~8.89 N kg ha^{-1} higher than that measured in 2023 and 2024 ha^{-1}, showing a clear gradual decline in soil fertility from CRP management to farming practice adoption.

Available M3-P was significantly affected by the two-way interaction of year × depth and by CC biomass removal treatments (Table 2.3). At the 0-5 cm depth, M-P concentration in 2024 (23.27 P kg ha^{-1}) had significantly higher P than 2023 (16.56 P kg ha^{-1}), while at the 5-15 cm depth, M3-P was not significantly different between sampling years. Across sampling depth, the UGR treatment had significantly higher M3-P concentration than the grazing treatments, indicating that grazing decreased available P. Although there was not a significant difference between the two grazing treatments, the more intensive grazing treatment (G-O) trended higher than T-H-L-H in plant available P. Compared to initial sampling, available P nearly doubled in the UGR treatment, while T-H-L-H and G-O were slightly higher than the initial available P analyses.

Soil pH was not significantly affected by any of the fixed effects in this study (Table 2.3). However, soil pH in the grazed treatments trended higher on average across the top 15 cm soil depth than the UGR treatment. Changes in pH from initial sampling across years was also minimal.

Time-to-Runoff

Initial sampling TTR values were 117% higher than the values measured in 2023 and 2024. Although there was not a significant treatment × year or treatment effect (Table 3.3), the decrease in TTR after one or two years of crop production is significant because it shows that addition of CCs did not maintain soil water infiltration from breakout of CRP to conventional farming practices. This trend was evident in the year effect analysis where TTR values continued to decrease from 9 min in 2023 to 6 min in 2024 (Figure 3.3).

Grain Sorghum Yield

Unlike the CC growing season, grain sorghum had adequate precipitation throughout the growing season in both years. However, the two-way effect of treatment × year and treatment alone did not affect grain sorghum yield (Table 3.4). Despite the insignificant treatment effect, grain sorghum yield trended in the following order: T-H-L-H > G-O > UGR. The trend can be attributed to experiment set up. Two of the UGR plots were on the outer edge of the project to allow for ease of animal transportation from one grazed plot to another, therefore the UGR treatment had a slight edge effect. Although treatment effect was minimal, an effect of year was observed with 2024 having 633 kg ha^{-1} higher grain sorghum yield than 2023.

Discussion

Cover crop biomass in 2023 and 2024 was limited by inadequate precipitation (Table 3.1). Studies within the region have reported similar issues with limited fall CC growth due to variable precipitation during winter and spring months (Simon et al., 2021; 2022). Particularly in 2024 when there was no significant difference between grazing intensity biomass remaining, the lack of CC growth made it difficult for the producer to visually estimate 50 and 90% of CC biomass removal. For instance, in 2023, actual biomass removed in the T-H-L-H grazing

intensity was ~60% of available CC biomass, while the G-O grazing intensity removed ~72% of CC biomass available. In 2024, CC biomass did not exceed 1000 kg ha^{-1}, and > 70% of available CC biomass was removed per grazing plot after the minimum of one day of grazing. Actual removal for the T-H-L-H grazing treatment nearly reached 80% biomass removed, and the G-O grazing intensity removed 74% of CC mass available. Therefore, making the grazing intensities essentially the same for 2024.

Variability in grazing removal estimation also led to variable residue cover results in 2023 and 2024. In 2023, residue cover in the G-O grazing intensity was significantly higher or trended higher than the T-H-L-H grazing intensity. This result could be tied to increased animal hoof traffic in the G-O grazing treatment due to longer grazing duration that tromped down available forage, which has shown to increase or be similar to total residue cover in un-grazed forage treatments (Carson et al., 2025; Obour et al., 2021; Simon et al., 2021; 2022). Similar biomass removal rates between grazing intensities in 2024 explains why residue cover was not different between grazing intensity treatments in that year.

