Soil properties affected by grazing, forage rotations, and tillage in the semi-arid dryland cropping systems central Great Plains

by

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Abstract

Annual forages in dryland cropping systems in the semi-arid central Great Plains could improve soil health and provide forage for livestock. A study was initiated in 2016 near Jetmore, KS to investigate tillage effects on grazed continuous winter triticale [×*Triticosecale Wittm.* ex A. Camus (*Secale* ×*Triticum*)]. The two treatments included minimal tillage (MT) and no-till (NT). A second story was conducted from 2012 to 2022 at the Southwest Research Extension Center near Garden City, KS. The crops in the rotations included winter triticale (T), forage sorghum [*Sorghum bicolor* (L.) Moench] (FS) and oats (*Avena sativa* L.) (O). Six treatments in an incomplete factorial combination of four crop rotation and two tillage treatments include FS-FS (NT), T/FS–FS–O (NT), T/FS–FS–O (RT), T/FS–FS–FS–O (NT), T/FS–FS–FS–O (RT), T-FS-O (NT). At Jetmore, Bulk density was greater pre-till (1.31g cm^{-3}) compared to the post-till (1.23 g cm^{-3}) and was lower under MT (1.24 g cm^{-3}) compared to NT (1.29 g cm^{-3}). Minimal tillage decreased water stable aggregate mean weight diameter, increased wind erodibility, and decreased dry aggregate stable MWD. Penetration resistance was unaffected by tillage systems. No-till had greater sorptivity in 2022 compared to MT. Time to runoff was greater in 2022 compared to 2021. Infiltration rate was unaffected by tillage. Soil organic carbon (SOC) stocks on a fixed depth basis was greater in pre-till than post-till in two of three years, greater in the 5- to 15-cm depth compared to 0- to 5-cm depth, and greater in NT than MT in 2022. Soil equivalent mass SOC stocks were greater in the pre-till compared to post-till and greater in the 5- to 15-cm soil depth than the 0- to 5-cm soil depth. Soil organic carbon concentration was greater in NT than MT in 2022 and greater in the 0- to 5-cm than the 5- to 15-cm depth. Nitrate-N concentration was greater in the MT and was in greater concentration in the 0- to 5-cm depth compared to the 5- to 15-cm depth. Soil phosphorus concentrations in the soil surface were greater pre-till than post-till (884 ppm vs. 554 ppm). Soil pH was slightly lower in NT compared to MT. Early forage biomass was greater in MT compared to NT, but consistent grazing leveled out forage production. Crude protein (CP), neutral detergent fiber digestibility (NDFD), and total digestible nutrients (TDN) were greater in the spring compared to summer. However, acid detergent fiber (ADF), neutral detergent fiber (NDF), and undigested neutral detergent fiber (UNDF) were greater in the summer compared to spring. Minimal tillage increased CP, NDF, and UNDF but decreased NDFD in 2022. Minimal tillage significantly reduced weed density compared to NT. Our findings suggest that MT had minimal effects on soil physical and chemical properties, significantly decreased weed population, and increased early season forage biomass. At Garden City, results showed treatments was not different for soil parameters except total nitrogen (TN), soil nitrate (NO_3^-) concentrations and soil potassium (K). Soil nitrate-N concentration was greatest in T/S-S-S-O (NT) and the lower nitrate concentrations in T/FS-FS-O (NT), T/FS-FS-O (RT), and T/FS-FS-FS-O (RT). Potassium concentration differed among forage rotations; T/S-S-S-O in NT had the highest level and FS-FS had the lowest level. Tillage had no significant differences in soil parameters except NO_3^-, K and WSA MWD. No tillage had more soil nitrates and K concentration than RT. However, RT had a higher WSA MWD compared to NT. Sorptivity, infiltration rate, and TTR was not significantly different among treatment. Sorptivity was greater in NT in 2021 but was greater in RT in 2022. Similarly, infiltration rate in 2021 infiltration rate was greater in NT but was greater in RT in 2022. Time to runoff was faster in NT in 2021 but was faster in RT in 2022. Time to run-off saw that 2021 was faster in run-off time compared to 2022. Our findings suggest that forage rotations can be used without negative impacts on soil physical and chemical properties and tillage had limited impacts on soil parameters.

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Dedication

I would like to dedicate my work to my grandfathers, Gerald Mauler and Don Sutter. They have been influential in inspiring my passion for agriculture. Both were farmers and ranchers that grew wheat as well as raised cattle. They both grew up in limestone houses on the prairies of Kansas and both went to countryside schoolhouses. They have experienced the hardships and joys of farming and ranching. I always enjoyed listening to my grandfathers' stories about how they used to farm when they were younger. Listening to these stories makes me truly appreciate the hard work and dedication it takes to successfully grow and raise crops and cattle.

Chapter 1 - Introduction and Literature Review

Introduction

Growing forages in the central Great Plains (CGP) can be very productive and profitable for producers, because of large market in the area as many feedlots and livestock operations are in this region. The GCP grows many kinds of forages such as annual, biannual, and perennial forages. Annual forage crops include triticale [×*Triticosecale* Wittm. ex A. Camus (Secale ×Triticum)], rye (*Secale cereale*), forage sorghum (*Sorghum bicolor* (L.) Moench), oats (*Avena sativa* L.), etc. Annual forages have two distinct growing seasons, cool season annual forages (ex. triticale, rye, wheat etc.) and summer annuals (forage sorghum, sorghum-Sudan grass, pearl millet). Biannual forages include turnips (*Brassica rapa*), rapeseed (*Brassica napus*), kale (*Brassica oleracea*), and sweet clover (*Melilotus officinalis*). Perennial forages include alfalfa (*Medicago sativa*), birds foot trefoil (*Lotus corniculatus*), red clover (*Trifolium pratense*), white clover (*Trifolium repens*), and timothy (*Phleum pratense*). Native rangeland is another available forage type in the semi-arid area with 7.08 million ha^{-1} in Kansas, 9.15 million ha^{-1} of rangeland in Nebraska, 9.31 million ha^{-1} in Oklahoma. Kansas has 1.09 million ha^{-1} of hay and haylage that includes 275,186 ha^{-1} of alfalfa harvested in 2022 ("USDA/NASS 2021 State Agriculture Overview for Kansas," 2023). Nebraska has 888,284 ha^{-1} of hay and haylage that includes 325,772 ha^{-1} of alfalfa harvested in 2022 ("USDA/NASS 2021 State Agriculture Overview for Nebraska," 2023). Oklahoma has 1.22 million ha^{-1} of hay that includes 89,031 ha^{-1} harvested of alfalfa ("USDA/NASS 2021 State Agriculture Overview for Oklahoma," 2023). All these different types of forages are critical to support the large cattle (*Bos taurus*) industry in the semi-arid region.

Dryland agriculture relies solely on the precipitation that falls during the growing season and in the CGP evaporation exceeds annual rainfall (Robinson and Nielsen 2015). Great Plains precipitation is about 20 to 35% of potential evapotranspiration (PET) (Peterson and Westfall, 2004). Dryland farming practices are possible with practices and management strategies such as reduced tillage and crop residue retention to help reduce evaporation and increase store water storage in during the fallow period. Due to these water limitations, fallow is a component of most crop rotations such as winter wheat (*Triticum aestivum* L.) -fallow or winter wheat -summer crop (ex. Corn (*Zea mays subsp.* Mays), grain sorghum (*Sorghum bicolor* Moench.), and sunflower (*Helianthus annuus* L.))- fallow in the semi-arid CGP region (Nielsen and Vigil,2018).

Annual forages can be grown for hay, silage, or grazing. In Kansas, 971,246 ha^{-1} were harvested for hay and haylage in 2021. Of this total, 263,046 ha^{-1} were alfalfa, and 716,294 ha^{-1} were crops other than alfalfa (Holman et al., 2022;US Department of Agriculture National Agricultural Statistics Service, 2022) Corn can be cut for silage and is the most common irrigated forage in the CGP. Corn silage is known for having high tonnage and is a high-energy crop that is favored for dairy operations (Nilahyane et al., 2020). Corn-silage is also highly palatable, easily digestible, and is easy to ensile due to high soluble sugar contents (Nilahyane et al., 2020; Ali et al., 2019). Alfalfa (*Medicago sativa*) requires irrigation for best productivity in the CGP and is the forage source greatest in crude protein, but lower in yield and energy than corn (Holman et al., 2016). Livestock producers tend to use both corn silage and alfalfa for the benefits that each contributes. However, due to decreasing irrigation well capacity, annual forages that yield well without irrigation are needed (Deines et al., 2020).

Annual forage production can also enhance available forage for livestock producers (Entz et al., 2002; Zilverberg et al., 2015). Winter triticale (×*Triticosecale*) is a hybrid between wheat and rye (*Secale cereale*) and is known for its winter hardiness and good forage quality. Winter triticale is also known for its drought tolerance compared to other small annual grains such as wheat, oats, barley. Compared to winter wheat for forage, winter triticale had greater winter hardiness, better forage productivity and greater nutritive value (Ayalew et al., 2018; Holman et al., 2009). Winter triticale is a viable alternative crop especially in nutrient-deficient environments with various biotic and abiotic stress factors (Blum, 2014; Ayalew et al., 2018). Under irrigation, winter triticale had higher water use efficiency compared to perennial ryegrass (*Lolium perenne* L.)(Neal et al., 2011). Winter triticale was able to limit water loss by evaporation with full canopies, however while water use efficiency did not decrease, yield generally declined by deficit irrigation compared to optimal irrigation. However, in another study, winter triticale yields were unaffected by irrigation under wheat-corn-triticale crop rotations in both irrigation and dryland systems (Nielsen et al., 2017) Oats (*Avena sativa*) are becoming a more common forage that is available throughout the GCP. Oats are not winter hardy, have a short growing season planted in the spring and harvested in early summer, and have low tonnage but high feed quality (Obour et al., 2019; Coblentz and Cavadini, 2016). Spring triticale (x *Triticosecale Wittmack*) also can be grown in the CGP. Spring triticale is planted in early spring and harvested early summer like oat production. Oats under irrigation did not affect yield and increased water use efficiency in response to deficit irrigation (Neal et al., 2011). Forage sorghum (*Sorghum bicolor* (L.) Moench) is also known for its drought and heat tolerance (Holman et al., 2019). Forage sorghum is also known for its high tonnage of possible forage, though it has low protein quality compared to forages such as alfalfa(Marsalis et al., 2010). Forage sorghum is a summer annual and is planted in the summertime and is harvested in the fall. One of the advantages of forage sorghum is the less water use and requires 25% less water compared to corn (Martin et al., 1976), and may deplete less water from the soil (Merrill et al., 2007). Under irrigation systems, forage sorghum yield was unaffected by different irrigation rate and forage sorghum was one of the few warm season forage species with the greatest ability to maintain water use efficiency under deficit irrigation (Neal et al., 2011). Another study noted that under water-stress conditions forage sorghums and brown mid-rib (BMR) forage sorghum can produce higher forage yield with acceptable nutritive value than corn silage (Bhattarai et al., 2020). Brown mid-rib traits reduce lignin so plants are more digestible. Other summer annuals include sorghum-sudan (*Sorghum bicolor* [L.] *Moench x Sorghum Sudanese* [Piper) and sudan grass (Sorghum Sudanese [Piper]). Sorghum-sudan is a cross between forage sorghum and sudan grass. Sorghum-sudan and Sudan grass is a different variety of summer grass that also known for its high tonnage. Sudan grass is drought tolerant and does well in warm temperatures (Armah-Agyeman et al., 2002). The plant can grow to 4 to 6 feet tall (Roozeboom et al., 2008). Sudangrass has relatively thin stems. It tillers extensively and can regrow rapidly and is better suited to pasturing than other types of sorghum. While prussic acid poisoning is possible, the risk with sudangrass usually is less than with sorghum-sudangrass or forage sorghum. Sorghum sudan hybrids are the most numerous of the various types of summer annual grasses. They are high-producing forage grasses but has better forage quality with brown mid-rib hybrids. Forage quality also depends on harvest timing, as quality declines rapidly as plants mature. Regrowth after repeated clippings or grazing is lower than sudangrass and are best suited for hay or green chop.

Annual forages can be managed according to precipitation and forage growth. For example, in wet years native pasture and annual forage growth will be greater, and forage can be harvested and stored for dry years when forage is limited. In dry years, there may be insufficient forage growth to financially warrant mechanical harvesting but can be grazed out or harvested or hay when grazing options are not available. Hay can also be sold for profit to other producers, dairies, or feedlots. In 2021, Billman and colleagues found that high nutrient quality forages, such as triticale and oats, have the most potential for supplementing spring perennial pastures. The high crude protein feed types such as winter triticale, oats, and rye can add additional spring forage production and can help fill gaps in a forage rotation (Billman et al., 2021; Coblentz et al., 2020). Although irrigated forages are important, the depletion of the Ogallala aquifer makes dryland forage production important for the sustainability of the CGP livestock production.

Annual forages are grown as a short rotation crop or continuous cropping such as continuous forage sorghum or continuous winter triticale. In continuous systems without crop rotation, often weeds become problematic. Weeds are increasingly more resistant to herbicides and more difficult to control. Though it is uncommon, annual forage rotations are possible with combinations of winter triticale, forage sorghum, and oats to intensify and diversify forage rotations (Holman et al., 2021). Intensifying and diversifying crop rotations could help combat the herbicide-resistant weeds by using different modes of action, planting dates, rooting depth and canopy architecture (Anderson, 2000; Holman et al., 2021;Anderson, 2005). Tillage can also help in the control of weed management in a crop rotation (Obour et al., 2020a). In a two year study by Barberi found that crop rotation and minimal tillage does not increase weed numbers, however NT might increase weed numbers because of the higher seeds from the topsoil (Bàrberi and Lo Cascio, 2001). Double cropping can be used for grain production and annual forages (Lyons et al., 2019; Buxton et al., 1999; Sweeney et al., 2022). A possible double cropping system for forages could be winter triticale followed by double-crop forage sorghum (Holman et al., 2021). Growing forages can also reduce fallow in crop rotations and can increase profitability (Holman et al., 2022a; Holman et al., 2018).

Replacing fallow with annual forages can increase crop residue return to the soil surface and improve soil properties (Blanco-Canqui et al., 2013). Crop residues and extensive fibrous roots of annual forage crops can improve soil health by intensifying crop rotations, recycling nutrients back into the soil, and decrease soil erosion (Simon et al., 2021). Soil health is a crucial indicator for soil productivity and soil stability. Some examples of healthy soil indicators are greater amounts of soil organic carbon, improved water stable aggregation, increase water infiltration, micro-biological activity, available water holding capacity, and improved soil structure (Kelly et al., 2021; Simon et al., 2021). Healthy soils also have low penetration resistance, soil compaction, and have less degraded soils than soils that have become weathered and eroded.

Dryland cropping systems

Dryland crop production in the semi-arid CGP is known for its production of winter wheat and grain sorghum. Winter wheat was introduced in 1874 with Turkey red wheat that was well suited for the climate and region. The introduction of turkey red winter wheat made living on the CGP livable. Grain sorghum was introduced to western Kansas in 1884, however, it was not mass produced until the 20th century (Cunningham and Kenney, 1918). The CGP region is also known for its significant periods of drought and wind-blown soil loss. The soils in the CGP were formed by loess and usually consist of silt loams, silty clay loams, and loamy sand soil textural classes throughout the region (Cano et al., 2018; Ghimire et al., 2018). The High Plains region of the CGP includes western Kansas, western Nebraska, southeast Wyoming, and eastern Colorado. The annual precipitation gradually increases west to east, from 305 mm to 610 mm per year (Robinson and Nielsen, 2015). One of the key challenges faced by dryland crop producers is effectively utilizing the seasonal precipitation they receive each year, ensuring maximum capture and storage of moisture in the soil. This enables the moisture to be readily available for the next crop while minimizing evaporation. Successful implementation of these strategies can lead to significant reductions in crop yield loss for dryland producers. Crop yields in the semi-arid region of CGP are highly variable due to major deficits between rainfall and evaporation (Peterson and Westfall, 2004;Farahani et al., 1998). The standard dryland cropping system has been winter wheat-fallow in the CGP, and the fallow period utilizes sweep tillage to control weeds. One of the ways producers have been able to grow profitable crops in this region with limited moisture is practicing fallow. Fallow in the CGP historically has been a 12- to 14-month period between cash crops to help store soil moisture. Stored soil moisture during fallow helps stabilize grain crop production, particularly during dry years (Nielsen and Vigil, 2010). Although fallow stores moisture in the soil, its efficiency is limited to cropping management strategies such as residue and tillage practices (Blanco-Canqui et al., 2013). Nielsen and Vigil (2010) reported the mean precipitation storage efficiency of a 14-month fallow under wheat fallow systems was 20% for conventional till and 35% for NT. In the same study, fallow soil water increased 111 mm under conventional tillage and 188 mm under no-till. Crop rotation can also affect soil water storage. Soil water at the planting of sorghum after wheat was greater than planting sorghum after sorghum (Schlegel et al., 2017). Crop yield stability in wheat fields following fallow is countered by the relative inefficacy of precipitation storage during the fallow period. Previous research shows no more than 19-33% of precipitation was received during the fallow period in wheat-fallow systems stored in the soil between subsequent wheat crops

(Peterson and Westfall, 2004). Precipitation storage efficiency increased by growing wheat and grain crop more frequently than every other year (Farahani et al., 1998).

Tillage practices in the central Great Plains

Tillage is an essential practice in the dryland cropping systems production to reduce weed density, seed bed preparation and seed germination (Triplett and Dick, 2008; Obour et al., 2021) . With the development of animal power and tillage implements (ex. Horse pulling moldboard plow), tillage soon became common practice in agriculture. There are different types of tillage practices that producers use for different reasons. Conventional tillage is the use of tillage implement that incorporates the entire crop residue into the soil with the use of multiple passes. Strip tillage is a conservation system that uses a minimal tillage implement and leaves fifty percent of crop residue on the top of the soil. Strip tillage uses the benefits of conventional tillage by drying and warming the soil and the benefits of NT with low disturbing. Minimal tillage (MT) is similar to strip tillage with the goal of minimal soil disturbance. Reduced tillage (RT) is comparable to that of sweep disks, which is only designed to disturb the top 51 mm to 76 mm of the soil. Compared to no-tillage that minimizes soil disturbance, no-till had greater surface respiration, however the deeper depths saw lower permeate. No-till practices often see a severe stratification (Blanco-Canqui and Wortmann, 2020). Tillage practices affect soil water infiltration, evaporation, and storage in dryland cropping systems, which effects subsequent crop yield. Alan Schlegel and colleagues observed that implementing occasional tillage before winter wheat, rather than grain sorghum, had the least impact on subsequent crop yield compared to continuous no-till systems. (Schlegel et al., 2020). By preparing the soil for planting with tillage, farmers were able to establish a better stand of crops in dry years (Holman et al., 2021). However, tillage can increase wind and water erosion by reducing residue, decrease soil organic carbon (SOC), decrease soil structure, decrease soil structure and soil organic matter (SOM) (Zuber et al., 2015;Kibet et al., 2016). Most of the soil erosion occurred because there was no residue (Peterson et al., 2020). Before herbicides were common in controlling weeds during fallow, weeds could be managed with multiple passes with tillage (7-8 passes per season). The amount of tillage passes throughout the summer left the soil bare with no protection against wind or water erosion. Multiple tillage passes reduced soil aggregate size and continuity of soil pores. However, many studies have looked at reduced tillage (RT) practice that reduces the number of tillage operations (Obour et al., 2021). In a study looking at rotation and tillage in forage cropping systems, Holman et al., (2021) evaluated tillage, species, and crop rotation on forage production, specifically looking at winter triticale, forage sorghum, spring triticale, and oats. They observed that oat forage accumulation was mainly affected by the environment, no-till tillage or rotation. Forage sorghum was not affected by tillage and water use tended to be greater for reduced tillage compared to no-till. However, the interaction of tillage and environment significantly affected winter triticale forage yield. In conditions of high temperatures and low precipitation during January-March, the no-till triticale produced less forage accumulation than reduced tillage treatments. Triticale was the only crop in the rotation planted after tillage and was the only crop affected by tillage and environment. The increased soil water storage with reduced tillage increased forage yield compared to no-till (Holman et al., 2021).