Wind and water aggregate stability was minimally affected by grazing intensity, but WEF increased and wet-aggregate MWD decreased over time. As stated previously, this study location had been CRP grassland and was transitioned into farm production in 2021. As shown in previous research, soil properties degrade during that transition (Reeder et al., 1998), leading to the declining soil aggregate stability observed in the present study across years.

Soil compaction indicators (BD and PR) had variable results over the study sampling period. At the 0-5 cm depth, bulk density was significantly higher in the grazing treatments than UGR, which is similar to results seen in other grazing research (Blanco-canqui et al., 2021; Schomber et al., 2021). But, increased BD with grazing was not observed in the 5-15 cm depth.

Averaged across the 0-15 cm soil depth and across years, BD values were slightly higher than initial BD, following the same trend as wet and dry aggregate stability. Penetration resistance data was also similar to Blanco-canqui et al., (2021) who observed an increase in PR in one year of grazing compared to an UGR CC treatment in a three-year grazing study within a continuous corn cropping system with grazing of rye occurring between corn growing seasons in Nebraska. In this study, surprisingly T-H-L-H significantly increased PR compared to UGR and G-O averaged across the 0-15 cm soil depth in 2023, but no significant effect was observed across treatments in 2024 due to similar biomass removal rates. The increase in PR in T-H-L-H compared to G-O is an anomaly, because G-O had greater biomass removal in 2023.

Despite no significant effect of grazing intensity on SOC and POM concentrations, treatments trended in the following order: UGR>G-O>T-H-L-H averaged across both years and the 0-15 cm soil depth. The lack of significant treatment differences in SOC or POM is not surprising, as numerous studies have shown that if grazing is managed properly and adequate residue is left on the soil surface, grazing often maintains or increases SOC and POM concentrations in the soil when compared to UGR CCs (Obour et al., 2023; Simon et al., 2021; 2022). Lack of effect from the more intensified grazing system (G-O), which in theory should not have left adequate residue cover on the soil surface, again, was likely due to challenges associated with visually estimating amount removed in each grazing intensity because of limited biomass. By year, SOC concentrations changed minimally from initial sampling (post-CRP) to 2024. On the other hand, POM values declined drastically from initial sampling to 2024. Particulate organic matter is more sensitive to management than SOC. Consequently, the POM fraction is often depleted more rapidly and is an earlier indicator of soil quality degradation following grassland conversion (Cambardella and Elliot, 1992). This possibly explained why

POM values trended lower in 2024 when compared to initial sampling, and SOC concentrations remained relatively stable.

Similar to results seen in POM, plant available N was not different among grazing treatments, but did see a drastic change from initial sampling post-CRP to 2024. Often, the same POM pool that declines after return to crop production is also a major source of mineralizable N, so they both decline relatively quickly after grassland conversion (Reeder et al., 1998). Available P was significantly higher in the UGR treatment. These results contradict findings from Simon et al. (2021; 2022) which showed that grazing didn't reduce nutrient concentrations compared to UGR CC treatments. In the present study, the decline in soil P could be due to purposefully avoiding sampling near manure pats in the grazed plots that may be high in P.

Time-to-runoff was not significantly affected by grazing intensity, even though there was a slight increase in PR in the T-H-L-H grazing treatment in 2023, and grazing treatments increasing BD in the 0-5 cm soil depth. There was a significant decline in TTR from study initiation to 2024 sampling. This again can be attributed to soil decline from converting CRP to farm production.

Although there was a slight reduction in available P, grain sorghum yields were not reduced by grazing in this study. Because grazing did not compact soil layers beyond root limiting threshold, and N and P fertilizer was supplied at each sorghum planting, a change in yield would not be expected with the adequate moisture received during the grain sorghum growing season.