No-Till

No-till (NT) farming is a cropping practice that is designed to reduce the amount of soil disturbed from planting and eliminates a tillage pass need. No-till (NT) crop production, especially corn production, began in the 1960s (Triplett and Dick, 2008). It was made possible with the advancements in herbicides and improved planters. No-till practices have become more widely used since the introduction and improvement of these advancements. No-till farming is planting a crop into a field that has not been previously tilled and is planted directly into the crop residue. Weed control in no-till systems can be achieved with herbicides rather than with tillage(Triplett and Dick, 2008). Integrating no-till with a crop rotation that includes seasonal intervals of a cool season and a warm season crop can improve weed management as well as a perennial crop such as alfalfa. Weed density is reduced, and time of emergence is delayed, lessening impact of weeds on crop growth. Additional benefits of NT leaves crop residue on the ground, significantly reducing soil erosion, compared to the tillage practices that incorporate all remaining residue into the soil. The conversion from tillage to NT cropping systems has allowed cropping intensity to be increased from winter wheat-fallow to winter wheat-summer crop (corn, grain sorghum, or sunflower)-fallow. No-tillage allows individual producers to manage more acreage with reduced energy, labor, and machinery inputs.

Today's dryland cropping system is rapidly changing with new technology such as variable rate technology for both herbicide and fertilizer, using different imagery such as infrared and NDVI to identify problem spots in fields with unmanned aerial vehicles or drones, and the rotation of herbicides with different modes of action (Nazarko et al., 2005; Shang et al., 2021). The use of multiple modes of action reduces the likelihood of herbicide resistant weeds to just one specific herbicide mode of action. No-till improves soil health indicators such as soil aggregate stability, reduces erosion, and water infiltration (Page et al., 2013;Blanco-Canqui and Ruis, 2018). Increasing crop intensity and reduced fallow can improve soil health and water use efficiency. Since NT farming can plant through plant material and untilled fields, grain producers can plant instantly after harvest of the previous crop. No-till cropping practices can help reverse the soil carbon losses from over a century of degrading cropping practices and contributing to a sustainable agroecosystems and better supports farmers across the Great Plains (Peterson et al., 2020).

A major decision for dryland farmers in the Great Plains is when and how frequently to use fallow. The relationships between stored soil moisture levels at planting and crop yield can be used as a tool to assist farmers with making planting decisions (Lenssen et al., 2007). The long term use of NT should be encouraged with the benefits of erosion resistance with residue cover and improved soil quality factors.(Dabney et al., 2004; Triplett and Dick, 2008) . However, the erosion resisting soil qualities can be lost within a single year of fallow management (Dabney et al., 2004). No-till can provide an opportunity to rapidly expand production while protecting soil against erosion. Desirable soil conditions formed under permanent vegetation, increased organic matter and stable macropores, will be retained with NT production (Triplett and Dick, 2008). Triplett and Dick (2008) also concluded that a long-term trend toward increased worker productivity with NT has occurred with larger equipment, fewer operations for soil preparation, less cultivation, and increased use of herbicides. However, herbicide resistant weeds are problematic in NT systems, reducing crop yields. Herbicide resistant weed populations can be managed with appropriate combinations of rotation of crops and herbicide modes of action (Triplett and Dick, 2008).

Alternative crops and crop rotations are being evaluated in dryland NT systems for the potential to increase precipitation use efficiency (PUE), improve soil physical properties, reduced dependence on N fertilizers, and for develop alternative markets (Hansen et al., 2012). The inclusion of annual forage crops in cropping systems can improve precipitation use efficiency and resilience to climate change in the Great Plains and forage crops can help meet emerging markets. No-till cropping systems will continue to play an important role in the sustainability of dryland cropping in the Great Plains. However, farmers and managers will need to adapt to technology changes and challenges of NT production.

Annual forages in the central Great Plains

There is a diverse array of productive annual forage crops that can be grown in dryland CGP cropping systems (Holman et al., 2021). Both cool and warm season annual grass and broadleaf species can be grown for forage in the CGP. These species vary in their productivity and profit potential. The most common forages grown in the CGP are triticale, forage sorghum, and oats. Annual forages are regarded as high in crude protein (CP), digestibility, and dry matter production (DM production) (Obour et al., 2019; Holman et al., 2019). Unlike broadleaves [(turnips (*Brassica rapa*), radish (*Raphanus sativus*), soybeans (*Glycine max*. L.)], grasses have significant regrowth potential which can be used as grazing or multi-cut hay. Annual forages also provide an advantage over grain and seed production with respect to hail damage. Grain and seed crops are incredibly vulnerable to hail, especially when reproductive stages are reached. A severe hail event can completely decimate a grain crop, with more significant effects occurring later in the growing season (Lollato et al., 2018). Although grain crops can be decimated by hail, forage can regrow and still produce a harvestable yield after a late-season hail event (Lauer et al., 2004). Farmers face challenges incorporating annual forages into dryland wheat systems when there are no local markets for harvested forage and if there is no livestock on the farm. Where a market does exist, the demand for forage can fluctuate from year to year depending on precipitation, with higher prices in drier years and lower prices in wetter years (Carr et al., 2021)

Hay

Many forages in the CGP are frequently harvested as hay, such as alfalfa, winter triticale, winter and spring oats, and forage sorghum. In some cases, even perennial forages can be harvested for hay in the CGP such as warm season native hay (big bluestem, little bluestem, Indian grass) and smooth brome (*Bromus inermis* Leyss). Hayed forages can provide beneficial forage during different times of the year when perennial pastures are unable to meet livestock needs or stored for use during periods of drought. It is also used as roughage in background or feedlot rations. The CGP encompasses various agricultural operations, including backgrounding, feedlot, dairy farms, stocker, and cow/calf operations. As a result, there is a significant demand for forage production. Of all the domestic feedlots in the U.S., 51.7% of the U.S. production is located in CGP as of April 2022, occurring in the three states, Nebraska (22%), Kansas (20.7%), and Colorado (9%) (USDA, 2021).

Growing forages in place of fallow can increase profit and is more profitable than covers crops in dryland cropping systems (Holman et al., 2018). Net returns were more stable over time for cropping systems that included forages than grain-based cropping systems (Nielsen et al., 2016 Entz et al., 2002). Annual forage can be grown every year to produce a large quantity of feed for livestock. One of the benefits of haying annual forages is easy storage of hay bales, which can be readily used when the producer needs extra forage. However, there are some concerns about harvesting annual forage as hay. Harvesting annual forages as hay results in more field traffic (swath, rake, bale, and stack) than grain crops that might result in surface compaction. However, long-term research in southwest Kansas concluded spring and winter triticale harvested for hay had no negative effects on soil compaction, SOC, and erosion parameters (Blanco-Canqui et al., 2013). Another concern is the expense of hay equipment. Haying equipment is expensive to purchase and maintain and can be more then what producers are willing pay. However, producers can hire someone with hay equipment to harvest and bail the hay to reduce equipment cost. In cost comparisons of custom rates and the total cost of to own and operate farm machinery in Kansas, they noted that on average custom rates for a Kansas farm harvesting 1000 acres are 20.4% lower than true cost to own and operate machinery (Beaton et al., 2003). They also mention that custom rates would need to be increased by 25.6 percent, on average, to cover all ownership and operating costs. In 2022, the average custom rate for the entire haying operation in Kansas was $25.45 per bale for large round bales and $31.00 per bale for large square bales (Tsoodle and Laird, 2022). Harvesting forage needs to occur at the correct plant growth stage and humidity in order to retain forage quality.

Hay storage losses come from the moisture content at baling and loss during storage, storage conditions, environmental conditions such as relative humidity, air temperature, air movement, and the plant species being harvested. Hay baled with moisture contents greater than 20% can develop mold, which results in dry matter loss and reduced feed quality. This could also lead to hay bales catching fire due to spontaneous combustion. Moisture content that is too dry for baling decreases dry matter from leaf shattering. When baling, it is important to make the bale as dense you can (Russell et al., 1990). High-density (189 kg m^{-3}) had higher dry matter (DM) concentration and lower proportion of nitrogen after 4-months and 9-months. A dense bale will help shed precipitation, sag less, and have less surface area to absorb moisture. Using net wrap will reduce bale sag and maintain bale shape. Storing bales end to end in long lines in northwest to southeast direction whenever possible (Niemeyer, 2014). Space adjacent rows at least 10 feet apart. Stacking bales usually increased losses. Covering hay with a tarp or building helps preserve hay and is important if storing for more than a year.

Silage

Silage is fermented forage with improved nutrient value compared to baled hay. Ensiling feed is common throughout the CGP with Kansas harvesting 97,125 ha^{-1} of corn silage and

34,398 ha^{-1} of sorghum silage (“USDA/NASS 2021 State Agriculture Overview for Kansas,” 2023). In Nebraska, 105,218 ha^{-1} of corn silage and 12,545 ha^{-1} of sorghum silage (“USDA/NASS 2021 State Agriculture Overview for Nebraska,” 2023). In Oklahoma, 10,117 ha^{-1} of corn silage and 9,308 ha^{-1} of sorghum silage was harvested(“USDA/NASS 2021 State Agriculture Overview for Oklahoma,” 2023). Silage can provide forage with improved digestibility, lower in nitrates, and a mixed ration with improved palatability. The success of ensiling crops depends on five general areas: crop, harvest management, packing and covering, additives, and feed out management. For ensiling, producers must harvest the crop at the desired moisture, and quickly pack out the crop as soon as possible to start the fermentation process. Harvest, packing, and feed out are critical stages for producing feed high in nutritive value. When harvesting corn for silage, the corn should be harvested at 35% dry matter or 65% moisture, ½ to ¾ milk line. For forage, the forages dried to below 65% g or less than 35% dry matter, lactic acid bacteria (LAB) are stressed and decreases production. Excess moisture of more than 70% moisture encourages the growth of undesirable bacteria of Clostridia that decreases the protein in the silage (Muck et al., 2020). To minimize losses in a tractor spreader, spread fresh silage into thin layers within a bunker or over pile, using 800 lbs of tractor weight per ton of silage. By packing silage tight, less oxygen is present in the silage pile, which reduces respiration and can minimize silage losses. One of the benefits of silage is the option to salvage a failed crop lost to drought. Drought crops are frequently high in nitrates and ensiling reduces nitrate levels with enterobacteria (Spoelstra, 1985). Although enterobacteria decreases protein, it does have a special characteristic of reducing nitrate to nitrite (NO_2-N). Enterobacteria also can help inhibit clostridia which can lead to more silage spoilage and can impair milk quality. Forages high with nitrates can reduce nitrate levels by 40-60% with proper fermentation

(Drewnoski et al., 2019). Excessive nitrates will not always be reduced to safe values during ensiling so it’s important to analyze the feed before feeding. For corn, the ideal time to harvest for safe storage and maximum product is R5 for the corn life cycle (Moran, 2005).

The first step of the silage process starts at harvest and under ideal conditions of moisture, chop length, and firm packing lasts only a few hours. This initial phase continues until either the oxygen supply or water-soluble carbohydrates have been depleted. During this phase temperature is increased as crop ferments from ongoing cell respiration where carbon dioxide, water and heat are produced. In poorly sealed and/or packed silos, bunk life of the resulting feed can be reduced since the initial growth of aerobic spoilage organisms (yeasts and Bacillus species) occur during this phase. Once feed out occurs, yeasts can rapidly increase in numbers causing heating in the feed bunk and lowered feed consumption.

The second phase of ensiling begins when the oxygen supply is depleted and generally lasts no longer than 72 hours. During this phase, anaerobic hetero fermentation occurs by *Enterobacteria.* This bacterium can tolerate the heat produced during the aerobic phase and are viable in a pH range of 5 to 7. These hetero fermenters produce both acetic and lactic acid but tend to be inefficient at producing these acids relative to nutrients lost in the fermenting crop. When the pH drops below 5, homo-fermenters predominate and phase 3 of silage fermentation begins. The third stage lasts less than 24 hours. During the third step, temperature and pH of the silage decreases. Eventually, the bacteria in this phase become inhibited and phase 4 lactic acid bacteria increase. temperature is stabilized and water-soluble carbohydrates are converted to lactic acid by homo-fermentative bacteria. When the terminal pH is reached, the forage is preserved within the silo. Phases 2, 3, and 4 generally are completed within 10 days to 3 weeks from harvest. Thus, the general recommendation is to wait at least 3 weeks before feeding newly harvested forages. The length of this fermentation process will vary depending on the crop harvested (related to buffering capacity), moisture, and maturity of the ensiled crop. Properly applied, high-quality inoculants may decrease the fermentation time required.

The fifth phase lasts through storage where the fermentation process is stable as long as oxygen does not penetrate silage, with temperatures being between 75 and 85° F. Storage of at least 6 months is required for NDF to become more digestible and starch more available in the rumen. The final sixth phase, which occurs during feed out, is just as important and often neglected. This phase requires minimizing face disturbance to limit reintroducing oxygen into the silage, otherwise there is dry matter loss and feed made unpalatable for livestock.

The inhibition of clostridial bacteria is critical to successful silage preservation. Clostridial bacteria can begin growing the start of the fermentation process if silage is not ensiled correctly. However the proper way to prevent clostridial bacteria from is to insure that the silage is not overly wet (>700 g kg^{-1}) (Muck et al., 2020). A drier crop tends to have a higher concentration of solutes dissolved in the residual plant moisture, raising osmotic pressure. Lactic acid bacteria (LAB) are more tolerant of higher osmotic pressure than other bacteria and helps inhibit the growth of clostridial bacteria. However, crops that are ensiled at critical dry levels are more susceptible to heating and spoilage due to high osmotic pressure reducing the overall microbial growth rate.

Compared to baled hay, silage harvest losses are less. However, silage storage loss can be greater. Silage dry matter loss occurs from a long aerobic phase or oxygen entering the pile. Packing the pile and covering will reduce oxygen content and adding an inoculant can speed the rate of ensilage, helping minimize loss. Inoculants can also decrease yeast counts and heating during feed out. However, good silage handling and preservation practices are more important than inoculants. For drive-over piles, you should not have side slopes that exceed 3:1 slope. This allows for water to drain off the pile and for safer packing with equipment. For silos, you should cover silage immediately after filling. After covering silage with plastic, weight plastic down with tire sidewalls or sandbags which touch to keep all layers of plastic close to the silage top surface. Uncovered silage results in losses in organic matter of 47% within the upper 508 mm and 11% losses within the next 508 mm. This area represents over 25% of the total amount of feed stored in the silo structure. Covering silage reduced these losses to 20% in the upper 508 mm and 5% in the next 508 mm. Feeding spoiled silage results in decreased feed intake even when fed to heifers or dry cows and may result in diseases, such as listeriosis.

Forage nutritive value

Forage nutrient content varies by crop species and maturity. Producers must consider these factors when growing forages and factor the nutrient requirement of the type of livestock being fed. Crude protein (CP) is an estimate of protein concentration in a feed or forage that is based on total nitrogen concentration. Generally calculated as total N x 6.25 because N concentration of plant protein averages about 16%. Total protein content of forages can be quite variable among species. Legumes typically contain higher protein levels on a total herbage basis as compared with grasses. Proteins found in forages have no unique structural features that set them apart from other herbaceous plants at least regarding the herbage portion of the plant. Most plant proteins are synthesized in the cytoplasm (75%) with the remaining proteins being synthesized within the chloroplast and mitochondria (25%).

Lipids have the primary function of biological activity within the plant include the inositol lipids. The surface lipids such as waxes and cutin, provide an indigestible, impervious barrier on the exterior plant surface to reduce water loss and provide protection against pathogens and toxins. Surface lipids also inhibit plant digestion by ruminants because they limit bacterial penetration into the inner plant structures. Plant lipids fractions serve either energy storage or membrane-component functions. Energy storage lipids are composed mainly of triacyclglycerols, which accumulate in seeds to provide an energy reserve for germination and early plant growth. The majority of fatty acids as unsaturated fats. Polyunsaturated fatty acids with two or three double bonds comprise the majority of fatty acids. Cutting and drying of forages may cause significant reductions in fatty acid content and percentage of unsaturated fatty acids, depending on the length of exposure to elevated temperature and air. Hay making also leads to similar changes in forage lipids.

With the increase concerns of environmental issues and producers becoming more economically sustainable, predicting forage quality has become an important part of animal management. There are a variety of ways to measure forage quality. Peter J. Van Soest was one of the most influential animal scientists, who revolutionized how researchers measure the nutritional value of forages. Van Soest developed a detergent analysis system to precisely measure nutritional yields in large farm animals. Van Soest et al. (1994) stated “acid detergent fiber (ADF) are more consistently associated with digestibility while other components particularly hemicellulose and neutral-detergent fiber (NDF) are more closely related to voluntary intake” (Cherney and Parsons, 2020). Most forage laboratories adopted ADF and NDF as a routine analysis to predict dry matter digestibility. Neutral detergent fiber is the portion of plant derived feedstuffs of limited digestibility. It is the most common measure of fiber used for animal feed analysis. Many forage scientists equate NDF to plant cell walls. Forage NDF is a major factor affecting feed intake and rumen fill in high-producing dairy cows. Neutral detergent fiber digestibility (NDFD) is the digestibility of NDF determined as the difference in NDF in a forage before and after in vivo or in vivo digestion (Mertens and Grant, 2020). In Vitro True Digestibility (IVTD) is an anaerobic fermentation that is done in the lab and simulates digestion as it occurs in the rumen. Acid detergent fiber (ADF) is an insoluble residue following extraction of herbage with acid detergent (Van Soest, 1964). Lignin is an organic chemical of very low digestibility that strengthens and hardens the walls of plant cells especially those of vascular tissues and the epidermis. Ash is the residue remaining after complete burning of combustible matter; consist mainly of minerals in oxidized form. Total digestible nutrients (TDN) is the sum of the digestibility of the organic components of plant materials or seed. For both warm and cool season grasses, TDN is calculated as TDN=(NCF*0.98) +(CP*0.87) +(FA*0.97*2.25) +(NDFn*NDFDp/100)-10 (Cherney and Parsons, 2020). NCF is non fibrous carbohydrates and is a percentage of dry matter (DM), fatty acids (FA) is a percentage of DM, NDFn is the nitrogen-free neutral detergent fiber, and NDFDp is the 48-hour IV$_T$D. Starch is an insoluble but readily digested storage carbohydrate, such as amylose and amylopectin formed from the hundreds of linked glucose units (Proctor et al., 2022). Milk per acre is determined by calculating milk per ton of forage times the forage yield (Undersander et al., 1993). Net energy for gain (NEG) is the amount of energy in the forage that is available to be used for growth of livestock (Proctor et al., 2022). Net energy for maintenance (NEM) is amount of energy in the forage that is available for maintenance of livestock and serves as an indicator of voluntary forage intake (Proctor et al., 2022). Net energy for lactation (NEL) is the amount of energy in the forage that is available to be used for milk production of livestock (Proctor et al., 2022).

Water use

The water use of annual forages is considerably less then grain production because of additional water use during grain fill compared to biomass growth only in forages (Nielsen et al., 2005). A research review of forage water use in the CGP reported forage systems were highly efficient in precipitation use efficiency (PUE) (Nielsen et al., 2006). Water use efficiency (WUE) is higher for crop rotations that include forages than crop rotations that do not (Hatfield et al., 2001;Holman et al., 2021;Nielsen et al., 2005). Forage is harvested earlier compared to grain crops and the time that forages uptake water is shorter. In a 6-year study near Akron, CO, found that the greatest average WUE among forage crops grown was 22.8 kg ha^{-1} mm^{-1} for forage pea, and the least was 11.4 kg ha^{-1} mm^{-1} for corn silage (*Zea mays* L.) (Nielson et al., 2005). They examined that continuous forage cropping systems had the greatest precipitation use efficiency (PUE). Precipitation use efficiency was highest for systems with forage production of 8.4 kg ha^{-1} mm^{-1} - 5.4 kg ha^{-1} mm^{-1} (Forage millet-Forage triticale-Corn silage) compared to the other continuously cropped rotations where the PUE ranged from 5.9 kg ha^{-1} mm^{-1} - 2.8 kg ha^{-1} mm^{-1}. In the CGP, the highest PUE was seen in the systems with forage production compared to a wheat-sorghum-fallow crop rotation. Research conducted in the northern Great Plains (NGP) on the annual warm season grasses such as foxtail (*Setaria italica* L.), proso millet (*Panicum mileaceum* L.), and sorghum-sudangrass (*Sorghum bicolor* (L.) Moench x *Sorghum sudenense* Stapf.). The water used in this study was observed at 157 mm and WUE (25.1 kg ha^{-1} mm^{-1}) of total biomass and did not vary among tillage treatments or types of forage (Lenssen & Cash., 2011). An 8-year study near Garden City Kansas researched what forage rotations and tillage practices can increase forage productivity as well which rotation and tillage practices observed the highest WUE. The study included a continuous forage sorghum with NT (S-S), triticale/sorghum-sorghum-oat in NT and RT practices (T/S–S–O), triticale/sorghum-sorghum-sorghum-oat in both NT and RT practices (T/S–S–S–O), and triticale-sorghum-oat in NT practices (T–S–O). Results showed annualized forage accumulation with S–S and T/S–S–S–O

(NT and RT) rotations were 31–58% greater than T/S–S– O (NT) and T–S–O (NT). Annualized WUE from each rotation was in the order T/S–S–S–O (RT) = T/S–S–S–O (NT) > T/S–S–O (RT) = T/S–S–O (NT) > T–S–O (NT) = S–S (NT). Sorghum forage accumulation was 43% greater and water use was 23% greater in a nondouble crop sequence than sorghum double crop after triticale (Holman et al., 2021).

Annual forages in crop rotation

Annual forages can be used to intensify crop rotations by replacing a portion of the fallow period. Adding different crops into crop rotations can be used to intensify cropping systems and can add profitability and sustainability for grain production and forage production. Long-term rotations of three years or longer studies that include annual forages have been conducted in the CGP recently (Holman et al., 2021). The research shows that the four-year rotation (T/S-S-S-O) had a greater annualized forage productivity than the three-year (T/S-S-O or T-S-O) cropping systems regardless of tillage practice. The benefits of including forage crops were demonstrated in short-term field experiments. A review done by Carr et al., (2021) researched how to include annual forages to replace fallow period in the cropping system W-F reported that annual forages offer flexibility in planting date that enables farmers to shift to planting later in the spring that could extend the predicted growing seasons but could expose grain crops to higher temperatures during pollination and grain development (Wienhold et al., 2018; Carr et al., 2021). However, planting forages late in the spring can lead to decreased forage yield. Replacing fallow with forages instead of grain crops helps reduce the likelihood of subsequent wheat crop failure by increasing PUE and WUE in the cropping system(Nielsen et al., 2005). Crop rotation systems must become more diverse and increase crop intensity to maximize soil-water storage and WUE due to rising temperatures in the CGP (Tanaka and

Anderson, 1997; Zentner et al., 2001). These results suggest that forages could be used to intensify wheat-based dryland farming in the semi-arid regions of the CGP. However, cropping too intensively can cause crop failure as well. Tanaka and other researchers hypothesized that dynamic cropping systems which include annual forages in grain-based rotations improved crop production resilience (Tanaka et al., 2002) .

Many livestock producers that grow annual forages have continuous systems, such as continuous winter triticale or continuous forage sorghum. However, forage crops of winter and summer annuals can be used together to create a forage rotation. Forage crops, especially annual cool season grasses, are well adapted to temperate semiarid regions, producing good yields with nutritive values suitable for overwintering cattle in the CGP (Obour et al., 2020b; Holman et al., 2018; Holman et al., 2021). Forage sorghum is a warm season forage that is well adapted to the GCP region (Holman et al., 2020). A crop rotation that includes both cool season and warm season forages can contribute to efficient capture of precipitation and resources available at different seasons of the year. A study near Garden City Kansas, measured forage productivity and nutritive value of warm and cool season forages (Holman et al., 2020). They found that forage productivity was greatest with continuous forage sorghum or a winter triticale double crop forage sorghum-sorghum- crop rotation. However, the winter triticale/forage sorghum crop rotation was hard to implement due to the insufficient time and soil water available at planting. They concluded that winter triticale/forage sorghum-sorghum-sorghum-oat rotation had greater crop diversity and water use efficiency compared sorghum- sorghum-sorghum-oat rotation. Forage nutritive value was affected by the forage type but not the crop rotation. However, there is no incentive for farmers to incorporate annual forages into their crop rotations when there is no market for harvested forages or if there is no livestock in the farm.

Integrating forage and livestock systems

Farms have become increasing specialized in either crop or livestock production over time as operation size grew (MacDonald and McBride, 2009). Although specialization has resulted in lower food prices and increased accessibility, specialization has also led to environmental cost, such as air pollution from feedlots, phosphorus and nitrogen contaminants in waterways, and high concentrations of manure in localized areas (MacDonald and McBride, 2009). An alternative solution to these concerns is to integrated crop-livestock production systems. Integrated crop-livestock systems are farms where animals and crops are produced with the goal to utilize the products of one to help grow the other (Hilimire, 2011). Advantages of integrated-crop livestock systems are an opportunity of improved soil quality and to have economic diversity. Farmers that have already integrated beef cattle production in to cropland in the Great Plains improved profitability (Small and McCaughey, 1999). Adding cattle to a legume crop rotation doubled the rate of soil carbon accumulation (Drinkwater et al., 1998). However, some of the limitations or disadvantages of an integrated crop livestock system is the lack of livestock management experience and livestock infrastructure cost and development. Kansas Farm Management Association (KFMA) investigated data comparing farm profits of crop only farm income vs farms that had integrated systems from 1984-2013(Rempe et al., 2015). Integrated farms averaged a $6,000 higher net income compared to crop only farms every year for the period 1984-1999 and from 2000 to 2005 saw a $21,000 net farm income per year advantage. However, gains by crop only farms averaging $74,000 higher net farm incomes compared to integrated systems from 2006-2013. This resulted in decreased in livestock, because of the decrease in livestock profitability, and more farmers opted for the more profitable crop only operation.

Annual forages are essential for making integrated crop-livestock systems work. Some of the advantages of crop-livestock integration include crop yields increases, improvements in soil quality, and pest management benefits compared to crop-only systems (Hilimire, 2011). Integrating animals into crop production could provide cost-effectiveness on-farm sources of soil fertility in the form of manure with manure spreading. A 4-year study in 2009 study in Illinois assessed yield and soil quality under a cattle/corn integrated system in comparison to a system continuously cropped with corn (Maughan et al., 2009). The study found significantly higher corn yield in the system where cattle grazed a winter cover crop (CC) subsequently planted with corn than in the continuously cropped system (11.5 Mg ha^{-1} vs. 10.8 Mg ha^{-1}). They also observed that integrated systems had greater total nitrogen, total carbon and larger soil aggregates than the continuous corn. In a 5-year study in Texas measured soil microbial, chemical, and physical properties in continuous cotton and integrated crop-livestock systems (Acosta-Martínez et al., 2004). The study found that SOC was greater in the integrated crop-livestock system in the 0- to 5-cm depths in perennial pasture compared with continuous cotton system (13.5 g kg^{-1} vs. 9.0 g kg^{-1}).

However, it is important to note not all benefits are realized in the semi-arid regions where forage-induced drought can impact subsequent grain crops in the rotation. Some of the obstacles that prevent greater adoption of integrated crop-livestock systems in the CGP are the lack of adequate managerial skill resulting from specialization of crop or livestock (Hilimire, 2011). Integrated crop-livestock systems are complex systems and require skills that are not needed in specialized agriculture (Russelle et al., 2007; Sulc and Franzluebbers, 2014). Many farms lack livestock infrastructure which limits crop-livestock integration. The other challenges facing integrated crop-livestock systems are increased knowledge of both crop and livestock production. Crop farmers often do not have training in animal care and often it takes many years to learn proper livestock care (Russelle et al., 2007). However, when integrated systems are implemented, economic and environmental benefits are enhanced.

There has been in increased interest in cattle grazing crop residue after grain harvest in the CGP and rotating dual-use CCs with grain crops. Forage CCs can be any types of CC, from grass species (triticale, cereal rye, oats), legume species (cowpeas, sunn hemp, forage soybeans), and brassica species (rapeseed, radish, turnip). A two-year grazing study was conducted near Sidney Nebraska that evaluated different CCs for dry matter production and diet quality as a forage mixture after porso millet stuble (Titlow et al., 2014). The annual forage mixtures contained: pigeon pea (*Cajanus cajan* L. Millsp.), oat (*Avena sativa*), and turnip (*Brassica rapa*) for annual forage grazing. A combination of pigeon pea, oat, and turnip provided more digestible forage and had greater nutritive value of crude protein (CP) and in vitro dry matter disappearance (IVDMD) than perennial pasture of crested wheatgrass (*Agropyron cristatum L.*). Incorporating annual forages into dryland wheat systems was a focus of on whether dryland crop livestock integration systems would help improve soil quality, economic diversity, and pest control(Krall and Schuman, 1996). They observed that dryland integrated crop livestock production systems are agroclimatic zone specific, and they represent an ecologically and economically sustainable form of agriculture. However, the land area that is devoted to this production system is limited in the Great Plains. Carr, Russelle and colleagues were interested in developing integrated crop-livestock systems patterned after Australian ley farming, where wheat was rotated with self-regenerating, hard-seeded annual legumes grazed by sheep (*Ovis Aries*) (Carr, 2004; Carr, 2006; Russelle et al., 2007). They saw that ley farming had several benefits compared with wheat-fallow to dryland wheat farmers in Australia with greater profitability, reduced fertilizer inputs, and pest suppression. However, it is important to notice and be aware of possible toxicities from forages as well.

A possible toxicity to look out for is nitrate poisoning and prussic acid from different summer annual forages (sorghum-sudangrass, forage sorghum, sudan grass, etc.) (A. Williamson, 2019). During times of drought, nitrates accumulate in the lower portion of the forage at a rate that is greater than what is normally present in the forage. It is toxic if the forage is consumed in excessively. Testing to test nitrate levels in forages is a great way of measuring potential toxicity for livestock. For cattle, any rate of nitrate nitrogen (NO^{-3} N) higher than 1000 parts per million dry matter basis can cause problems and any level higher than 1,700 ppm can be acute toxicity. A way to reduce high nitrates is to delay harvest until stress conditions have passed will help to lower nitrate levels within the crop. Excessive nitrates typically accumulate at the base of the plant. Chopping or mowing the forage much higher than usual will also help to reduce the amount of nitrate harvested. Ensiling the forage could reduce nitrate levels by half by the time fermentation process has been completed. It is always recommended to not feed toxic forage to livestock; however, unfortunately at times a significant portion of a feed supply will have high nitrate accumulation, deeming it necessary to feed due to a shortage of non-toxic feed on the farm. If forage is known to have higher than ideal nitrate levels, diluting the forage by incorporating a low-nitrate forage into the diet will reduce the overall nitrate consumption by the animal. Introducing the toxic forage slowly will help to get animals adapted to nitrate levels, as well as feeding small amounts frequently rather than at one large feeding. Heavy rates of fertilization and drought can also cause high levels of prussic acid accumulation. The greatest levels of prussic acid can be found in the leafier areas of the plant. All species of sorghum contain prussic acid within the vegetative portion of the plant. Sudangrass contains approximately 40 percent less prussic acid than other sorghums. However, a sorghum x sudangrass hybrid contains a greater level of the toxic compound than sudangrass alone. An option for incorporating a summer annual forage crop while reducing the risk of prussic acid poisoning selecting pearl millet and foxtail millet, which do not contain toxic levels of prussic acid. Therefore, these forages can be utilized any time. To reduce prussic acid, it is advised that you should wait to harvest forages after a "killing frost". A killing frost is defined as a frost period that is severe enough to end the growing season. After a killing frost, toxic prussic acid does not begin to decline until after the leaves have died. It is safer to wait at least 7-10 days after a killing frost to graze or green chop forage. If forages regrow after a non-killing frost, do not graze or feed until the regrowth has reached a minimum of 2 feet in height or 2 weeks, as the regrowth will likely contain high, very toxic levels of prussic acid. Ensiling these forages helps to reduce the risk of toxic levels of prussic acid, as some of the toxic components escape during the fermentation process as gas. Sorghum silage should not be fed any earlier than 3-4 weeks after harvest as a precaution.

Weed Management in annual forages

Annual forages can suppress weeds by plant competition largely through its large biomass and canopy closure, reducing early season weed density, growth, and seed production. The competition of weeds for water and nutrients can result in a substantial crop yield loss (Oerke, 2006). Kochia (*Kochia scoparia L.*) is one of the most challenging weed species in CGP croplands. Kochia emergence primarily occurs from early April to late June (Anderson and Nielsen, 1996), having a crop growing during this period can reduce seedling establishment. Tillage is a useful tool to control weeds during fallow periods. No-till systems can benefit kochia because majority of weed seed will stay near the surface of the soil and can provide optimum germination conditions for kochia (Kumar et al., 2018). Since the 1990s, weed control has been achieved using herbicides, while tillage has been reduced or eliminated (Anderson et al., 1999). However, NT systems are experiencing increasing difficulty managing herbicide resistant weeds, including the broad-spectrum contact herbicide glyphosate (Heap 2010). While tillage can help control weeds, tillage can decrease water stable aggregates (WSA) and increased water and wind erosion (Obour et al., 2020a). Weeds can greatly reduce cereal grain and oilseed yield and reduce grain value if contaminated with weed seed. Similarly, weeds in forages can decrease forage yield and decrease forage quality.

Incorporating annual forages into semi-arid dryland wheat systems can suppress weeds in both spring seeded and fall seeded forages by providing competition against weeds the entire growing season (Schoofs and Entz, 2000). The study was a two-year study that assessed the influence of annual forages on weed density in cropping systems. All forage systems were at least as effective as the sprayed wheat control in suppressing wild oat (*Avena fatua* L.); however, effects on other weeds were variable. Biennial crops such as sweet clover (*Melilotis officinalis* L.) provided the best early season weed control. Long-season systems such as winter triticale and the triticale intercrop (spring and winter triticale) provided the best late season weed control. Forages shifted the weed community composition away from wild oat and green foxtail (*Setaria viridis* L. Beauv.) to a similar or greater extent than herbicide-treated wheat. However, forages alone did not eliminate the need for herbicides in the cropping systems. Annual forages may play an important role in integrated weed management, however further research to refine forage-based weed management systems is needed. A two-year study was conducted determine whether tillage and nitrogen fertilizer application influenced crop and weed biomass, water use, water use efficiency and forage quality of porso millet, foxtail millet, and sorghum-sudan grass (Lenssen and Dennis Cash, 2011). Seed production of green foxtail and redroot pigweed were 70% less in sorghum x sudan grass than proso millet. This is likely because crop biomass was larger for sorghum-sudan grass compared to the other warm season grasses. Crop WUE was also greater for sorghum-sudan grass compared to foxtail and proso millets. Weed biomass was three times greater in spring barley than winter triticale and winter wheat forage crops (Lenssen, Cash, & Carlson, 2015). Both forage species and growing season impacted weed growth and is weed species specific (Lenssen & Cash, 2011; Schoofs & Entz, 2000). Studies conducted in Canada in the 1990s found that forage plants were as effective as chemical herbicides for control of wild oat (*Avena fatua* L.) weeds (Schoofs and Entz, 2000). Forage species included winter triticale grazed, spring triticale in silage, spring/winter triticale intercrop, alfalfa hay (*Medicago sativa* L.), sorghum-Sudan grass (*Sorghum bicolor* [L.] Moench x *Sorghum Sudanese* [Piper]), fall rye (*Secale cereale* L.) grain crop, and a sweet clover (*Melilotis officinalis* L.) / winter triticale double crop of hay and then grazing. All forage systems were at least as effective as the sprayed wheat control in suppressing wild oat. However, effects on other weeds, especially broadleaved species, were variable. Biennial crops provided the best early season weed control, while long-season systems such winter triticale and the triticale intercrop provided the best late season weed control. Forages shifted the weed community composition away from wild oat and green foxtail to a similar or greater extent than herbicide-treated wheat. However, forage systems that did not provide season-long crop competition tended to have more broadleaved weeds. Forages alone did not eliminate the need for herbicides in the pea crop. In this way integrated agriculture can decrease the need for purchased herbicides. The inclusion of cool-season forages in crop rotations in the northern Great Plains, formerly a common practice has been observed to reduced weed competition in cereal based grain cropping systems (Nazarko et al., 2005). Weeds associated with spring- planted barley did not produce seed, regardless of broadleaf weed, imparting weed control benefits to subsequent crops by impacting the weed seed bank and subsequent weed-crop interactions in grain crops (Lenssen et al., 2015).

Livestock grazing in integrated systems can also help with weed management because some weed species palatable. A 15-year study looking at integrated crop livestock systems grazing intensities affect weed emergence and seed bank in NT management in subtropical Brazil (Schuster et al., 2016). Higher sward heights in the winter-grazed CC reduced the number of weed species, the density of emerged weed seedlings, and the weed seed bank size compared with the non-grazed control. Fifteen years after adopting low grazing intensities (30- and 40-cm sward heights) in the integrated crop livestock systems, the size of the weed seed bank was reduced by 42.1% compared with the non-grazed treatment. Decreasing the grazing intensity reduced the number of weed species, the density of emerged weed seedlings, and the weed seed bank density. Integrated weed management strategies should consider minimizing grazing intensities in an integrated crop livestock system. Grazing fields in fallow or after the cropping period takes advantage of the forage value of weeds and crop residues and accelerates nutrient cycling by converting vegetation to manures with more concentrated and more readily available nutrients. Dowling & Wong (1993) studied the effect of grazing and herbicide use in the final months of annual grass pastures before two successive wheat crops in New South Wales, Australia (Wong et al., 1993). The wheat in this region is rotated with annual grass pastures. In the first wheat crop, annual grass seed and seedling densities was reduced 91%–99% by herbicides plus grazing or grazing alone, compared to no pre-planting weed control. The most weed suppressive treatment was heavy grazing, which consisted of 10 total grazing days over a six-week period at a stocking rate of 533 sheep ha^{-1}. Preseason herbicide and grazing treatments were not effective against broadleaf weeds. Broadleaf weed densities were inversely proportional to densities of annual grasses, with the no grazing–no-herbicide treatment having the most annual grasses and the fewest broadleafs. Wheat yields were higher in treatments with preseason vegetation management for both years of the two-year wheat sequence.

With the increase in herbicide resistance weeds such as kochia and palmer amaranth (*Amaranthus palmeri*), it will become more important in dryland wheat systems to use non-herbicide control methods such as annual forages for weed suppression (Petrosino et al, 2015). Multi-tactic, cultural systems consisting of taller cultivars, N fertilizer at planting, NT and delayed planting could eliminate the need for herbicide application in proso millet infested with redroot pigweed (Anderson, 2005). However, annual forages do not always help with weed suppression. In another study, when sorghum sudan grass was taller than millet (Lenssen and Cash, 2011), neither tillage or nitrogen management influenced weed density prior to canopy closure (Mid-July). Foxtail millet (*Setaria italica* L.) under NT had a higher density of broadleaf weeds (18 m^{-2}) than all other treatment combinations of proso millet and sorghum sudan-grass which averaged 9 m^{-2} (Lenssen and Dennis Cash, 2011). Integrated systems can be used to manage weed and pest populations both by the direct effects of livestock feeding habits and by the indirect effects of pasture on weed and pest populations (Hilimire, 2011).

However, there are toxicities of grazing common weeds in the CGP. Some common weeds are highly toxic while others are moderately toxic. Some of the weeds that are toxic are lambsquarter (*Chenopodium album*), pigweed (*Amaranthus retroflexus*), Kochia (*Bassia scoparia*). Lambs quarter is considerably edible, however under certain conditions, plant production of oxalates can increase to levels livestock when large amounts of the leaves are consumed in a short period. Lambs quarter can also accumulate toxic levels of nitrate especially if growing in rich organic soils or if its fertilized as might occur when it grows in arable cropland (L. Voss, 2022). Sudden death may occur because of acute respiratory failure induced by the formation of methemoglobin. If the nitrate poisoning is suspected, methylene blue should be administered intravenously and recommended dose range for methylene blue is 4-15 mg/kg body weight administered as a 2%-4% solution. Excessive administration of methylene blue to animals other than ruminants will result in hemolytic anemia due to Heinz body formation. Pigweed can accumulate oxalates and nitrates. Pigweeds can have as much as 30% oxalate in the dried plant and ruminants eating large amounts of the plant are very likely to be poisoned. The soluble oxalates in the plant are absorbed from the gastrointestinal tract and then bind with calcium in the blood to produce insoluble calcium oxalate. There is no specific treatment other than supportive therapy. Administration of insulin, glucose and fluids intravenously may help manage the hyperkalemia and renal failure. If the animal's urine output stops and creatinine levels remain high despite aggressive fluid therapy, the prognosis is very poor (L. Voss, 2022). Although kochia can be grazed and utilized to for forage, there is a various toxicity problem may occur with harvested or grazed plants. Kochia has been associated with oxalates and nitrates poisoning. Oxalate accumulation as high as 6 to 9 percent are not uncommon in nearly mature green plants. These problems typically have occurred when animals have been moved from overgrazed or drought-limited native pasture an onto a postharvest wheat field or where kochia plants have grown up and appear to be a ready source of forage for livestock (Hollis and van der Merwe, 2010).