Conclusion

Results showed that T-H-L-H and G-O CC grazing strategies significantly reduced CC residue amount, height, and residue cover compared to UGR CCs. Cover crop management had

no significant effect on SOC or POM, while P concentrations were reduced by T-H-L-H and G-O in this short-term study. Grazing treatments increased soil BD at the 0-5cm depth compared to UGR CCs though values were far from root limiting thresholds for silt-loam soils. T-H-L-H increased soil PR in 2023 averaged across the 0-15cm depth, but again values were far below root limiting thresholds. Soil WEF, MWD, TTR, and subsequent grain sorghum yield were unaffected by CC management. Nearly every soil health parameter declined from initial soil sampling to 2024, but this is entirely due to soil property decline after conversion of CRP grass to cropland. These results provide initial evidence that increasing grazing intensity maintained soil health indicators and subsequent grain crop yields similar to UGR CCs, except for slight increases in soil compaction indicators within the grazed treatments. Farmers and ranchers may be able to graze CCs at greater intensities than T-H-L-H to maximize livestock gains while maintaining soil health. Nevertheless, these observations were made in a 2-year study and under exceptional drought conditions, which made biomass removal rates difficult to achieve. Further investigation will be necessary under conditions of average or above average precipitation when wet soils may be more susceptible to degradation by cattle hoof traffic, and CC biomass is adequate for implementing grazing intensities.

References

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

Blanco-Canqui, H., Drewnoski, M.E., MacDonald, J.C., Redfearn, D.D., Parsons, J., Lesoing, G.W., Williams, T. (2021). Does cover crops grazing damage soils and reduce crop yields? Agrosystems, Geosciences & Environment, 3(1), 1–11. https://doi.org/10.1002/agg2.20102

Burke, J. A., Lewis, K. L., DeLaune, P. B., Cobos, C. J., and Keeling, J. W. (2022). Soil water dynamics and cotton production following cover crop use in semi-arid ecoregion. Agronomy Journal, 12:1306. https://doi.org/10.3390/agronomy12061306

Cambardella, C. A., and Elliott, E. T. (1992). Particulate soil organic-matter changes across a grassland cultivation sequence. Soil Science Society, 56:777–783. https://doi.org/10.2136/sssaj1992.03615995005600030017x

Carson, Z. C., Obour, A. K., Holman, John D., Simon, L., and Roozeboom, K. L. (2025) "Crop Production and Soil Properties Impacts of Integrating Annual Forages and Ruminant Livestock into Wheat-Based Cropping Systems," Kansas Agricultural Experiment Station Research Reports*:* Vol. 11: Iss. 4. https://doi.org/10.4148/2378-5977.8716

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

Grossman, R.B., and Reinsch, T. G. (2002). Bulk density and linear extensibility. In: Dane, J. H. and Topp, G. C., editors, Methods of soil analysis. Part 4. SSSA Book Ser. 5. Soil Science Society of America, 201–225. https://doi.org/10.2136/sssabookser5.4.c9

Holman, J.D., Arnet, K., Dille, J., Maxwell, S., Obour, A., et al. (2018). Can cover or forage crops replace fallow in the semiarid central great plains? Crop Science, 58:932–944. doi: 10.2135/cropsci2017.05.0324.

Holman, J. D., Assefa, Y., and Obour, A. K. (2020). Cover-crop water use and productivity in the high plains wheat-fallow crop rotation. Crop Science Society of America, 61:1374-1385. https://doi.org/10.1002/csc2.20365

Holman, J. D., Obour, A. K., and Assefa, Y. (2021). Productivity and profitability with fallow replacement forage, grain, and cover crops in W-S-F rotation. Crop Science, 62, 913–927. https://doi.org/10.1002/csc2.20670

Holman, J. D., Obour, A. K., and Assefa, Y. (2022). Forage sorghum grown in a conventional wheat-grain sorghum-fallow rotation increased cropping system productivity and profitability. Canadian Journal of Plant Science, 103: 61-72. http://dx.doi.org/10.1139/CJPS-2022-0171

Kansas Department of Agriculture (2025). Kansas Farm Facts. Retrieved July 8, 2026, from: https://www.agriculture.ks.gov/home/showpublisheddocument/14700/639015680188930000