Soil benefits of annual forages

A limited information is available on annual forges or integrated crop/livestock production on soil health compared to grain only cropping systems. Annual forages can intensify cropping systems and diversify rotations which might increase water infiltration, soil carbon, nutrient cycling, soil structure, and soil aggregation. Grazing annual forages can add benefits to the soil in ways that crop production only cannot. A five-year study of integrated beef cattle and cotton system found higher SOC, soil aggregate stability, soil microbial biomass carbon, soil microbial nitrogen, and soil enzyme activity in integrated forage/cotton plants than continuous cotton plants (Acosta-Martínez et al., 2004). Replacing fallow with annual forages production enhanced near-surface soil physical factors in previous research (Blanco-Canqui et al., 2013; Simon et al., 2021). However, these improvements were modest or transient and quickly reverted to pre-treatment levels upon cessation of annual forage production (Carr et al., 2021).

Bulk density and porosity

Yield limiting soil compaction is a major concern for crop producers when grazing annual forages in crop production fields. Compaction is observed by increased bulk density (BD) and decreased soil porosity, which is often caused by heavy field equipment or grazing cattle, particularly when the soil is wet. There is limited information of annual forage impact on BD. Soil compaction is less of a concern in northern climates due to the soils frequent freeze-thaw cycle that can reduce compaction problems during the winter (Carr et al., 2021). A one-time shallow tillage operation can alleviate soil compaction near the soil surface when compaction develops (Obour et al., 2021). Previous research showed inclusion of annual forages in wheat-based cropping systems can see moderate reduction in near surface soil BD , however, accrued improved soil physical properties from annual forages likely requires a long-term strategy (Blanco-Canqui et al., 2013).

Compaction can also be observed in grazed livestock fields due to heavy hoof traffic and when grazing in wet field conditions, especially in NT fields (Mapfumo et al., 1999; Baumhardt et al., 2011). In small plots with short duration grazing, soil compaction only occurred in 1 of 5 years with cattle grazing when soils were grazed wet (Obour et al., 2020c). A study in eastern Nebraska measuring CC grazing impacts on soil properties and crop yields in irrigated NT systems found grazing CC reduced aboveground CC biomass without affecting soil physical properties including BD, penetration resistance, water infiltration, water stable aggregates, wind erodible fraction, soil organic carbon, and soil microbial biomass. The study found that CC grazing reduced CC biomass without affecting soil penetration resistance, BD, water aggregate stability, water infiltration, organic matter concentration, particulate organic matter concentration, and microbial biomass compared with nongrazed CC. Nongrazed CC had no effect except for little improvement of soil microbial properties. However, corn silage had negative effects most near surface soil properties but not crop yield. Cover crop did not offset negative impacts of corn silage on soil properties (Anderson et al., 2022). Soil surface BD decreased with standing CCs and that grazed CC BD was similar to that of fallow (Kelly et al., 2021).

Soil aggregation

Soil water stable aggregates are an important soil property that impacts physical processes of soil. Stable aggregates have greater resistance to wind and water erosion, which in the CGP is a major concern. In the CGP region, soil is at most risk of erosion in the late winter to early spring (Hansen et al., 2012). The Dust Bowl years are an example of wind erosion can be a major concern for not only agriculture, but society as well. One of the soil physical properties that can measure the likelihood of susceptible of soil to water erosion is water stable aggregates (WSA). By including annual forage in the rotation, producers can minimize the risk of erosion by intensifying their crop rotation systems. Few studies have evaluated annual forage effects on water erosion. Water erosion did not increase after one season of grazing, but significantly increased after with both heavy and light grazing increasing runoff by 3.3 mm and sediment loss increased by 0.26 annually (Mg ha^{-1}) Blanco-Canqui (2016). Baling corn residue decreased time to runoff by 8 to 14 minutes and increased runoff by 13 mm and sediment loss by 2.7 Mg ha^{-1} compared to grazing following rain events, which was not different from the control treatment of no residue removal (Blanco-Canqui et al., 2016a). These results suggest that consecutive grazing events may increase the risk of water erosion in the long term. The increased water erosion with grazing was primarily attributed to the reduced residue cover following grazing. The effect of reduced cover on increased water erosion is well documented (Lindstrom, 1986; Blanco-Canqui and Lal, 2009). Similarly, a study in western Kansas evaluating grazed and hayed CCs observed WSA were consistently larger with standing and grazed CC compared to fallow. However, WSA with hayed CCs were larger than fallow in 1 of the 2-yr study (Simon et al., 2021).

Few studies have measured annual forage impacts on wind soil erosion. However, in a study done by (Blanco-Canqui et al., 2016b) grazing and baling corn residue had similar effects on wind soil erosion. The differences in wind erodibility parameters of geometric mean diameter (GMD) and wind erodibility fraction (WEF) between grazing and control treatments were not different but there was a consistent trend for reduced soil aggregate size under both light and heavy grazing relative to the non-grazed control. This finding suggests that heavy residue grazing may increase wind erosion risks in the long term. Baling effects were only significant in the spring and not in the fall, which suggests that corn residue baling increases the wind erosion potential in springtime when winds are high and residue cover is limited. This study like others, suggested that soil erodibility increases as residue cover decreased (Lindstrom, 1986; Blanco-Canqui and Lal, 2009).

There recently has been an interest in replacing fallow with CCs or forage crops (Holman et al., 2018). Harvesting a forage crop rather than growing a CC can generate economic returns to help offset the cost of growing the crop plus yield reduction in the subsequent grain crop. However, forage harvest reduced the amount of residue cover. Harvesting a forage crop rather than growing a CC may directly undermine the purpose of intensifying crop rotations to conserve soil and water resources and enhance system productivity (Holman et al., 2018). Other findings from this study previously reported growing a CC or forage in place of fallow improved SOC and WSA after 5 yr. of growing CCs in place of fallow, but the effects on soil properties lasted <9 months after the CC was terminated (Blanco-Canqui et al., 2013). A five-year study near Brownell KS looked into the forage productivity, nutritive values, and effects of dual-purpose CCs on soil properties in a NT winter wheat, grain sorghum, fallow cropping systems. Cover crops grown in the place of fallow which were hayed, grazed, or left standing. Soil BD was unaffected by haying or grazing compared to standing CCs. Mean weight diameter of water stable aggregates increased with standing and grazed CCs (2.89 mm) compared to fallow (1.67 mm) in both years but hayed CC was greater than fallow in 1 yr. Improving soil properties and productivity is a lofty goal; however, if it is not profitable, it will be unachievable.

Water infiltration

There are no studies that have reported water infiltration with annual forage cropping systems. However, there is studies that have reported water infiltration on CCs and CCs that are utilized for forages (Blanco-Canqui et al., 2013; Obour et al., 2020c). Cover crops can improve soil water infiltration through increased porosity. Water infiltration is the measurement of water absorption rate in soil. Low water infiltration is an indicator of soil compaction, and greater potential for increase water erosion.

Tillage has advantages of promoting water infiltration in the loosened soil (Baumhardt et al., 2017). However, tillage destroys macropores, promotes increased soil drying and reduces water use efficiency, and can cause compaction and a tillage pan formation (Triplett and Dick, 2008) A study in Bushland Texas looked to quantify grazing and tillage effects on infiltration, sediment transport, and aggregate stability during fallow periods after sorghum and wheat (Baumhardt et al., 2017). Sediment concentration and yield for both fallows were numerically larger with grazing. Sediment concentration from stubble-mulch tillage increased significantly over NT for either fallow, but soil loss differed only for wheat fallow. Mean final infiltration rate and amount did not differ significantly with grazing during either fallow, but final infiltration amount was 20% lower for grazed than for ungrazed paddocks. Since stubble mulch tillage after grazed wheat increased final infiltration rate and final infiltration amount over NT, occasional stubble mulch tillage to disrupt compaction from trampling may increase water conservation for dryland cropping systems combining grazing with NT residue management.

No-till practices can help improve water infiltration. Humberto and Sabrina (2018) looked up-to-date synthesis of NT impact on soil physical properties based on a comprehensive compilation of global published studies. They compared data on soil physical properties among NT, reduced till, and conventional till systems, and discussed factors influencing tillage system effects. No-till increased wet aggregate stability by 1 to 97%, water infiltration by 17 to 86%, and available water by 44%. No-till benefits for reducing compaction risks and improving structural quality increased in the long term. However, changes in soil physical properties appear to be confined to the upper 10 cm depth. Reviews on NT and soil C have also concluded that NT can cause stratification of soil organic C in the upper 5 or 10 cm depth. Thus, NT-induced increases in near-surface (<10 cm depth) soil organic C concentration most likely improved wet aggregate stability and available water capacity, and reduced compactibility. One-time tillage of NT soils does not seem to negatively affect soil physical properties.

Soil organic matter and nutrients

An increase in phosphorus due to grazing or manure application is only a benefit when levels are not likely to contribute to environmental pollution (Hilimire, 2011). Integrated crop and livestock systems are not the solution to reducing soil degradation or soil erosion loss. However, with proper management producers could see some benefits from integrated management. Integrated crop-livestock systems can increase soil organic matter, macronutrient, and trace mineral needs of the soil microbial community and crops (Russelle et al., 2007), and potentially decrease the need for purchased fertilizer.

Cover crops of triticale and oats grown as forage had forage dry matter mass potential >3,000 kg ha^{-1} in the CGP dryland environment (Simon et al., 2021). Simon et al., (2021) researched on what effects dual purpose CCs had on soil properties in a NT winter wheat-grain sorghum-fallow dryland cropping system. They found that soil organic carbon (SOC) stocks in the 0-to-15-cm depth in 2019 were similar among CC treatments. Stocks with standing and hayed CCs were greater than fallow which was similar to grazed CCs. However, in 2020, stocks were less with hayed CCs compared to grazed or standing CCs and all were similar to fallow. Obour et al., (2020) looked into a similar study. They noted that CCs harvested as hay, grazed, or left standing had no SOC differences in the surface 0- to 5-cm soil depth between treatments or compared to fallow. However, the CC treatments did increase SOC concentration within 5- to 15-cm depth compared to fallow. The SOC similarity between treatments is due to the large proportion of belowground biomass from CC roots contributing to SOC. This study suggests CCs could be utilized for forage with minimal to no impacts on SOC (Obour et al., 2020c).

A 4-year study on a large scale research farm near Pana, Illinois looked at soil quality and corn yield under crop-livestock integration (Maughan et al., 2009). Three treatments evaluated in the study were continuous corn, winter CC mixture (oat, cereal rye, and turnip), and cool season pasture. In the integrated system, cool season pastures and winter CC treatments combined, had significantly higher total nitrogen than continuous corn. The higher total nitrogen content at the 0- to 5-cm depth for cool season pasture compared to continuous corn was likely due to the presence of red clover and white clover that fixated nitrogen as well as manure and urine that could contribute to a significant amount of nitrogen in soil. Annual tillage in the winter CCs incorporated all the residue and manure into the soils and could explain why the amount high amount of nitrogen and cold winters slow down the turnover rates of nitrogen. Turnips in the winter CCs mixture also could have helped scavenge nitrogen.

Cover crops can be harvested for forage as well and do not need to be grazed by cattle. A three year study at two locations Spring Hill and Knoxville Tennessee researched the forage yield, quality, and impact on subsequent cash crop in an integrated forage/row crop system (Bracey et al., 2022). There are sixteen treatments that include wheat, cereal rye, barley, oat, triticale (×Triticosecale Wittmack), crimson clover, arrowleaf clover (Trifolium vesiculosum Savi), berseem clover (T. alexandrinum L.), red clover (T. pratense L.), common vetch (Vicia sativa L.), hairy vetch, woolypod vetch (V. villosa Roth subsp. varia (Host) Corb.), Austrian winter pea, canola, forage radish (Raphanus sativus L.), and purple- top turnip (Brassica rapa L.) and two management systems: CC terminated and left as residue before cash crop planting and CC that is harvested for residue and terminated before cash crop planting. Ten soil samples were taken to a depth of 15 cm from each plot two months after CC termination and were analysis for WEC (water-extractable organic carbon), WEN (water-extractable organic N), pH, TEC (total exchange capacity), P, K, Mg, Ca, S, Mn, B, Zn, Fe, Al, Cu, and Na as well as NO_3, NH_4, and PO_4. Cover crop species did impact soil properties in the subsequent cash crop with differences observed in soil NO_3, WEN, pH. Harvesting CCs for forage also showed slight, but significant, increases in WEN. Differences in soil nitrogen among species were expected due to the differences in nitrogen content and estimated nitrogen release among species. Little variation among species was observed in the remaining soil minerals and soil carbon. Changes in WEN from harvesting CCs as forage were less than 1 mg kg $^{-1}$, making it unlikely to have practical implications on management.

Tillage can affect soil nutrients as well as crop rotations and integrated crop livestock systems. A two-year study near Hays Kansas examined strategic tillage effects on crop yields, soil properties and weeds in dryland NT systems (Obour et al., 2021). Treatments were three crop rotations of continuous winter wheat, wheat-fallow, and wheat-grain sorghum-fallow and subplots of reduced till NT and strategic tillage. They found strategic tillage compared to NT had no effect on SOC or nitrogen concentrations. Soil phosphorus was not different among the tillage treatments though reduced tillage increased potassium concentration near the soil surface. The SOC concentration was significantly affected by rotation and depth with 27% greater SOC in the 0 to 5- cm depth with continuous wheat compared to wheat-fallow and wheat-sorghum-fallow at the same depth. The SOC concentrations below 5 cm depth were not affected by tillage or crop rotation. NO_3^-N concentration in the 0 to 5 cm depth with strategic tillage was greater than NT or reduced tillage. The concentration of NO_3^-N was not affected by tillage in either the 5 to 15 or 15 to 30 cm depths. Tillage had no effect on NH_4^-N concentration below the 5 cm depth. Soil P concentration was unaffected by tillage or crop rotation. Soil P concentration in the 0 to 5 cm depth was greater than soil P concentrations at the 5 to 15 cm or 15 to 30 cm depths. The

Mehlich-3 K concentration in the 0 to 5 cm depth was less with strategic tillage compared to soils under reduced tillage.

Objectives and hypothesis

The objectives of these studies were to:

1. Quantify minimum tillage effects on weed population, soil health, and forage yield compared to no-tillage and determine the effects of eliminating tillage from the system.

Hypothesis: Minimum tillage reduces weed density, increases forage yield, and alleviate compaction in a grazed annual forage system

2. Identify annual forage rotation components that have positive effects on soil properties and forage productivity in a dryland cropping system.

Hypothesis: Increasing annual forage cropping intensity and diversity can produce a greater quantity of forage while improving soil properties compared to less intensive and less diverse annual forage rotations and that no-till will have greater soil health then tilled systems.

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Chapter 2 - Forage productivity, weed density, and soil properties affected by grazing and tillage of winter triticale

Abstract

Grazing annual forages provides many benefits including increasing cropping system diversity and intensity, resting perennial rangeland, providing better forage nutritive value when native rangeland is dormant, increasing livestock carrying capacity, and increasing profitability of the enterprise. However, there are concerns grazing can cause soil compaction, degrade soil structure, reduce water infiltration, and cause soil degradation in no-tillage (NT) systems. In addition, herbicide-resistant weeds are becoming increasingly more difficult to control in NT systems. Tillage may help correct some of these potential soil quality and herbicide-resistant weed concerns. The objective of this study was to quantify minimum tillage (MT) effects on soil properties, forage yield and quality, and weed species population and density compared to NT. The study was conducted from 2016-2022 near Jetmore, KS, however this paper presents results from 2020 to 2022. The experiment had two tillage treatments, NT and MT, in a grazed continuous winter triticale [×*Triticosecale Wittm.* ex A. Camus (*Secale* ×*Triticum*)] cropping system. Bulk density was greater pre-till (1.31g cm^{-3}) compared to the post-till (1.23 g cm^{-3}) across tillage treatments. Mean weight diameter (MWD) of water stable aggregates (*MWDWSA*) was not affected by tillage. Wind erodibility was increased, and dry aggregate mean weight diameter *(MWDDA)* decreased with MT. Soil organic carbon (SOC) stocks on a fixed depth basis was greater in pre-till than post-till in two of three years, with pre-till averaging 19% more than post-till. Soil organic carbon stocks on a fixed depth basis was greater in the 5- to 15-cm depth compared to 0- to 5-cm depth, and greater in NT than MT in 2022. Soil equivalent mass SOC stocks were also greater in the pre-till compared to post-till. As with fixed-depth SOC, SOC

equivalent mass was greater in the 5- to 15-cm soil depth compared to 0- to 5-cm soil depth. There was no tillage effect on SOC stocks calculated on equivalent soil mass SOC basis. Nitrate (NO_3^--N) concentration was greater with MT and was more in the 0- to 5-cm depth compared to the 5- to 15-cm depth. Soil phosphorus and potassium were not affected by tillage, yet potassium concentrations in the soil surface were greater pre-till than post-till (884 ppm vs. 554 ppm). Secondary nutrients were not affected by tillage; however, soil pH was slightly lower in NT (5.81) compared to MT (5.94). No-till had greater sorptivity in 2022 compared to MT. Time to runoff was greater in 2022 compared to 2021. Infiltration rate was unaffected by tillage in 2022. Penetration resistance was high due to frequently dry soil conditions, but no measurable differences between tillage systems were observed. Early forage biomass was greater in MT compared to NT, but consistent grazing leveled out forage production across tillage treatments by the end of the crop cycle. No differences between tillage treatments in forage biomass were measured after regrowth. Crude protein (CP), neutral detergent fiber digestibility (NDFD), and total digestible nutrients (TDN) were greater in the spring compared to summer. However, acid detergent fiber (ADF), neutral detergent fiber (NDF), and undigested neutral detergent fiber (UNDF) were greater in the summer compared to spring. Minimal tillage increased CP, NDF, and UNDF but decreased NDFD in 2022. Minimal tillage significantly reduced weed density and weed species compared to NT. Our findings suggest that MT had minimal and short-term effects on soil physical and chemical properties, did not affect soil penetration resistance or soil water infiltration rate, increased early season forage biomass, and significantly decreased weed population.

Introduction

Grazing annual forages in dryland cropping systems has been promoted as a method to integrate crop and livestock systems (Krall and Schuman, 1996; Hilimire, 2011). Benefits of this system include livestock manure returning nutrients for crops, livestock utilizing crop residue, and increased soil organic carbon (SOC) (Zilverberg et al., 2014; Allen et al., 2012). Annual forages can provide rest for native grazing lands and extend the grazing season (Holman et al. 2023b; Obour et al., 2021b). Annual forages, including triticale [×*Triticosecale Wittm.* ex A. Camus (*Secale* ×*Triticum*)], oats (*Avena sativa* L.), forage sorghum (*Sorghum bicolor* Moench.) and sorghum-sudan grass (*Sorghum bicolor* [L.] Moench *x Sorghum Sudanese* [Piper]) and sudan grass (*Sorghum Sudanese* [Piper]), can provide high quality feed for livestock (Holman et al. 2023a; Lenssen et al., 2015a; Lenssen and Dennis Cash, 2011; Oliver et al., 2005). Winter triticale and oats are similar in forage quality with higher crude protein and greater digestibility, while forage sorghum produces large quantities of lower quality feed for livestock. Annual forages are more resilient to variable climates in the central Great Plains (CGP) than grain crops because water required to produce forage is relatively smaller compared to a grain crop (Nielsen et al., 2005; Nielsen et al., 2006). They can help mitigate reduced grass production in dry years and increase market diversification and profit when integrated with grain crops, and are more efficient in water use compared to grain crops (Nielsen et al., 2005; Nielsen et al., 2016; Holman et al., 2018; Peterson et al., 2020). Grazing annual forages eliminates the expense of swathing, raking, baling, and transporting feed and may increase available soil nutrients (Martens and Entz, 2011). However, grazing annual forages could cause soil compaction due to livestock traffic especially after heavy rain events (>12.7 mm) or along travel paths to water (Mapfumo et al., 1999; Maughan et al., 2009). Although livestock can and will eat most weeds in fields (Lenssen and Dennis Cash, 2011; Bosworth et al., 1980), weeds can be a problem in dryland annual forages by reducing forage tonnage as well as forage quality (Lenssen et al., 2015a; Lenssen and Dennis Cash, 2011). There is also potential livestock toxicity risk (oxolate, carboxyatractyloside, nitrate, prussic acid, etc.) with some weed species (Hollis and van der Merwe, 2010; Gildersleeve et al., 2013). Many weed species have developed herbicide resistance, which makes weed control challenging (Obour et al., 2021b). However, annual forages can be more competitive than grain crops at limiting weed growth due to more biomass growth and narrow row spacing that reduces light interception (Lenssen et al., 2015). Grazing or haying annual forages before weeds produce viable seed can help improve weed control. Additionally, tillage can be used to help control herbicide-resistant weeds and alleviate soil compaction (Holman et al., 2021b).

Full tillage has been detrimental in semi-arid cropping systems (Kelly et al., 2021; Merrill et al., 1999) but occasional tillage or MT has not reduced crop yields and has been an important practice in dryland cropping systems (Schlegel et al. 2020; Vandeveer et al. 2023). Tilling the soil permits moisture and air to permeate the upper soil profile, allowing seeds to germinate, encouraging root growth, controlling weed growth, and incorporating fertilizers into the soil. Tillage can affect soil water storage in dryland cropping systems by disturbing soil structure, reducing water infiltration, and increasing evapotranspiration (Hatfield et al., 2001). By preparing the soil for planting with tillage, crop stands can be established with less competition from weeds (Obour et al., 2021a). Tillage ahead of winter triticale increased soil water content at planting and often increased forage yield (Holman et al. 2021b). However, tillage can increase wind and water erosion, as well as decrease SOC, soil structure, and soil organic matter (SOM). Most soil erosion occurs when there is little to no residue cover (Peterson et al., 2020). Tillage practices can be varied, with intensive tillage being most likely to leave the soil bare without protection against wind or water erosion. Six et al. (2002) reported that repeated tillage operations reduced soil aggregate size and continuity of pores, which increased erodibility and decreased water infiltration rate, as well as increased oxidation of soil carbon by reducing SOM in soil aggregates. Other studies have found that MT or reduced tillage (RT) did not negatively affect soil properties, including water and wind erosion susceptibility compared to no-till (NT) (Obour et al., 2021a; Zuber et al., 2015).

No-till farming is a soil conservation practice that improves soil health and water infiltration. These improvements have enabled farmers to intensify crop rotations and reduce fallow frequency (Triplett and Dick, 2008; Dhuyvetter et al., 1996). Modern NT farming equipment can plant through crop residue making NT a common practice for farmers in the CGP. Winter wheat residue is considered advantageous in this region for storing soil water and reducing soil erosion. A challenge for dryland farmers in the CGP is having sufficient water storage at time of crop planting. Triplett and Dick (2008) reported that no-till improved water capture, minimized erosion, and enabled increased cropping intensification, all of which contributed to greater biomass production and increased organic matter in the soil (Triplett and Dick, 2008). No-till practices can help reverse the soil carbon losses from over a century of degrading cropping practices and contribute towards a sustainable agroecosystem (Peterson et al., 2020). The long-term use of NT should be encouraged to promote soil health and soil conservation (Dabney et al., 2004; Triplett and Dick, 2008). However, the erosion-resisting soil qualities associated with NT can be lost within a single year of a tillage event (Grandy et al., 2006). Grandy et al. (2006) observed that the water stable aggregate mean weight diameter (MWDWSA) in the 0- to 20-cm soil depth decreased 35% within 60 days of tillage in long-term

NT soils. However, other tillage research has found no effect on water stable aggregates after a single tillage event compared to NT (Blanco-Canqui et al. 2010).

Herbicide-resistant weeds are becoming more common and challenging to control each year (Heap, 2023; Nazarko et al., 2005; Triplett and Dick, 2008). Intensifying and diversifying crop rotations could help combat the herbicide-resistant weeds by using different modes of action. By adding more crops to a rotation, this allows growers to change up planting date, rooting depth, and canopy architecture of the crops that can help suppress weeds (Anderson, 2000; Holman et al., 2021b; Anderson, 2005). Tillage can help with weed management in a crop rotation (Obour et al., 2020a). Barberi and Lo Cascio (2001) found that crop rotation and minimal tillage does not increase weed numbers, however NT might increase weed numbers because of the higher seeds from the topsoil in a two-year study in central Italy.

There is limited research on tillage effects when grazing annual forages on system productivity or soil physical and chemical properties. Furthermore, most grazing studies have been conducted in small research plots, and few studies have quantified season long, large-plot livestock grazing. The objective of this study was to quantify MT effects on weed populations, soil health, and forage yield and quality of grazed winter triticale compared to NT. Our hypothesis was that MT would reduce weed density, increase forage yield, and alleviate compaction in a grazed annual forage system, but also could adversely affect soil properties compared to NT.

Materials and methods

Experimental Design

This study was initiated in 2016 with data collected during the 2020, 2021 and 2022 growing seasons after treatment effects had sufficient time to produce potential differences. Other than a baseline soil sample at the beginning of the study, the field was not sampled until after several years of treatment implementation to capture long-term effects on forage yield and soils. The study was located near Jetmore, KS on an on-farm cooperator field (37°54'4" N, 99°51'57" W). The soil type was a mixture of Dale silt loam, rarely flooded, with 0-1% slope and Penden and Campus clay loam, with 3 to 6 percent slopes. The climate in this region of the High Plains is considered semi-arid. The mean annual temperature is 13 °C, and the long-term annual precipitation is 590 mm (Kansas Mesonet). The study was a randomized complete block design with 4 replications. Treatments were MT and NT during the summer-fallow period of grazed continuous winter triticale cropping system. The MT treatment was imposed by tilling twice during the summer-fallow period between winter triticale crops using a Minimizer sweep plow (Premier Tillage, Quinter, KS) between July 1 and August 1. The sweep plow is a minimum disturbance equipment commonly used in the region for weed control. The NT treatment was there from long-term NT of more than 10 years. The individual plots were 15 m wide and 396 m long.

Crop Management

Both MT and NT treatments received the same herbicide applications, which usually consisted of a mixture of glyphosate, dicamba, and 2-4, D. Herbicides were applied between June 1 and July 1. The herbicides we used were to try to control summer annual weeds such as kochia (*Kochia scoparia* (L.)) and pigweeds (*Amaranthus retroflexus*). Triticale was planted between mid-September and early October and was grazed from fall (Nov or Dec) through spring with the length of grazing period depending on forage availability. Stocking rates were adjusted to the amount of plant growth, which was dependent on precipitation. Initial stocking density was 560 kg ha^{-1} from fall until active spring growth, then 1,120 kg ha^{-1} during the active spring growth period. Plots were part of a larger 45 ha field, and cattle had access to the entire field to achieve season-long, large-herd grazing effects on plots. Livestock were moved to an adjacent native grass pasture either before or soon after heavy rain events (>12.7 mm) for a few days to allow the soil surface to dry to minimize surface compaction. Otherwise, livestock were left on the field to graze. Grazing ended between May 15 and June 15 either after triticale reached heading stage (Feekes 10.1) in wet years or until most crop biomass had been removed by grazing in dry years.

Soil Analysis

Soil sampling occurred in June and August in each year of the study (2020, 2021, and 2022) before and after tillage operations were conducted in the MT treatment during the summer-fallow period. In 2020 and 2021, soil properties, including bulk density, SOC, pH, NO_3^--N, NH_4^+-N, P, K, and water stable aggregates, were measured before and after first tillage. In 2020 only, an adjacent perennial grass pasture dominated by buffalograss (*Bouteloua dactyloides*), sideoats grama (*Bouteloua curtipendula*), blue grama (*Bouteloua gracilis*), and little bluestem (*Schizachyrium scoparium*) was also sampled for comparison with the annual winter triticale grazing plots. In 2020 only, soil samples were analyzed for secondary nutrients including Zn, Fe, Mn, and Cu in addition to macronutrients, which were quantified all three years. In 2021 and 2022, soil penetration resistance, dry stable aggregates, water stable aggregates, and bulk density were measured. At each sampling time, two intact cores (5-cm diam.) were taken from 0-5- and 5-15-cm soil depths from each plot using a custom-made bulk density sampler fitted with an AMS bulk density handlebar (AMS, Inc., American Falls, ID) for determination of bulk density. The samples were dried at 105 ^oC for 48-hr. Bulk density was determined as the mass of oven-dry soil divided by the volume of the core.

Ten soil cores of 2.5 cm diameter were randomly taken from the 0-5- and 5-15-cm soil depths to determine pH, SOC stocks, NO_3^--N and NH_4^+-N, P, K, Zn, Fe, Mn, and Cu. Subsamples from each depth were air-dried and ground to pass through a 2 mm sieve and analyzed for soil chemical properties. Soil pH was analyzed using a 1:1 (soil/water) ratio using deionized water and an OAKTON PC 700 Benchtop pH meter (OAKTON Instruments, Vernon Hills, IL). Soil NO_3^--N and NH_4^+-N were determined colorimetrically after the soil samples were extracted with 2 M KCl. Available P was determined by the Mehlich-3 extraction method (Mehlich, 1984), and P concentration following extraction was measured using inductively coupled plasma-optical emission spectrometry (ICP-OES). Exchangeable potassium (K) concentration was determined by ICP-OES after NH_4OAc extraction (Knudsen et al., 1982). Iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu) were extracted by the DTPA extraction method (Lindsay & Norvell, 1978), and nutrient concentrations were measured using atomic absorption spectrometry. Soil organic carbon concentration was determined by dry combustion using a CN analyzer after pretreating samples with 10% (v/v) HCl to remove carbonates (Nelson and Sommers, 1996). Carbon concentrations were converted to mass on a fixed-depth basis by multiplying concentrations by soil bulk density by the thickness of the soil layer. Carbon stocks were also determined by using minimal soil equivalent mass to determine SOC stocks on an equal mass basis (Mikha et al., 2013).

Soil samples were collected from 0- to 5-cm depth with a flat shovel to determine wet and dry aggregate stability. Samples were passed through sieves with 4.75- to 8.0 mm mesh and then were air dried. The 4.75 to 8.0 mm aggregate samples were used to estimate water-stable aggregates by the wet-sieving method (Nimmo and Perkins, 2002). Sand corrections were completed for each aggregate size, and the data was then used to compute aggregate size distribution (ASDWSA) and mean weight diameter (MWD) of water stable aggregate (MWDWSA). In 2021 and 2022, dry aggregate stability was measured. Half of each sample was separated and air-dried to determine dry aggregate stability using a system of nested rotary sieves having 19-, 6.3-, 2-, 0.84-, and 0.42-mm diameter openings (Chepil, 1962). Mass of soil in each size class were used to compute aggregate size distribution – dry aggregates (ASDDA), mean weight diameter - dry aggregates (MWDDA) as well as wind erodible fraction (WEF) as the percentage of dry aggregates <0.84 mm in diameter. In August of 2021 and 2022, sorptivity and time-to-runoff (TTR) were measured with a Cornell Sprinkle Infiltrometer (Ogden, van Es, and Schindelbeck, 1997). In August of 2022, infiltration rate for 60 minutes was also measured. Penetration resistance was measured in August of 2021 and June and August of 2022 with 10 random points within each plot using a hand cone penetrometer (Eijkelkamp Co., Giesbeek, The Netherlands). Penetration resistance readings were divided by the area of the cone (2 cm^2) to determine MPa cm^{-2}. Gravimetric water content measurements were taken at the time of measuring penetration resistance and was calculated by the ratio of water contained in soil to the dry weight of soil (weight of wet soil-weight of dry soil)/weight of dry soil). Penetration resistance measurements were then adjusted to field capacity gravimetric water content of 0.30 (g/g)(Busscher et al., 2001).

Forage Sampling

Biomass samples were collected throughout the growing season to quantify productivity throughout the life cycle of the winter triticale. In 2021 and 2022, triticale biomass was measured in November, March, and June to estimate fall, spring, and summer forage availability by cutting all biomass within two 0.23-m^{-2} quadrats at two inches above soil surface. Samples were oven-dried at 50°C until a constant weight was reached to determine dry matter. Dried biomass samples were ground to pass through a 2-mm screen using a Wiley Mill (Thomas Scientific, Swedesboro, NJ) and subsequently ground to pass through a 1-mm screen using a UDY Cyclone sample mill (UDY Corporation, Fort Collins, CO). Ground biomass samples were analyzed for forage nutrient content by a commercial lab (Servitech Inc. Dodge City, KS). Forage composition was characterized by crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF) organic matter, undigested neutral fiber organic matter after 240 hours (UNDF), neutral detergent fiber digestibility after 240 hours (NDFD), and total digestible nutrients (TDN) using a Foss 6500 near infrared spectroscopy (NIR) systems (Foss Analytical Systems, Hillerød, Denmark).

Weed density

In 2020, 2021, and 2022 weed density was determined before tillage in June and repeated in August after tillage had been imposed in the MT treatment and herbicide application to all treatments. The number of individuals weed species was counted within a 0.23-m^2 quadrat in June and a 9.3 m^2 quadrat in August. Three quadrats were measured in each plot during both June and August measurements. A larger quadrat was used in August due to low weed density following tillage and herbicide application.

Statistical analysis

Statistical analysis of soil physical and chemical properties, forage biomass, forage nutritive value, weed density, weed species, and infiltration rate were conducted using PROC GLIMMIX in SAS ver. 9.3 (SAS Institute, 2012, Cary, NC). Data was analyzed within each year. Tillage, depth, time, as well as their interactions were considered fixed effects with replication considered random. Within each year, BD, soil organic carbon based on fixed effects, soil organic carbon based on equivalent mass, soil organic carbon based on concentrations, NO3--N, NH4+-N, P, and K concentrations were analyzed by sampling time, tillage, and soil depth. Mean weight diameter of water aggregates, MWDWSA, MWDDA, WEF, penetration resistance, forage productivity forage nutritive value, weed density, and weed species was analyzed by tillage and sampling time. Infiltration rate, soil sorptivity, and time to runoff was analyzed by year and tillage. Other soil nutrients including Zn, Fe, Mn, Cu, and pH were analyzed by tillage and soil depth. Treatment effects were considered significant at $P \leq 0.05$.

Results

Long-term weather patterns

The average precipitation from 2019 to 2022 was 441 mm, 149 mm below average (Table 2.1.). During the study period most of the rainfall fell in the spring (April - June) and summer. This is in contrast to the 30-year average of most precipitation occurring in the summer (July – September). The 30-year average precipitation for Jetmore, KS was 590 mm with most moisture occurring in the month of July. In 2019, 56% (306 mm) of the annual precipitation was received in the spring and 17% (93 mm) occurred during summer months. In 2020, spring received 29% (134 mm) and summer received 40% (190 mm) of the annual precipitation. In 2021, 39% of the annual precipitation (183 mm) was received in the spring and summer received

24% (111 mm) of annual precipitation. In 2022, spring received 39% (109 mm) and summer received 42% (118 mm) of the total annual precipitation. Although precipitation was below average for all years, rainfall amounts, and timing were sufficient to grow a successful forage crop except in 2022. Precipitation in 2022 was significantly less than the long-term average and insufficient for crop demand.

Soil physical properties

The three-way interaction of time × tillage × depth was not significant for BD in any year or across years (Table 2.2). The only significant two-way interaction was time × depth in 2021 when BD was 18% lower post-till compared to pre-till in the 0- to 5-cm soil depth but not in the 5- to 15-cm depth averaged across tillage treatments. The main effect of time varied across the years of this study. In 2020, soil BD was 5% greater post-till compared to pre-till. However, in 2021, soil bulk density was 11% lower post-till compared to pre-till. Time was not significant in 2022 but BD tended to be greater pre-till, and pre-till BD was 6.5% greater than post-till BD when averaged across years. The main effect of depth was consistent across years with BD averaging 18% less in the 0- to 5-cm depth than in the 5- to 15-cm depth. Tillage was not significant in any year, but across years BD was 4% less in MT than in NT.

The two-way interaction of time × tillage was signficnat for MWDWSA in 2022 when post-till NT was 69% greater than post-till MT (Table 2.3). In all years except 2021, MWDWSA was less in pre-till than post-till. Averaged across years, post-till was 42% greater than pre-till. Similarly, in all years except 2020, MWDWSA was less in MT than NT. In 2021, NT was 46% greater than MT and in 2022, NT was 54% greater than MT. Averaged across years there was a strong tendency (P=0.097) for MT having lower MWDWSA than NT.

The two-way interaction of time × tillage was significant for water stable aggregate size distribution in 2022 (Table 2.4). In 2022, post-till NT had 107% more aggregates in the 8.0-2.0 mm than post-till MT. Pre-till NT was not different from pre-till MT in the 8.0-2.0 mm size. Post-till NT had 40% more aggregates in the 2.0-0.25 mm size fraction compared to post-till MT. The proportion of aggregates the <0.25 mm in post-till NT was 76% less compared to post-till MT. Water stable aggregate size distribution in 2020 was different for pre-till compared to post-till in the 8.0-2.0 mm size distribution where post-till was 188% greater than pre-till. However, in the 2.0-0.25 mm size class, pre-till was 75% greater than post-till. In 2022, post-till was 281% greater than pre-till in the in the 8.0-2.0 mm size distribution. In the 2.0-0.25 mm size class, post-till was 36% greater than pre-till. In the <0.25 mm size class, pre-till was 24% greater than post-till. In 2021, NT had 61% more aggregates in the 8.0-2.0 mm size, but MT had 21% more aggregates in the <0.25 mm size distribution. Aggregate size distribution was not different between pre-till NT and MT. Post-till in the 8.0-2.0 mm size distribution was 3-fold greater than pre-till. Similarly, post-till in the 2.0-0.25 mm was 36% greater than pre-till. In the <0.25 mm, pre-till was 24% greater than post-till.

For dry stable aggregate mean weight diameter (MWDDA), there was no significant two-way interaction of time × tillage (Table 2.5). Similar to MWDWSA, MWDDA, at time of sampling tended to be greater post-till than pre-till. There was no difference between sampling times in 2021, but post-till had 67% greater MWDDA than pre-till in 2022. Averaged across years, there was a tendency (P=.058) for post-till MWDDA to be 20% greater than pre-till. Although not significant in 2021, MWDDA tended to be less in MT than NT. In 2022, NT was 33% greater than MT. Across years, MWDDA was 16% smaller in MT than NT.

Dry stable aggregate size distribution observed a significant two-way interaction of time × tillage in both 2021 in the <0.42 mm size class (Table 2.6). In 2021, post-till NT has 72% less aggregates in the <0.42 mm size class compared with post-till MT. Pre-till NT and MT were not different in this size distribution. In 2022, aggregates in the 19.0-6.3 mm size measured pre-till was 117% less than post-till. Aggregate size fraction in the 0.84-0.42 pre-till was 54% greater than post-till. Aggregate size fraction in the <0.42 mm pre-till was 40% greater than post-till. In 2021, MT had 37% more aggregates in the <0.42 mm size than NT. In 2022, NT had 33% more aggregates than MT in the 6.3-2.0 mm size class. Similarly, NT had 23% more aggregates in the 2.0-0.84 mm than MT. No-till in the <0.42 mm had 55% more aggregates than MT.

Wind erodible fraction (WEF) had a two-way interaction of time × tillage in 2021 were post-till MT was 33% more erodible than NT in August (Table 2.7). Except in 2021, post-till had greater WEF than pre-till. Average across years, MT had more WEF than NT.

Soil penetration resistance was not measured pre-till in 2021. There was no significant two-way interaction of time × tillage for penetration resistance (Table 2.8). At time of sampling in 2022 there was a tendency (P=0.07) for lower resistance post-till than pre-till. However, there was no difference in penetration resistance between tillage treatments.

Infiltration

There was no two-way interaction of year × tillage for sorptivity, time to run-off, and infiltration rate. Soil sorptivity was unaffected by tillage in 2021 but was 18% greater in NT compared to MT in 2022 (Table 2.9.). However, soil sportivity averaged across years, sorptivity was not significantly different for the interaction of year × tillage, tillage, or year. Time to run-off was not affected by treatment but was 63% greater in 2022 than 2021. Infiltration rate was only measured in 2022 and was not affected by tillage treatments.