Landry, E., Janovicek, K., Lee, E. A., and Deen, W. (2018). Winter cereal cover crops for spring forage in temperate climates. Agronomy Journal. 111(1), 217–223. https://doi.org/10.2134/agronj2018.03.0214

Mehlich, A. (1984). Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. Communications in Soil Science and Plant Analysis, 15:1409–1416. https://doi.org/10.1080/00103628409367568

Nelson, D. W. and Sommers, L. E. (1996). Total carbon, organic carbon, and organic matter. Soil Science Society of America, 961–1010. https://doi.org/10.2134/agronmonogr9.2.2ed.c29

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

Nielsen, D. C., Lyon, D. J., Hergert, G. W., Higgins, R. K., Holman, J. D. (2015). Cover Crop Biomass Production and Water Use in the Central Great Plains. Agronomy Journal, 107:2047-2058. https://doi.org/10.2134/agronj15.0186

Nielsen, D. C., Vigil, M. F., and Hansen, N. C. (2016). Evaluating potential dryland cropping systems adapted to climate change in the central great plains. Agronomy Journal, 108: 2391-2405. doi: 10.2134/agronj2016.07.0406

Nimmo, J.R., and Perkins, K. (2002). Aggregate stability and size distribution. Methods of soil analysis, Part 4-Physical methods. Soil Science Society of America Book Series No. 5. https://doi.org/10.2136/sssabookser5.4.c14

NOAA. (2026). Regional Climate Centers: National Oceanic and Atmospheric Administration. Retrieved May 31, 2026, from: https://www.ncei.noaa.gov/regional/regional-climate-centers

Obour, A. K., Simon, L. M., Holman, J. D., and Johnson, S. K. (2021). Does grazing Cover crops impact soil properties? K-State Research and Extension vol. 7: Iss. 5. https://doi.org/ 10.4148/2378-5977.8078

Obour, A. K., Dille, J., Holman, J. D., Simon, L. M., Sancewich, B., and Kumar, V. (2022a). Spring-planted cover crop effects on weed suppression, crop yield, and net returns in no-tillage dryland crop production. Crop Science Society of America, 62:1981-1996. https://doi.org/10.1002/csc2.20801

Obour, A.K., Holman, J. D., Assefa, Y. (2022b). Grain sorghum productivity as affected by nitrogen rates and available soil water. Crop Science 62:1360-1372.

DOI: 10.1002/csc2.20731

Obour, A. K., Holman, J. D., Simon, L. M. (2023). Grazing cover crops improved soil health in dryland cropping systems. Kansas Agricultural Experiment Station Research Reports: Vol. 9: Iss. 6. https://doi.org/10.4148/2378-5977.8486

Ogden, C. B., Van Es, H. M., and Schindelbeck, R. R. (1997). Miniature rain simulator for field measurement of soil infiltration. Soil Science Society of America Journal, 61(4), 1041–1043. https://doi.org/10.2136/sssaj1997.03615995006100040008x

Peterson, G.A. and Westfall, D.G. (2004). Managing precipitation use in sustainable dryland agroecosystems. Annals of Applied Biology, 144(2), 127–138. https://doi.org/10.1111/j.1744-7348.2004.tb00326.x

Ratliff, L.F., Ritchie, J.T., and Cassel, D.K. (1983). A survey of field measured limits of soil water availability and related laboratory-measured soil properties. Soil Science Society of America Journal, 47, 770 – 775. https://doi.org/10.2136/sssaj1983.03615995004700040032x

Reeder, J., Schuman, G., and Bowman, R. (1998). Soil C and N changes on conservation reserve program lands in the Central Great Plains. Soil & Tillage Research., 47(3), 339–349. https://doi.org/10.1016/S0167-1987(98)00122-6

Simon, L.M., Obour, A.K., Holman, J.D., Johnson, S.K., and Roozeboom, K.L. (2021). Forage productivity and soil properties in dual-purpose cover crop systems. Agronomy Journal, 113, 5569–5583. https://doi.org/10.1002/agj2.20877

Simon, L.M., Obour, A.K., Holman, J.D., and Roozeboom, K.L. (2022). Long-term cover crop management effects on soil properties in dryland cropping systems. Agriculture, Ecosystems & Environment, 328, 1–11. https://doi.org/10.1016/j.agee.2022.107852

Thomas, G. W. (1996). Soil pH and soil acidity. In Sparks, D. L. (Ed.), Methods of soil analysis part 3: Chemical methods (pp. 475–490). SSSA.