Soil chemical properties

A significant three-way interaction of sampling time × tillage × soil depth was observed in 2020 when SOC (based on fixed depth) pre-till MT was 37% greater than NT (Table 2.10.). There was little difference within a soil depth between tillage treatments, except in 2022 at the 0- to 5-cm depth NT was greater than MT. Except in 2022, SOC in pre-till was greater than post-till. Yet in 2022, pre-till in MT was also greater than post-till. In all years SOC was greater in the 5- to 15-cm soil depth than 0- to 5-cm depth and across years was 76% greater in the 5- to 15-cm depth. In 2022, SOC was greater in NT than MT.

Soil organic carbon based on equivalent soil mass (ESM SOC) was similar to fixed depth SOC stocks with a couple of notable differences (Table 2.11.). Across years and tillage treatments, ESM SOC was lower post-till at both the 0- to 5-cm and 5- to 15-cm then pre-till 0- to 5-cm and 5- to 15-cm. Also, across years, ESM SOC was lower in the 5- to 15-cm soil depth in NT than MT. There was no difference between tillage treatments in the 0- to 5-cm soil depth. we did not observe any difference between tillage but did measure a difference at sampling times. Soil organic carbon concentration results were similar to fixed depth SOC, with one exception (Table 2.12.). Soil organic carbon concentration was greater in the 0- to 5-cm soil depth than 5- to 15-cm soil depth.

There was no three-way interaction of time × tillage × depth for soil NO_3^--N. The two-way interaction of time × depth was greater in post-till than pre-till at both depths and tillage treatments apart from 2022 (Table 2.13). Across years, soil NO_3^--N pre-till in the 0- to 5-cm and 5- to 15-cm soil depth was less than post-till in the 0- to 5-cm and 5- to 15-cm soil depth. The two-way interaction of time × tillage was not significant in 2020 or 2021, but in 2022 soil NO_3^--N was 71% less in the NT compared to MT in post-till sampling time. Across years, soil NO_3^--N was greater in post-till sampling than pre-till sampling. Similarly, soil NO_3^--N was greater in the 0- 5-cm than 5- 15-cm soil depth. Tillage was not significant in 2020 or 2021, but in 2022 and across years soil NO_3^--N was greater in MT than NT.

Soil NH_4-N was measured pre-till in 2020 and pre- and post-till in 2022 (Table 2.14.). Soil NH_4^+-N results were similar to NO_3^--N results. In 2022, pre-till MT in the 0- to 5-cm was 25% greater compared to pre-till NT in the 0- to 5-cm depth. Similarly post-till MT in the 0- to 5-cm depth was 86% greater than post-till NT in the 0- to 5-cm depth. No significant differences in the 5- to 15-cm soil depth for 2022. There was a significant two-way interaction of tillage × depth in 2022. In 2022, NT in the 0- to 5-cm soil depth was 84% greater than the NT in the 5- to 15-cm soil depth. Similarly, MT in the 0- to 5-cm soil depth was 87% greater compared to MT in the 5- to 15-cm soil depth There was a significant two-way interaction of time × tillage in 2022. In 2022, pre-till NT was 35% less than the pre-till MT. Post-till NT had 451% less NH_4^+-N than post-till MT. There were no differences between sampling times and depth. However, soil NH_4^+N in MT was 49% greater than NT.

Soil phosphorus (P) was generally unaffected by treatment except in 2022 (Table 2.15.). There was no significant three-way interaction of time × tillage × depth for soil P. In 2022, P concentration in the 0- to 5-cm soil depth NT was greater than MT, and greater pre-till than post-till. Across all years, soil P was greater in the 0- to 5-cm than 5- to 15-cm soil depth.

There was no significant three-way interaction of time × tillage × depth for soil potassium (K) (Table 2.16). A significant two-way interaction of time × depth was observed in 2021 and 2022. The 0- to 5-cm depth had the greatest K concentration in the pre-till and was 28% greater than post-till. There were no differences between pre-till and post tillage in the 5- to 15-cm. Similarly, pre-till in the 0- to 5-cm depth saw the largest concentration and was 46%

greater than post-till 0- to 5-cm. Pre-till in the 5- to 15-cm depth was 45% greater than the post-till. Soil potassium across years was greater pre-till than post-till, and greater in the 0- to 5-cm than 5- to 15-cm soil depth.

There was no significant two-way interaction of tillage × depth for Zinc (Zn), iron (Fe), manganese (Mn), and copper (Cu) concentrations (Table 2.17). Similarly, Zn, Fe, Mn, and Cu were not affected by tillage (Table 2.17.). Zinc was 83% greater and Mn was 16% greater in the 0- to 5-cm than 5- to 15-cm soil depth. Soil pH was 1.7% greater in the 0- to 5- cm than 5- to 15-cm depth, and was 2.2% greater in MT than NT.

Forage productivity and nutritive value

Forage productivity was greater in MT than NT in fall of 2021, but there was no difference between tillage treatments at other periods or year (Table 2.18.). Forage biomass varied across sampling times and years depending on precipitation timing. In 2021 there was no difference in forage biomass between tillage treatments. Yet in 2022 forage biomass was greater in MT than NT. Across years, forage nutrient values (CP, ADF, NDF, UNDF, NDFD, and TDN) were similar across years. In 2021 forage nutrient value was similar between tillage treatments within a sampling time. In 2022 CP was greater at spring sampling in MT than NT, and UNDF was greater at summer sampling in MT than NT (Table 2.19.). In both years and across years, CP, NDFD, and TDN was greater in the spring and ADF, NDF, and UNDF was greater in the summer (Table 2.20).

Weed density and species abundance

Few weeds were counted pre-till and herbicide application in 2020, and post-till and herbicide no weeds were observed (Table 2.21). Each year and across years, weed density was greater pre-till and herbicide application than post-till and herbicide burndown. Weed density was greater pre-till NT than pre-till MT. The top five weed species in terms of abundance were cheatgrass (CG), little barley (LB), henbit (HB), yellow mustard (YM), and large crabgrass (LG). Tillage did not affect cheatgrass (*Bromus tectorum*) in 2020 (Table 2.22). However, there was a significant two-way interaction of time × tillage in 2021 when pre-tillage in NT had 79% more cheatgrass compared to pre-tillage in MT, but there was no significant difference between post-tillage NT and MT. Time did not have a significant effect on CG in 2021. However, there was a significant difference in the main effect of tillage with NT having 79% more CG compared to MT. No significant two-way interaction of time × tillage nor the main effects of time or tillage was observed for CG in 2022.

Little barley (*Hordeum pusillum*) was the second most abundant weed species in the study. In 2020, NT had 91% more LB compared to MT (Table 2.22). A significant two-way interaction of time × tillage in 2021 occurred when pre-till NT plots had 89% more weeds than pre-tilled MT. However, both post-tilled plots of NT and MT were not different. Pre-tillage had 100% more LB compared to post-tillage. No-till recorded 89% more weeds than MT. In 2022, there was a significant two-way interaction of time × tillage for LB. The pre-tilled plots in NT had 86% weed numbers compared to pre-tillage MT plots. However, post-tilled plots in NT and MT were not significantly different. Pre-tillage had 100% more LB weeds than post-tillage and NT had 86% more LB compared to MT.

Henbit (*Lamium amplexicaule*) (HB) was the third most abundant weed species. In 2020, there was no significant difference between tillage practices (Table 2.22). In 2021, there was no significant two-way interaction observed between time × tillage. Similarly, the main effect of time × tillage did not observe differences between sampling times and tillage practices. Henbit was not observed in weed totals in 2022.

Yellow mustard (*Sinapis alba* L.) (YM) was the fourth most abundant weed species observed in this study. In 2020, YM was unaffected by tillage (Table 2.22). In 2021, there was no significant interaction observed between time and tillage. However, there was a significant difference in time, where pre-tillage sampling had 3.3 more YM plants compared to post-tillage sampling. The effect of tillage, however, was not significant. In 2022, a significant two-way interaction between time and tillage was observed, with pre-tillage NT showing a 67% greater weed abundance compared to pre-tillage MT. However, in August, both NT and MT did not exhibit a significant difference. The main effect of time was also significant, with pre-tillage averaging 1.84 more YM plants compared to post-tillage. Similarly, the main effect of tillage was significant, with NT showing a 67% greater abundance compared to MT.

Large crabgrass (*Digitaria sanguinalis*) (LC) was the fifth most abundant weed species in this study (Table 2.22). In 2020, no LC weeds were observed at our sampling time. In 2021, a significant two-way interaction of time × tillage was observed were pre-tillage NT averaged 6.13 more LC plants compared to pre-tillage MT (Table 2.20). There were no differences between post-tillage NT and MT. Time was significantly different were pre-tillage was 99% greater compared to post-tillage. Similarly, NT averaged 3.08 more LC plants compared to MT. In 2022, there was no significant two-way interaction of time × tillage, as well as the main effect of time and tillage observed for LC.

Discussion

Compaction from grazing is a major concern for crop producers, especially in NT systems. In our study, MT had lower BD than NT. Results from this study support our hypothesis that MT would alleviate compaction issues from livestock grazing. (Franzluebbers and Stuedemann, 2008; Baumhardt et al., 2017). Franzluebbers and Stuedemann (2008) observed cattle grazing cropland increased soil bulk density. However, this contrasts with what we observed in our study where bulk density decreased from our initial measurements. Baumhardt et al., 2017 measured greater BD in NT (1.29 Mg m^{-3}) compared to stubble mulch (1.12 Mg m^{-3}) after harvest of dual-purpose grazed winter wheat. It is important to note that although BD in our study was higher in NT than MT, it was likely not high enough to limit plant root growth or water infiltration (Bengough et al., 2011). In our study, soil penetration resistance values were similar between MT and NT but showed a tendency for lower penetration resistance after tillage. This is similar to a study in Georgia that measured greater penetration resistance in NT than conventional tillage (Franzluebbers and Stuedemann, 2008). Similarly, stubble mulch tillage decreased penetration resistance to the tillage layer (0-10 cm depth) compared to NT plots (Unger and Jones, 1998). A possible reason why we didn’t observe any difference in penetration resistance between tillage systems could be due to the time of sampling before and after tillage.

Soil structure and aggregation are important characteristics to limit water and wind soil erosion. Although both water and wind erosion are a concern, wind erosion is a frequent concern and water erosion can be particularly erosive in the semi-arid CGP. In this study, tillage decreased MWDWSA and MWDDA. Other grazing studies also have found that tillage reduced aggregate size compared to NT (Franzluebbers and Stuedemann, 2008; Baumhardt et al., 2017).

Other studies also found that tillage increased WEF compared to NT (Baumhardt et al., 2015; Hansen et al., 2012).

Infiltration rate is an important measure of soil health because it indicates how well the soil can absorb and retain precipitation. A high infiltration rate is a sign of good soil structure and porosity. In our study, infiltration rate did not differ between tillage practices. A study in Bushland Texas by Baumhardt et al., (2017) investigated the grazing and tillage effects on water infiltration during fallow periods of a winter wheat-grain sorghum-fallow rotation. After wheat harvest, NT had significantly lower infiltration rate than stubble-mulch tillage. This contradicts our results where we observed no effect of tillage practices on water infiltration. Not all studies observed a significant tillage difference. Franzluebbers and Stueduemann (2008) observed that tillage system had no significant effect on infiltration rate similar to our study. However, in their study, infiltration rate and soil water content were reduced by grazing CC compared to ungrazed CC. In our study, cattle were removed when field conditions became wet, and plots were not located in traffic lanes to water source. Had cattle been allowed to remain on the field during wet conditions or traffic lanes sampled, this study may have also measured differences in water infiltration between treatments.

Soil organic carbon stocks play an important role in soil health. McVay et al., (2006) investigated management effects on different soil physical properties, including SOC, across five different locations throughout Kansas (Manhattan, Hays, Parsons, Tribune, Ashland Bottoms). They observed that SOC was greatest with NT compared to other tillage systems, except at Tribune, the site with the least annual precipitation (McVay et al., 2006). Our study location was in closest proximity and soil type as Tribune, and SOC was unaffected by tillage at both sites. These similarities between sites may have been in part due to environment, soil type, and the type of tillage system used. At both Tribune and our study, a sweep plow was used that left residue on soil surface and had minimal soil mixing. The other locations in McVay et al. 2006 used a combination of chisel and sweep plow with greater soil disturbance. Furthermore, our study was continuously cropped with little fallow and grazing, which may have returned more organic matter to the system than a cropping system with more frequent fallow. Overgrazing can lead to soil compaction, which can decrease SOC stocks (Abdalla et al., 2018). Quiroga et al., (2009) in Argentina investigated grazing effects on SOC in CT and NT, where SOC was greater in NT than CT near the surface level (0-0.10 m). Although our study did not observe a tillage effect on SOC, we did observe that pre-till while the cattle were grazing had higher concentrations of SOC compared to post-till when cattle had been off the field for a couple months. The difference in SOC stocks between depths could be explained by the soil mass of each depth. Since there is less soil mass in the 0- to 5-cm depth, there are less SOC stocks in that depth compared to the 5- to 15-cm depth. However, when we calculated SOC on soil equivalent mass, we did not observe any differences between depths. Soil organic carbon concentrations were higher in 0- to 5-cm depth.

Soil NO_3^--N plays a vital role in plant growth and is essential for plants to produce proteins. The results from this study are similar to others that found NO_3^--N content was greater with tillage compared to NT (López-Bellido et al., 2013). A possible reason for the lower soil nitrate-N content in NT was due to less N mineralization in NT due to slower decomposition and more N immobilization associated with less soil and residue disturbance.

Organic nitrogen must be mineralized to be plant available. This can be accomplished from either mineralization or ammonification. Ammonification is the primary process that converts reduced organic nitrogen (R–NH_2) to reduced inorganic nitrogen (NH_4^+) through the action of microorganisms known as decomposers (Galloway, 2003). Mineralization is the heterotrophic microbial transformation of N from the organic state to an inorganic NH_4^+-N or NO_3^--N (Connor et al., 2011). In our study, we observed that soil NH_4^+-N concentration was inconsistent between years, however average NH_4^+-N was greater in MT compared to NT. These results are similar to a study in the northern Great Plains that measured N availability after thirty years of tillage and cropping rotation (Sainju et al., 2015). They observed that tilled continuous wheat had greater soil NH_4^+-N concentrations than NT continuous wheat. They suggested that greater soil NH_4^+-N concentration was due to increased mineralization in tilled plots. This could explain why we observed higher levels soil NH_4^+-N concentrations in MT compared to NT in the current study.

Tillage could reduce nutrient stratification by mixing surface soil with lower depths. In the present study, tillage increased soil pH. Tillage has consistently shown to increase pH by mixing with deeper soil (Franzluebbers and Hons, 1996; Obour et al., 2017; Tarkalson et al., 2006). In the present study, we observed that soil Zn, Fe, Mn, and Cu were not affected by tillage; however, Zn and Mn concentrations differed by soil depth. This is similar to Obour et al. (2017), who observed that reducing tillage intensity increased Fe and Mn in the upper soil profile. Soil P concentration was not affected by tillage in the present study. This contrasts with Obour et al. (2017), who observed higher P accumulation in the surface level in the NT compared to CT and RT. A possible reason for not observing a tillage difference could be that the tillage operation imposed in our study did not mix the soil enough to make a difference. In the present study, there was a significant difference in soil P, with the 0-5 cm having greater accumulation compared to 5-15 cm. This is due to phosphorus being relatively immobile within soils and tending to accumulate near the soil surface. Cattle grazing could have increased plant available soil P in grazing systems by converting organic P in plant material to inorganic plant-available form from ruminant digestion (Martens and Entz, 2011). Soil K was not affected by tillage but differed with depth in the present study. Similar to the present study, Obour et al. (2017) found that K was not affected by tillage but did differ with depth. The lack of tillage effects could be due to the clay content in the soil and greater cation exchange capacity than other soil types with less clay content. In the semi-arid Great Plains, the low precipitation limits leaching of the cations in the soil. Therefore, it is common to measure greater concentrations of K in the upper surface of soils. The soils in the present study are known for being calcareous that are extremely high in K. The lack of tillage effects could also be due to all the forage being harvested either by grazing or haying, reducing differences in uptake, and cycling of K between NT and MT.

The results from this study partially support our hypothesis that MT increases winter triticale forage yield in semi-arid CGP. In 2022, we observed that MT produced significantly more forage compared to NT. However, no significant differences in forage yield between tillage treatments were observed in 2021. This could be due to different weather patterns from 2021 to 2022. This result is similar to the results that Holman et al. (2021a) observed near Garden City, Kansas in an experiment testing which forage rotation accumulated the most forage using winter triticale, forage sorghum, and spring oats. In their study, triticale forage yield was increased with RT compared to NT due to increased plant available water at planting. Another study near Sidney, Montana found forage barley productivity was affected by tillage, but it varied by year (Lenssen et al., 2015b). Barley biomass in the first 3 years of the study (2005, 2006, and 2007) varied with NT increasing biomass in 2005 and 2006, but tilled plots increased biomass in 2007. After 2007, there were no differences in barley biomass between tillage practices. This variability in forage yield response to tillage was similar to our study. Another study found wheat and grain sorghum grain yield was similar with either a single tillage pass or NT near Garden City and Tribune, Kansas (Schlegel et al., 2020). However, another study in Tribune Kansas found that there was yield advantage for NT over CT and RT in both winter wheat and grain sorghum (Schlegel et al., 2018). Crude protein is an essential nutrient for livestock and is positively correlated with forage digestibility where ADF and NDF are negatively correlated with forage digestibility (Lee, 2018). Our results showed nutritive value decreased as the plant matured. Other studies have reported similar findings (Obour et al., 2020b). Obour observed that forage CP and fiber digestibility were greater when the forage CC just headed, compared to when harvested at later maturity. Tillage had varying effects on forage nutrients results in our study. No significant differences of any nutrient parameters were observed in 2021. However, in 2022 CP, NDF, and UNDF decreased under NT compared to MT, and NDFD increased with NT compared to MT. This result is similar to what Holman et al., 2023 observed near Garden City, Kansas (Holman et al., 2023)). They observed that CP, ADF, and NDF were not affected by tillage treatment.

The competition of weeds for water and nutrients can result in a substantial crop yield loss (Oerke, 2006). Tillage is a useful tool to control weeds during fallow periods. Our results were consistent with other studies that investigated tillage effects on weed density. Schreiber (1992) investigated the influence of tillage, crop rotation, and weed management on giant foxtail (*Setaria faberi* L.) population and corn yield. The author observed that NT consistently contained more giant foxtail seed than CT. It is important to note that they saw the greatest effect of reducing giant foxtail with crop rotation. A similar study by Obour et al., (2021a) found NT had a significantly higher weed density compared to reduced tillage and strategic tillage in a wheat-sorghum-fallow rotation.

Weed species varied between tillage practices. In our study, there wasn't a consistent tillage effect on weed species, but MT consistently had lower weed density compared to NT. Our results were different from Blackshaw et al. (1994), who noted that Dandelion (*Taraxacum offinale* Weber), sowthistle (*Sonchus oleraceus*), downy brome *(Bromus tectorum* L.), redroot pigweed (*Amaranthus retroflexus*), and Russian thistle (*Salsola tragus*) populations increased with NT. However, flixweed *(Descurainia sophia* (L.) Webb ex Prantl.), field pennycress (*Thlaspi arvense*), wild buckwheat (*Fallopia convolvulus* L.) and common lambsquarter (*Chenopodium album*) decreased under NT plots. In our study, we observed MT decreased weed species numbers. However, this wasn't always consistent year to year. This was possibly due to the year-to-year variability, cattle grazing, and deposit weed seed in adjacent plots, and different weed species in the present study.

Grazing can also impact weed species community. A study in Brazil investigating grazing effects on weed seedlings in NT systems (Schuster et al., 2016) demonstrated that grazing intensity played a key role in weed seed banks. Moderate grazing intensity reduced weed emergence compared with high grazing intensity; however, weed emergence in the non-graze was equivalent to the moderate grazing intensity. No emerged weed seedlings were found in the non-graze (NG) treatment during the winter. This study would suggest that grazing at a light to moderate stocking intensity would have less weed density than high stocking intensity. We can assume that our grazing intensity would be considered high based on the duration of grazing and amount of biomass removed. This could be in part why we observed high weed density in the NT plots compared to MT, however some weed species such as kochia (*Kochia scoparia* (L.)) are also resistant to many herbicides and tillage is an effective weed control method.

Conclusion

Tillage had minimal effects on soil physical properties in our study. This could be caused from the wet and drying cycle between sampling time, limiting grazing to only when field conditions were drier, and not sampling heavy traffic areas. Minimal tillage decreased BD, MWDWSA, MWDDA and increased WEF. Tillage did not affect penetration resistance or infiltration rate. Minimal tillage had little to no effect on soil chemical properties, other than decreased soil pH with NT. Weed density was reduced with MT, although tillage did not affect weed species abundance. Minimum tillage produced equal or greater initial forage biomass, but after grazing and regrowth there was no difference between tillage treatments. Forage nutritive value including CP, NDFD, TDN greater and lower ADF, NDF and UNDF in the spring compared to summer. Crude protein, NDF, UNDF was lower under NT compared to MT, however, NT had higher NDFD compared to MT in 2022 but overall averages was not significantly different between tillage treatments. Weed density can be reduced with tillage in cropping systems. From the results of this study, we concluded to accept our hypothesis and suggest MT could be used in annual forage grazing systems with minimal negative effects soil physical and chemical properties while reducing weed density.

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Tables

Table 2.1 Monthly precipitation from 2019 to 2022 near Jetmore, KS.

Month[a]	Precipitation				
	2019	2020	2021	2022	30-yr average
	mm				
January	17	28	8	14	15
February	19	37	2	1	18
March	29	17	112	33	40
April	8	5	17	3	49
May	202	59	105	51	82
June	96	70	61	55	83
July	23	138	32	66	89
August	67	38	44	10	78
September	3	14	35	42	46
October	40	10	38	0	52
November	8	42	10	5	18
December	35	13	0	4	20
Annual	547	470	465	283	590

Data from Kansas Mesonet (Kansas Mesonet)

Table 2.2 Time, tillage, and soil depth effects on bulk density in grazed winter triticale in the 0-5 cm and 5-15 cm soil depths in 2020, 2021, and 2022 near Jetmore, KS

Factor[a]	**2020**	**2021**	**2022**	**Average**
	g cm^{-3}			
Time × Tillage × Depth				
Pre-NT-0-5	1.22	1.40	1.15	1.25
Post-NT-0-5	1.32	1.36	0.93	1.13
Pre-MT-0-5	1.16	1.17	1.08	1.20
Post-MT-0-5	1.28	1.09	0.85	1.06
Pre-NT-5-15	1.35	1.43	1.36	1.40
Post-NT-5-15	1.41	1.35	1.41	1.38
Pre-MT-5-15	1.38	1.35	1.30	1.37
Post-MT-5-15	1.38	1.33	1.31	1.34
P>F	0.3259	0.4273	0.4213	0.9012
Time × Depth				
Pre-0-5	1.19	1.38 a[b]	1.11	1.23
Post-0-5	1.30	1.13 b	0.89	1.10
Pre-5-15	1.36	1.39 a	1.38	1.38
Post-5-15	1.40	1.34 a	1.36	1.36
P>F	0.1397	0.0010	0.4298	0.3327
Tillage × Depth				
NT-0-5	1.27	1.29	1.04	1.20
MT-0-5	1.22	1.23	0.97	1.13
NT-5-15	1.38	1.39	1.38	1.39
MT-5-15	1.38	1.34	1.36	1.35
P>F	0.3126	0.8995	0.5500	0.5662
Time × Tillage				
Pre-NT	1.28	1.42	1.25	1.33
Post-NT	1.37	1.26	1.17	1.26
Pre-MT	1.27	1.36	1.24	1.29
Post-MT	1.33	1.21	1.08	1.20
P>F	0.6673	0.8490	0.2917	0.6649
Time				
Pre-till	1.28 b	1.39 a	1.25	1.31 a
Post-till	1.35 a	1.24 b	1.13	1.23 b
P>F	0.0058	<.0001	0.3534	0.1705
Depth				
0-5 cm	1.24 b	1.26 b	1.00 b	1.16 b
5-15 cm	1.38 a	1.37 a	1.37 a	1.37 a
P>F	<.0001	0.0003	0.0064	0.0001
Tillage				
NT	1.33	1.34	1.21	1.29 a
MT	1.30	1.28	1.16	1.24 b
P>F	0.2707	0.0507	0.1767	0.0094

[a] Pre=Pre-till, Post=Post-till, NT=No-tillage, MT=Minimal tillage

[b] Values within a factor within column followed by the same letter are not different at α = 0.05.

Table 2.3 Time and tillage effects on water stable aggregate mean weight diameter (MWDWSA) in grazed winter triticale in the 0-5 cm soil depth in 2020, 2021, and 2022 near Jetmore, KS.

Factor[a]	2020	2021	2022	Average
	mm			
Time × Tillage				
Pre-NT	1.01	0.98	0.43 c[b]	0.81
Post-NT	1.78	1.64	0.98 a	1.48
Pre-MT	0.91	0.78	0.34 c	0.70
Post-MT	1.86	1.00	0.58 b	1.10
P>F	0.7976	0.1900	0.0072	0.3676
Time				
Pre-till	0.96 b	0.88	0.39 b	0.75 b
Post-till	1.82 a	1.32	0.78 a	1.29 a
P>F	0.0086	0.1106	<.0001	0.0001
Tillage				
NT	1.40	1.31 a	0.71 a	1.15
MT	1.39	0.90 b	0.46 b	0.90
P>F	0.9744	0.0251	0.0004	0.0976

[a] Pre=Pre-till, Post=Post-till, NT=No-tillage, MT=Minimal tillage

[b] Values within a factor within column followed by the same letter are not different at α = 0.05.

Table 2.4 Sampling time and tillage effects on water stable aggregate size distribution in grazed winter triticale near Jetmore, KS.

Factor[a]		**8- to 2-mm**	**2- to 0.25-mm**	**<0.25-mm**
		%	%	%
2020	Time × Tillage			
	Pre-NT	11.64	55.40	33.20
	Post-NT	29.14	34.27	35.45
	Pre-MT	9.77	50.55	39.88
	Post-MT	32.58	26.20	44.40
	P>F	0.6948	0.7627	0.9064
	Time			
	Pre-till	10.71 b	52.98 a	36.54
	Post-till	30.86 a	30.24 b	39.92
	P>F	0.0021	0.0072	0.6998
	Tillage			
	NT	20.39	44.84	34.32
	MT	21.18	38.38	42.14
	P>F	0.9077	0.2448	0.4258
2021	Time × Tillage			
	Pre-NT	13.85	25.88	60.29
	Post-NT	27.06	26.06	46.95
	Pre-MT	10.33	22.97	66.74
	Post-MT	15.05	21.65	63.33
	P>F	0.2213	0.7313	0.1790
	Time			
	Pre-till	12.09	24.42	63.51
	Post-till	21.05	23.86	55.14
	P>F	0.1204	0.8341	0.1299
	Tillage			
	NT	20.45 a	25.97	53.62 b
	MT	12.69 b	22.31	65.03 a
	P>F	0.0397	0.1198	0.0085
2022	Time × Tillage			
	Pre-NT	3.18 c	22.60 b	74.23 ab
	Post-NT	12.64 a	35.28 a	52.07 c
	Pre-MT	1.73 c	21.86 b	76.36 a
	Post-MT	6.12 b	25.14 b	68.90 b
	P>F	0.0158	0.0482	0.0105
	Time			
	Pre-till	2.46 b	22.23 b	75.29 a
	Post-till	9.38 a	30.21 a	60.48 b
	P>F	<.0001	0.0055	<.0001
	Tillage			
	NT	7.91 a	28.94 a	63.15 b
	MT	3.93 b	23.50 b	72.63 a
	P>F	0.0012	0.0268	0.0025

[a] Pre=Pre-till, Post=Post-till, NT=No-tillage, MT=Minimal tillage

[b] Values within a factor within column followed by the same letter are not different at α = 0.05.

Table 2.5 Time and tillage effects on dry stable aggregate mean weight diameter (MWDDA) in grazed winter triticale in the 0-5 cm soil depth in 2021 and 2022 near Jetmore, KS

Factor[a]	2021	2022	Average
	mm		
Time × Tillage			
Pre-NT	6.27	3.34	4.83
Post-NT	6.41	5.29	5.84
Pre-MT	5.82	2.30	4.09
Post-MT	5.60	4.17	4.87
P>F	0.6441	0.9327	0.6809
Time			
Pre-till	6.04	2.82 b[b]	4.46
Post-till	6.01	4.73 a	5.36
P>F	0.9546	0.0127	0.0588
Tillage			
NT	6.34	4.31 a	5.33 a
MT	5.71	3.24 b	4.48 b
P>F	0.1247	0.0245	0.0060

[a] Pre=Pre-till, Post=Post-till, NT=No-tillage, MT=Minimal tillage

[b] Values within a factor within column followed by the same letter are not different at α = 0.05.

Table 2.6 Time and tillage effects on dry stable aggregate size distribution in grazed winter triticale for Jetmore KS.

Factor[α]		19- to 6.3-mm	6.3- to 2.0-mm	2.0- to 0.84-mm	0.84- to 0.42-mm	<0.42 mm
			%			
2021	Time × Tillage					
	Pre-NT	38.86	27.29	12.70	7.40	16.52 ba
	Post-NT	39.26	28.40	12.46	7.44	12.14 b
	Pre-MT	34.87	27.87	13.00	7.81	18.36 ba
	Post-MT	33.98	25.11	11.86	8.01	20.94 a
	P>F	0.8662	0.4586	0.5111	0.8434	0.0111
	Time					
	Pre-till	36.86	27.58	12.85	7.61	17.44
	Post-till	36.62	26.75	12.16	7.72	16.54
	P>F	0.9651	0.7414	0.2056	0.9120	0.9273
	Tillage					
	NT	39.06	27.84	12.58	7.42	14.33 b
	MT	34.42	26.49	12.43	7.91	19.65 a
	P>F	0.2438	0.6018	0.8245	0.2213	0.0009
2022	Time × Tillage					
	Pre-NT	15.72	23.12	17.42	13.15	30.62
	Post-NT	31.53	23.56	15.43	8.39	20.96
	Pre-MT	9.94	15.92	13.60	14.48	46.12
	Post-MT	24.18	19.04	13.17	9.50	33.97
	P>F	0.8232	0.2321	0.2184	0.9101	0.5542
	Time					
	Pre-till	12.83 b	19.52	15.51	13.81 a	38.37 a
	Post-till	27.85 a	21.30	14.30	8.95 b	27.47 b
	P>F	0.0215	0.3909	0.5419	0.0012	0.0047
	Tillage					
	NT	23.62	23.34 a	16.42 a	10.77	25.79 b
	MT	17.06	17.48 b	13.39 b	11.99	40.05 a
	P>F	0.0859	0.0003	0.0006	0.2232	<.0001
Average	Time × Tillage					
	Pre-NT	26.39	25.23	15.06	9.91	23.83
	Post-NT	35.93	25.97	14.02	7.69	16.87
	Pre-MT	21.75	22.02	13.37	10.77	32.51
	Post-MT	29.53	21.94	12.66	8.55	27.64
	P>F	0.7283	0.8157	0.7873	0.9975	0.5780
	Time					
	Pre-till	24.07	23.63	14.21	10.34	28.17
	Post-till	32.73	23.95	13.34	8.12	22.26
	P>F	0.4643	0.9048	0.4999	0.5920	0.9998
	Tillage					
	NT	31.16 a	25.60 a	14.54 a	8.80	20.35 b
	MT	25.64 b	21.98 b	13.02 b	9.66	30.08 a
	P>F	0.0371	0.0464	0.0207	0.0972	<.0001

[α] Pre=Pre-till, Post=Post-till, NT=No-tillage, MT=Minimal tillage

[b] Values within a factor within column followed by the same letter are not different at α = 0.05.

Table 2.7 Time and tillage effects on wind erodible fraction (WEF) in grazed winter triticale in the 0-5 cm soil depth in 2020, 2021, and 2022 near Jetmore, KS

Factor[a]	**2021**	**2022**	**Average**
		%	
Time × Tillage			
Pre-NT	23.90 ab[b]	43.75	32.37
Post-NT	19.28 b	29.29	24.63
Pre-MT	26.13 ab	60.56	42.00
Post-MT	28.85 a	43.40	36.35
P>F	0.0191	0.6333	0.5085
Time			
Pre-till	25.01	52.15 a	37.18 a
Post-till	24.07	36.34 b	30.49 b
P>F	0.9185	0.0021	0.0225
Tillage			
NT	21.59 b	36.52 b	28.50 b
MT	27.49 a	51.98 a	39.18 a
P>F	0.0013	0.0003	<.0001

[a] Pre=Pre-till, Post=Post-till, NT=No-tillage, MT=Minimal tillage

[b] Values within a factor within column followed by the same letter are not different at α = 0.05.

Table 2.8 Time and tillage effects on penetration resistance in grazed winter triticale in 2021 and 2022 near Jetmore, KS

Factor[a]	2021	2022	Average
	MPa cm^{-2}		
Time × Tillage			
Pre-NT	.	0.99	.
Post-NT	1.82	0.91	1.36
Pre-MT	.	1.05	.
Post-MT	1.69	0.95	1.33
P>F	0.1568	0.8045	0.5027
Time			
Pre-till	.	1.02	.
Post-till	.	0.93	.
P>F		0.0720	
Tillage			
NT	.	0.95	.
MT	.	1.00	.
P>F		0.1692	

[a] Pre=Pre-till, Post=Post-till, NT=No-tillage, MT=Minimal tillage

[b] Values within a factor within column followed by the same letter are not different at α = 0.05.

Table 2.9 Tillage effects on soil sorptivity, time to run-off (TTR), and infiltration rate in grazed winter triticale in 2021 and 2022 near Jetmore, KS

Factor[a]	**Sorptivity**	**TTR**	**Infiltration rate**
	— cm min$^{-0.5}$—	min	cm hr^{-1}
2021			
Tillage			
NT	1.32	3.31	.
MT	1.46	4.20	.
P>F	0.3555	0.1477	.
2022			
Tillage			
NT	1.39 a[b]	6.31	5.07
MT	1.18 b	5.79	5.68
P>F	0.0160	0.6159	0.7134
Average			
Year × Tillage			
2021-NT	1.32	3.31	.
2021-MT	1.46	4.23	.
2022-NT	1.41	6.59	.
2022-MT	1.17	5.67	.
P>F	0.1002	0.2195	
Year			
2021	1.39	3.77 b	.
2022	1.29	6.13 a	.
P>F	0.3632	0.0023	
Tillage			
NT	1.37	4.95	.
MT	1.32	4.95	.
P>F	0.6555	0.9998	

[a] NT=No-tillage, MT=Minimal tillage, TTR= Time to run-off

[b] Values within a factor within column followed by the same letter are not different at $\alpha = 0.05$.

Table 2.10 Time, tillage, and soil depth effects on fixed depth SOC stocks in grazed winter triticale in the 0-5 cm and 5-15 cm soil depths in 2020, 2021, and 2022 near Jetmore, KS.

Factor[a]	2020	2021	2022	Average
	Mg ha^{-1}			
Time × Tillage × Depth				
Pre-NT-0-5	12.51 d[b]	13.64	11.86	12.76
Post-NT-0-5	11.25 d	9.33	9.22	9.73
Pre-MT-0-5	10.37 d	13.76	10.93	11.70
Post-MT-0-5	11.01 d	9.25	6.91	8.85
Pre-NT-5-15	19.39 b	20.81	19.57	19.90
Post-NT-5-15	18.07 bc	17.41	16.90	17.52
Pre-MT-5-15	23.30 a	19.88	20.90	21.28
Post-MT-5-15	17.02 c	18.37	16.07	17.12
P>F	0.0125	0.4229	0.5540	0.2286
Time × Depth				
Pre-0-5	11.44 c	13.70	11.39	12.23
Post-0-5	11.13 c	9.29	8.06	9.29
Pre-5-15	21.35 a	20.35	20.23	20.59
Post-5-15	17.54 b	17.89	16.49	17.32
P>F	0.0020	0.0872	0.9202	0.7328
Tillage × Depth				
NT-0-5	11.88 b	11.49	10.54 b	11.25
MT-0-5	10.69 b	11.51	8.92 c	10.27
NT-5-15	18.73 a	19.11	18.23 a	18.71
MT-5-15	20.16 a	19.13	18.48 a	19.20
P>F	0.0500	0.9983	0.0080	0.0715
Time × Tillage				
Pre-NT	15.95	17.23	15.71 ab	16.33
Post-NT	14.66	13.37	13.06 ab	13.62
Pre-MT	16.83	16.82	15.91 a	16.49
Post-MT	14.66	13.81	11.49 b	12.99
P>F	0.2371	0.5122	0.0115	0.3211
Time				
Pre-till	16.39 a	17.02 a	15.81	16.41 a
Post-till	14.34 b	13.59 b	12.27	13.29 b
P>F	0.0004	<.0001	0.1002	<.0001
Depth				
0-5 cm	11.28 b	11.50 b	9.73 b	10.76 b
5-15 cm	19.45 a	19.12 a	18.36 a	18.96 a
P>F	<.0001	<.0001	0.0004	<.0001
Tillage				
NT	15.31	15.30	14.39 a	14.97
MT	15.42	15.32	13.70 b	14.72
P>F	0.8553	0.9759	0.0436	0.5322

[a] Pre=Pre-till, Post=Post-till, NT=No-tillage, MT=Minimal tillage

[b] Values within a factor within column followed by the same letter are not different at α = 0.05.

Table 2.11 Time, tillage, and soil depth effects on equivalent soil mass SOC Mg ha^{-1} in grazed winter triticale in the 0-5 cm and 5-15 cm soil depths in 2020, 2021, and 2022 near Jetmore, KS

Factor[a]	**2020**	**2021**	**2022**	**Average**
	Mg ha^{-1}			
Time × Tillage × Depth				
Pre-NT-0-5	5.52	5.15	5.65	5.44
Post-NT-0-5	4.52	4.25	4.83	4.53
Pre-MT-0-5	4.58	5.32	5.41	5.10
Post-MT-0-5	4.58	4.43	4.31	4.44
Pre-NT-5-15	16.39	16.94	16.39	16.57
Post-NT-5-15	14.87	14.94	14.58	14.81
Pre-MT-5-15	17.03	17.08	17.42	18.25
Post-MT-5-15	14.31	16.13	14.26	14.85
P>F	0.0624	0.4411	0.0804	0.0513
Time × Depth				
Pre-0-5	5.04 c[b]	5.24	5.53 c	5.27 c
Post-0-5	4.55 c	4.34	4.57 d	4.49 d
Pre-5-15	18.34 a	17.01	16.90 a	17.41 a
Post-5-15	14.59 b	15.53	14.42 b	14.83 b
P>F	0.0031	0.2638	0.0010	0.0002
Tillage × Depth				
NT-0-5	5.02	4.70	5.24 b	4.99 c
MT-0-5	4.57	4.88	4.86 b	4.77 c
NT-5-15	15.63	15.94	15.48 a	15.69 b
MT-5-15	17.30	16.60	15.84 a	16.55 a
P>F	0.0639	0.4644	0.0195	0.0273
Time × Tillage				
Pre-NT	10.96	11.04	11.02 a	11.00
Post-NT	9.70	9.60	9.70 b	9.67
Pre-MT	12.43	11.20	11.42 a	11.67
Post-MT	9.44	10.28	9.28 b	9.65
P>F	0.1255	0.4362	0.0101	0.1511
Time				
Pre-till	11.69 a	11.12 a	11.22 a	11.34 a
Post-till	9.57 b	9.94 b	9.49 b	9.66 b
P>F	0.0003	0.0001	<.0001	<.0001
Depth				
0-5 cm	4.80 b	4.79 b	5.05 b	4.88 b
5-15 cm	16.47 a	16.27 a	15.66 a	16.12 a
P>F	<.0001	<.0001	<.0001	<.0001
Tillage				
NT	10.33	10.32	10.36	10.34
MT	10.93	10.74	10.35	10.66
P>F	0.2758	0.2170	0.9439	0.1826

[a] Pre=Pre-till, Post=Post-till, NT=No-tillage, MT=Minimal tillage

[b] Values within a factor within column followed by the same letter are not different at α = 0.05.

Table 2.12 Time, tillage, and soil depth effects on SOC concentrations in grazed winter triticale in the 0-5 cm and 5-15 cm soil depths in 2020, 2021 and 2022 near Jetmore, KS.