Unger, P. (1998). Cover crop effects on soil water relationships. Journal of Soil and Water Conservation, 53:200–207. http://dx.doi.org/10.15666/aeer/1602_14131426

USDA-NRCS (2022a). Kansas supplement to conservation enhancement activity: E340C Use of multi-species cover crops to improve soil health and increase soil organic matter. Obtained on 3 June 2026 from: https://www.nrcs.usda.gov/sites/default/files/2022-12/E340C-KS23.pdf

USDA-NRCS (2022b). Soil Health-Bulk Density, from: https://www.nrcs.usda.gov/sites/default/files/2022-11/Bulk%20Density%20-%20Soil%20Health%20Guide_0.pdf

USDA-NRCS (2002). National agronomy manual (3rd ed.). USDA Natural Resources Conservation Service.

Zadoks, J.C., Chang, T. T., and Konzak, C. F. (1974). A decimal code for the growth stages of cereals. Weed Research, 14, 415–421. https://doi.org/10.1111/j.1365-3180.1974.tb01084.x

Tables

Table 3.1. Total monthly and 30-year average precipitation for Russell County, KS over the study period.

Month	2022	2023	2024	30-yr Avg
		mm		
January	-	5.08	0.00	13.72
February	-	0.00	0.00	20.83
March	-	0.51	0.00	48.77
April	-	8.89	1.02	66.55
May	-	55.88	145.03	93.47
June	-	166.37	49.02	90.93
July	-	61.98	35.31	96.01
August	-	101.85	102.62	72.64
September	-	14.22	16.00	57.15
October	9.14	45.72	12.95	39.88
November	10.67	28.19	71.63	27.69
December	12.19	54.10	0.00	20.83
Annual	-	542.79	433.58	648.47

Table 3.2. Cover crop residue remaining, residue height, and residue cover averages and ANOVA table as effected by grazing intensities and year in Russell County, KS.

	Residue Remaining		Residue Height		Residue Cover	
	2023	2024	2023	2024	2023	2024
Treatment						
	kg ha^{-1}		cm		%	
UGR	1967a[†]	991a	55a	56a	76a	65a
T-H-L-H	795b	241b	43b	49b	70b	43b
G-O	541c	259b	28c	48b	76a	44b
Year						
2023	1101a		42b		73a	
2024	497b		51a		51b	
Test of Fixed Effects			P-values			
TRT	**<.0001**		**<.0001**		**0.0001**	
Year	**<.0001**		**<.0001**		**<.0001**	
TRT*Year	**0.0001**		**<.0001**		**0.0052**	

[†]Means within a column followed by the same lower-case number are not different (α =0.1) across each grazing intensity and year within each biomass parameter.

Table 3.3. Initial and 2-year averages and ANOVA table for effect of grazing intensity on soil chemical, bio-chemical, and physical properties in Russell County, KS.

Treatments	BD	PR	SOC	POM	N	P	pH	WAMWD	DAMWD	WEF	TTR
	-g cm^{-3}-	-Mpa-	-%-	-%-	-kg ha^{-1}-	-kg ha^{-1}-	-pH-	-mm-	-mm-	-%-	-min-
Initial	**1.25 ± 0.06**	-	**1.75 ± 0.15**	**1.00 ± 0.22**	**15.25 ± 1.44**	**12.51 ± 0.59**	**5.72 ± 0.14**	**1.23 ± 0.15**	**5.49 ± 0.32**	**23.74 ± 0.98**	**16.37 ± 0.73**
UGR	1.32a[†]	0.89a	1.86a	1.04a	6.47a	24.41a	5.51a	1.51a	4.51a	34.92a	7.61a
T-H-L-H	1.36a	0.86a	1.73a	0.88a	6.27a	15.19b	5.75a	1.48a	4.77a	32.73a	7.69a
G-O	1.36a	0.83a	1.75a	0.91a	6.31a	17.61b	5.76a	1.41a	5.01a	32.65a	7.37a
Test of Fixed Effects						P-values					
TRT	0.3076	0.8083	0.3230	0.3125	0.9881	**0.0560**	0.3585	0.8525	0.1980	0.4231	0.9520
Year	**0.0045**	**<.0001**	**0.0213**	**0.0085**	**0.0257**	**0.0066**	0.1714	**0.0006**	0.4368	**0.0655**	**0.0040**
TRT*Year	0.4740	**0.0156**	0.1666	0.2884	0.1713	0.7121	0.5048	0.4370	0.5745	0.3199	0.2847
Depth	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**0.0437**	0.7187	-	-	-	-
TRT*Depth	**0.0797**	0.5638	0.7246	0.7610	0.6397	0.4329	0.3128	-	-	-	-
Year*Depth	0.4058	**<.0001**	0.3586	0.9562	0.4496	**0.0821**	0.5070	-	-	-	-
TRT*Year*Depth	0.5526	0.9384	0.2351	0.8840	0.1130	0.5896	0.8381	-	-	-	-

[†]Means within a column followed by the same lower-case number are not different (α =0.1) across each treatment within each soil parameter. BD = bulk density; PR = penetration resistance; SOC = soil organic carbon; POM = particulate organic matter; N = nitrogen; P = phosphorus; WAMWD = wet aggregate mean weight diameter; DAMWD = dry aggregate mean weight diameter; WEF = wind erodible fraction.

Table 3.4. Effects of grazing intensity of cover crops on grain sorghum yield near Russell County, KS.

Treatment	Grain Sorghum Yield
	– kg ha^{-1} –
UGR	5432a
T-H-L-H	6019a
G-O	5998a
Year	
2023	5500b
2024	6133a
Test of Fixed Effects	P-values
TRT	0.1717
Year	**0.0314**
TRT*Year	0.6067

†Means within a column followed by the same lower-case number are not different (α =0.1) across each grazing intensity and year.

Figures

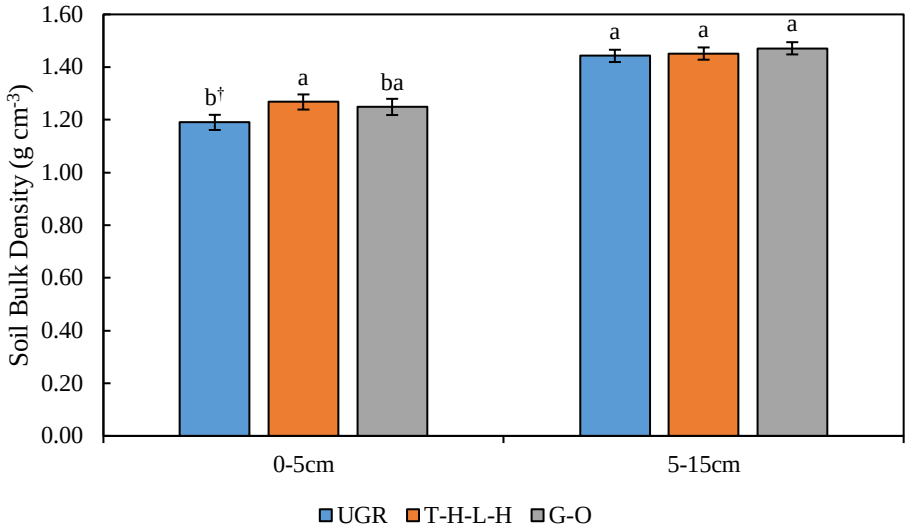

Figure 3.1. Effect of grazing intensity on soil bulk density at the 0-5cm and 5-15 cm soil depth in Russell County, KS. UGR = Ungrazed; T-H-L-H = Take-half-leave-half; G-O = Graze out.

†Means with the same letter are not significantly different (α =0.1) across treatments.

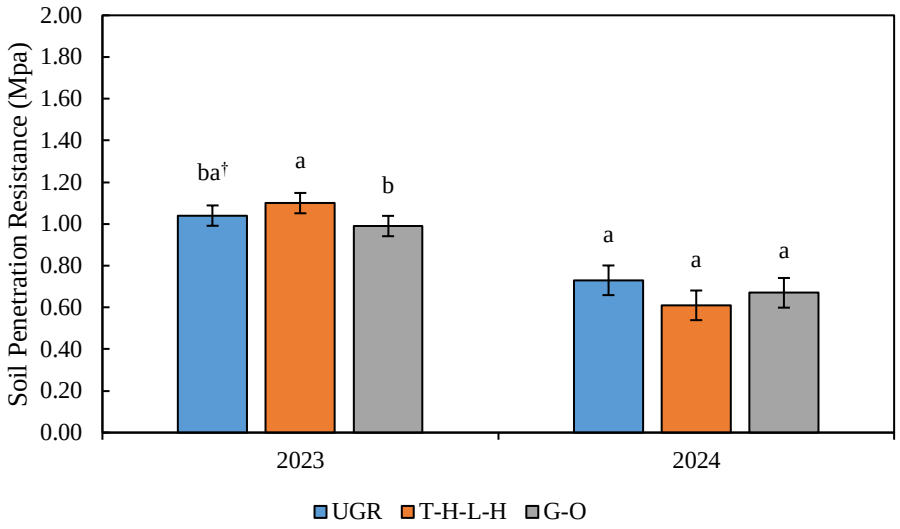

Figure 3.2. Effect of grazing intensity on penetration resistance within 2023 and 2024 averaged across the 0-15cm soil depth in Russell County, KS. UGR = Ungrazed; T-H-L-H = Take-half-leave=half; G-O = Graze Out.

†Means with the same letter are not significantly different (α =0.1) across treatments.

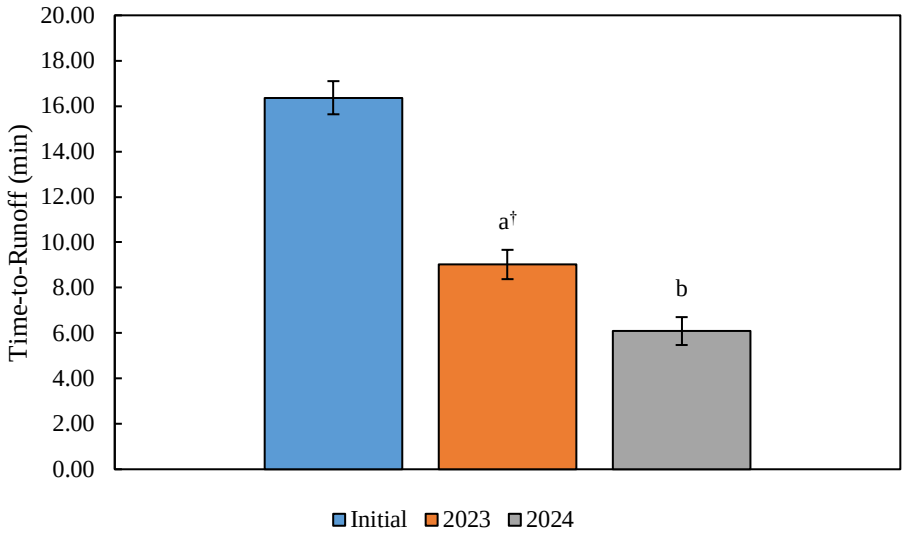

Figure 3.3. Effect of cover crop from initial implementation, to 2023 and 2024 on time-to-runoff in Russell County, KS.

†Means with the same letter are not significantly different (α =0.1) across treatments.