Factor[α]	2020	2021	2022	Average
	g kg^{-1}			
Time × Tillage × Depth				
Pre-NT-0-5	20.85 a	19.50	21.35	20.57
Post-NT-0-5	17.17 b	16.03	18.18	17.12
Pre-MT-0-5	17.09 b	20.08	20.51	19.24
Post-MT-0-5	17.24 b	16.84	16.14	16.74
Pre-NT-5-15	14.10 bc	14.53	14.08	14.23
Post-NT-5-15	12.77 c	12.87	12.53	12.73
Pre-MT-5-15	17.31 b	14.69	14.94	15.65
Post-MT-5-15	12.27 c	13.77	12.23	12.74
P>F	0.0301	0.8126	0.9578	0.0971
Time × Depth				
Pre-0-5	18.97	19.79 a	20.93 a	19.90
Post-0-5	17.21	16.43 b	17.16 b	16.93
Pre-5-15	15.70	14.61 c	14.51 c	14.94
Post-5-15	12.52	13.32 c	12.38 d	12.73
P>F	0.4232	0.0410	0.0003	0.2876
Tillage × Depth				
NT-0-5	19.01	17.76	19.76 a	18.85 a
MT-0-5	17.16	18.46	18.33 b	17.99 a
NT-5-15	13.44	13.70	13.30 c	13.48 b
MT-5-15	14.79	14.23	13.58 c	14.20 b
P>F	0.0614	0.8798	<.0001	0.0269
Time × Tillage				
Pre-NT	17.47	17.01	17.71 a	17.40
Post-NT	14.97	14.45	15.35 b	14.93
Pre-MT	17.20	17.39	17.73 a	17.45
Post-MT	14.75	15.31	14.18 c	14.74
P>F	0.9745	0.6576	0.0023	0.7384
Time				
Pre-till	17.34 a	17.20 a	17.72 a	17.42 a
Post-till	14.86 b	14.88 b	14.77 b	14.83 b
P>F	0.0095	<.0001	<.0001	<.0001
Depth				
0-5 cm	18.09 a	18.11 a	19.04 a	18.42 a
5-15 cm	14.11 b	13.96 b	13.44 b	13.84 b
P>F	0.0002	<.0001	<.0001	<.0001
Tillage				
NT	16.22	15.73	16.53 a	16.16
MT	15.98	16.35	15.96 b	16.09
P>F	0.7632	0.2634	0.0027	0.8442

[α] Pre=Pre-till, Post=Post-till, NT=No-tillage, MT=Minimal tillage

[b] Values within a factor within column followed by the same letter are not different at α = 0.05.

Table 2.13 Time, tillage, and soil depth effects on NO_3^--N values in grazed winter triticale in the 0-5 cm and 5-15 cm soil depths in 2020, 2021, and 2022 near Jetmore, KS.

Factor[a]	2020	2021	2022	Average
	g kg^{-1}			
Time × Tillage × Depth				
Pre-NT-0-5	5.66	4.87	26.84	13.06
Post-NT-0-5	42.38	26.75	25.28	31.47
Pre-MT-0-5	2.76	3.30	27.21	11.93
Post-MT-0-5	37.11	33.10	41.58	37.20
Pre-NT-5-15	3.89	1.87	10.93	5.56
Post-NT-5-15	11.25	10.06	11.87	10.92
Pre-MT-5-15	2.64	1.55	17.07	7.11
Post-MT-5-15	12.88	17.28	21.82	17.06
P>F	0.5608	0.9650	0.0545	0.6888
Time × Depth				
Pre-0-5	4.21 c[b]	4.09 c	27.02	12.50 b
Post-0-5	39.75 a	29.93 a	33.43	34.33 a
Pre-5-15	3.27 c	1.71 c	14.00	6.33 b
Post-5-15	12.07 b	13.67 b	16.84	13.99 b
P>F	<.0001	0.0061	0.4048	0.0306
Tillage × Depth				
NT-0-5	24.02	15.81	26.06	22.26
MT-0-5	19.93	18.20	34.39	24.57
NT-5-15	7.57	5.97	11.40	8.24
MT-5-15	7.76	9.41	19.45	12.09
P>F	0.3469	0.8066	0.9234	0.5872
Time × Tillage				
Pre-NT	4.78	3.37	18.88 c	9.31 c
Post-NT	26.82	18.41	18.57 c	21.19 b
Pre-MT	2.70	2.43	22.14 b	9.52 c
Post-MT	25.00	25.19	31.70 a	27.13 a
P>F	0.9543	0.0835	0.0033	0.0465
Time				
Pre-till	3.74 a	2.90 b	20.51 b	9.42 b
Post-till	25.91 b	21.80 a	25.14 a	24.16 a
P>F	<.0001	<.0001	0.0388	<.0001
Depth				
0-5 cm	21.98 a	17.01 a	30.23 a	23.41 a
5-15 cm	7.67 b	7.69 b	15.42 b	10.16 b
P>F	<.0001	0.0005	<.0001	<.0001
Tillage				
NT	15.80	10.89	18.73 b	15.25 b
MT	13.85	13.81	26.92 a	18.33 a
P>F	0.3900	0.1848	<.0001	0.0326

[a] Pre=Pre-till, Post=Post-till, NT=No-tillage, MT=Minimal tillage

[b] Values within a factor within column followed by the same letter are not different at α = 0.05.

Table 2.14 Time, tillage, and soil depth effects on NH_4^+-N in grazed winter triticale in the 0-5 cm and 5-15 cm soil depths in 2020 and 2022 near Jetmore, KS.

Factor[a]	2020	2021	2022
	g kg^{-1}		
Time × Tillage × Depth			
Pre-NT-0-5	22.72	.	65.05 b[b]
Post-NT-0-5	.	.	8.75 c
Pre-MT-0-5	7.27	.	87.22 a
Post-MT-0-5	.	.	62.32 b
Pre-NT-5-15	9.80	.	7.57 c
Post-NT-5-15	.	.	4.12 c
Pre-MT-5-15	6.45	.	11.02 c
Post-MT-5-15	.	.	8.67 c
P>F			0.0208
Time × Depth			
Pre-0-5	15.00	.	76.14
Post-0-5	.	.	35.54
Pre-5-15	8.13	.	9.30
Post-5-15	.	.	6.40
P>F		.	0.9995
Tillage × Depth			
NT-0-5		.	36.90 a
MT-0-5		.	74.77 a
NT-5-15		.	5.85 b
MT-5-15		.	9.85 b
P>F	0.3909	.	<.0001
Time × Tillage			
Pre-NT	16.26	.	36.31 b
Post-NT	.	.	6.44 c
Pre-MT	6.86	.	49.12 a
Post-MT	.	.	35.50 b
P>F		.	0.0140
Time			
Pre-till	.	.	42.72
Post-till	.	.	20.97
P>F		.	0.9994
Depth			
0-5 cm	.	.	55.84
5-15 cm	.	.	7.85
P>F	0.2286	.	0.9987
Tillage			
NT	.	.	21.37 b[b]
MT	.	.	42.31 a
P>F	0.1957	.	<.0001

[a] Pre=Pre-till, Post=Post-till, NT=No-tillage, MT=Minimal tillage

[b] Values within a factor within column followed by the same letter are not different at α = 0.05.

Table 2.15 Time, tillage, and soil depth effects on phosphorus (P) ppm in grazed winter triticale in the 0-5 cm and 5-15 cm soil depths in 2020, 2021, and 2022 near Jetmore, KS.

Factor[a]	**2020**	**2021**	**2022**	**Average**
	g kg^{-1}			
Time × Tillage × Depth				
Pre-NT-0-5	64	83	106	85
Post-NT-0-5	88	60	75	73
Pre-MT-0-5	56	86	96	80
Post-MT-0-5	82	73	59	70
Pre-NT-5-15	22	29	39	31
Post-NT-5-15	27	23	19	22
Pre-MT-5-15	32	43	45	40
Post-MT-5-15	29	38	15	27
P>F	0.6640	0.7303	0.7333	0.5489
Time × Depth				
Pre-0-5	60	85	101	82
Post-0-5	85	66	67	72
Pre-5-15	27	36	42	35
Post-5-15	28	31	17	24
P>F	0.1699	0.3522	0.5924	0.9832
Tillage × Depth				
NT-0-5	76	72	90 a[b]	79
MT-0-5	69	80	78 b	75
NT-5-15	24	26	29 c	26
MT-5-15	30	40	30 c	33
P>F	0.2661	0.6548	0.0093	0.0760
Time × Tillage				
Pre-NT	43	56	72	58
Post-NT	57	41	47	48
Pre-MT	44	65	71	60
Post-MT	55	56	37	48
P>F	0.8112	0.6378	0.0974	0.7893
Time				
Pre-till	44	60	72 a	59
Post-till	56	49	42 b	48
P>F	0.1424	0.1133	0.0009	0.0997
Depth				
0-5 cm	73 a	76 a	84 a	77 a
5-15 cm	27 b	33 b	30 b	30 b
P>F	<.0001	<.0001	<.0001	<.0001
Tillage				
NT	50	49	60 a	53
MT	50	60	54 b	54
P>F	0.9131	0.0958	0.0246	0.6395

[a] Pre=Pre-till, Post=Post-till, NT=No-tillage, MT=Minimal tillage

[b] Values within a factor within column followed by the same letter are not different at α = 0.05.

Table 2.16 Time, tillage, and soil depth effects on K ppm in grazed winter triticale in the 0-5 cm and 5-15 cm soil depths in 2020, 2021, and 2022 near Jetmore, KS.

Factor[a]	**2020**	**2021**	**2022**	**Average[†]**
	g kg^{-1}			
Time × Tillage × Depth				
Pre-NT-0-5	.	685	1117	900
Post-NT-0-5	615	494	584	557
Pre-MT-0-5	.	717	1025	869
Post-MT-0-5	584	518	577	551
Pre-NT-5-15	.	332	491	403
Post-NT-5-15	275	294	282	281
Pre-MT-5-15	.	393	501	438
Post-MT-5-15	285	378	267	304
P>F		0.8315	0.3656	0.6912
Time × Depth				
Pre-0-5	.	701 a[b]	1071 a	884
Post-0-5	599	506 b	580 b	554
Pre-5-15	.	362 c	496 b	421
Post-5-15	280	336 c	275 c	293
P>F		0.0207	0.0011	0.0877
Tillage × Depth				
NT-0-5	.	589	851	729
MT-0-5	.	618	801	710
NT-5-15	.	313	387	342
MT-5-15	.	385	384	371
P>F		0.5630	0.4438	0.4172
Time × Tillage				
Pre-NT	.	508	804	652
Post-NT	445	394	433	419
Pre-MT	.	555	763	653
Post-MT	435	448	422	428
P>F		0.9243	0.6247	0.7650
Time				
Pre-till	.	532 a	783 a	652 a
Post-till	.	421 b[b]	427 b	423 b
P>F		0.0036	<.0001	0.0006
Depth				
0-5 cm	.	603 a	826 a	719 a
5-15 cm	.	349 b	385 b	357 b
P>F		<.0001	<.0001	<.0001
Tillage				
NT	.	451	619	536
MT	.	501	592	540
P>F		0.1924	0.3934	0.7198

[a] Pre=Pre-till, Post=Post-till, NT=No-tillage, MT=Minimal tillage

[b] Values within a factor within column followed by the same letter are not different at α = 0.05.

[†] Average is based on 2021 and 2022 values

Table 2.17 Tillage and soil depth effects on Zn, Fe, Mn, Cu, and pH values in grazed winter triticale in the 0-5 cm and 5-15 cm soil depths in 2020 near Jetmore, KS.

Factor[a]	**Zn**	**Fe**	**Mn**	**Cu**	**pH**
	g kg^{-1}				
Tillage × Depth					
NT-0-5	1.41	40.00	65.22	1.34	5.87
MT-0-5	1.20	36.68	48.89	1.27	5.98
NT-5-15	0.54	35.67	48.99	1.37	5.76
MT-5-15	0.89	36.44	48.78	1.39	5.91
P>F	0.1806	0.5309	0.1073	0.4718	0.6394
Depth					
0-5 cm	1.30 a[b]	38.34	57.06 a	1.31	5.93 a
5-15 cm	0.71 b	36.05	48.89 b	1.38	5.83 b
P>F	0.0432	0.5152	0.0336	0.4019	0.0151
Tillage					
NT	0.97	37.84	57.10	1.36	5.81 b
MT	1.04	36.56	48.84	1.33	5.94 a
P>F	0.7251	0.6931	0.1018	0.6188	0.0249

[a] Pre=Pre-till, Post=Post-till, NT=No-tillage, MT=Minimal tillage

[b] Values within a factor within column followed by the same letter are not different at α = 0.05.

Table 2.18 Time and tillage effects on triticale forage yield in grazed winter triticale in 2021 and 2022 near Jetmore, KS.

Factor[a]	**2020-2021**	**2021-2022**	**Average**
	DM kg ha^{-1}		
Time × Tillage			
Spring-NT	810	821 b	852
Summer-NT	2732	472 c	1606
Fall-NT	91	859 b	486
Spring-MT	1055	762 b	876
Summer-MT	2632	390 c	1447
Fall-MT	105	1566 a	846
P>F	0.3575	<.0001	0.2101
Time			
Spring	932 b[b]	791 b	864
Summer	2682 a	431 c	1527
Fall	98 c	1212 a	666
P>F	<.0001	<.0001	0.3274
Tillage			
NT	1211	717 b	981
MT	1264	906 a	1056
P>F	0.5939	0.0050	0.5338

[a] NT=No-tillage, MT=Minimal tillage

[b] Values within a factor within column followed by the same letter are not different at α = 0.05.

Table 2.19 Time and tillage effects on forage nutritive values crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), undigested neutral detergent fiber (UNDF), neutral detergent fiber digestibility (NDFD), and total digestible nutrients (TDN) in grazed winter triticale in 2021 and 2022 near Jetmore, KS.

Factor[α]		CP	ADF	NDF	UNDF	NDFD	TDN
		%					
2021	Time × Tillage						
	Spring-NT	25.72	22.62	35.09	5.15	84.12	77.14
	Summer-NT	15.00	37.51	52.60	15.11	69.14	60.48
	Spring-MT	25.84	23.15	36.49	5.23	84.80	76.45
	Summer-MT	16.34	36.88	51.74	14.52	70.77	61.38
	P>F	0.3539	0.4183	0.2403	0.4579	0.5573	0.3247
	Time						
	Spring	25.78 a	22.88 b	35.79 b	5.19 b	84.46 a	76.80 a
	Summer	15.67 b	37.19 a	52.17 a	14.82 a	69.95 b	60.93 b
	P>F	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
	Tillage						
	NT	20.36	30.06	43.84	10.13	76.63	68.81
	MT	21.09	30.02	44.12	9.88	77.78	68.92
	P>F	0.2767	0.9503	0.7736	0.5699	0.1631	0.8977
2022	Time × Tillage						
	Spring-NT	18.48 b	28.75	41.24	8.86 c	77.07	70.47
	Summer-NT	11.75 c	36.83	51.90	13.77 b	71.82	61.30
	Spring-MT	22.58 a	27.92	41.87	9.14 c	76.89	71.29
	Summer-MT	11.57 c	36.96	53.83	14.87 a	70.34	61.26
	P>F	0.0259	0.2658	0.2118	0.0282	0.0541	0.3959
	Time						
	Spring	20.53 a	28.34 b	41.55 b	9.00 b	76.98 a	70.88 a
	Summer	11.66 b	36.90 a	52.87 a	14.32 a	71.08 b	61.28 b
	P>F	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
	Tillage						
	NT	15.12 b	32.79	46.57 b	11.32 b	74.45 a	65.88
	MT	17.07 a	32.44	47.85 a	12.01 a	73.61 b	66.27
	P>F	0.0400	0.4154	0.0176	0.0006	0.0156	0.4426

[α] NT=No-tillage, MT=Minimal tillage CP=Crude protein, ADF=Acid detergent fiber, NDF=Neutral detergent fiber, UNDF= Undigested NDF organic matter after 240 hours, NDFD= NDF digestibility after 240 hours, TDN=Total digestible nutrients

[b] Values within a factor within column followed by the same letter are not different at α = 0.05.

Table 2.20 Time and tillage effects on average forage nutritive values crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), undigested neutral detergent fiber (UNDF), neutral detergent fiber digestibility (NDFD), and total digestible nutrients (TDN) in grazed winter triticale near Jetmore, KS.

Factor[α]		CP	ADF	NDF	UNDF	NDFD	TDN
		%					
Average	Time × Tillage						
	Spring-NT	21.71	26.01	38.69	7.45	79.56	73.36
	Summer-NT	13.87	36.62	51.76	14.11	70.54	61.53
	Spring-MT	23.21	26.17	39.67	7.84	79.33	73.17
	Summer-MT	13.63	37.06	52.91	14.63	70.82	61.17
	P>F	0.3628	0.7802	0.8888	0.8238	0.6646	0.8782
	Time						
	Spring	22.46 a	26.09 b	39.18 b	7.64 b	79.45 a	73.27 a
	Summer	13.75 b	36.84 a	52.33 a	14.37 a	70.68 b	61.35 b
	P>F	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
	Tillage						
	NT	17.79	31.32	45.22	10.78	75.05	67.44
	MT	18.42	31.61	46.29	11.24	75.08	67.17
	P>F	0.5055	0.5463	0.0724	0.1162	0.9651	0.6274

[α] NT=No-tillage, MT=Minimal tillage CP=Crude protein, ADF=Acid detergent fiber, NDF=Neutral detergent fiber, UNDF= Undigested NDF organic matter after 240 hours, NDFD= NDF digestibility after 240 hours, TDN=Total digestible nutrients

[b] Values within a factor within column followed by the same letter are not different at α = 0.05.

Table 2.21 Time and tillage effects on weed density in grazed winter triticale in 2020, 2021, and 2022 near Jetmore, KS.

Factor[s]	**2020**	**2021**	**2022**	**Average†**
	weeds m^{-2}			
Time × Tillage				
Pre-NT	5.81	62.27 a[b]	25.34 a	43.95 a
Post-NT	.	1.06 b	0.05 b	0.56 b
Pre-MT	4.79	14.01 b	4.27 b	9.30 b
Post-MT	.	0.05 b	0.01 b	0.03 b
P>F		<.0001	<.0001	<.0001
Time				
Pre-till	.	38.14 a	14.80 a	26.62 a
Post-till	.	0.56 b	0.03 b	0.29 b
P>F		0.0035	<.0001	0.0007
Tillage				
NT	.	31.67 a	12.69 a	22.25 a
MT	.	7.03 b	2.14 b	4.66 b
P>F		<.0001	<.0001	<.0001

[s] Pre=Pre-till, Post=Post-till, NT=No-tillage, MT=Minimal tillage

[b] Values within a factor within column followed by the same letter are not different at α = 0.05.

† Average is 2021 and 2022 data only

*No weeds were observed in the post-till in 2020

Table 2.22 Time and tillage effects on the top 5 weed species including: Cheatgrass (CG), Little barley (LB), Henbit (HB), Yellow Mustard (YM) and Large crabgrass (LC) abundance in grazed winter triticale in 2020, 2021, and 2022 near Jetmore, KS.

Factor[a]	CG	LB	HB	YM	LC
	Weed numbers m^{-2}				
2020					
Time × Tillage					
Pre-NT	0.13	2.75	1.18	0.38	.
Pre-MT	0.00	0.24	2.77	0.56	.
P>F					
Time					
Pre-till	0.06	1.49	1.97	0.47	.
P>F					
Tillage					
NT	0.13	2.75 a	1.18	0.38	.
MT	0.00	0.24 b	2.77	0.56	.
P>F	0.3261	0.0030	0.1611	0.5136	
2021					
Time × Tillage					
Pre-NT	24.49 a	20.62 a	3.12	4.79	6.13 a
Post-NT	0.00 b[b]	0.00 b	0.00	0.00	0.04 b
Pre-MT	5.25 b	2.21 b	2.58	1.97	0.00 b
Post-MT	0.00 b	0.00 b	0.00	0.00	0.00 b
P>F	0.0240	0.0007	0.7198	0.1030	0.0007
Time					
Pre-till	14.87	11.41 a	2.85	3.38 a	3.07 a
Post-till	0.00	0.01 b	0.00	0.00 b	0.02 b
P>F	0.0680	0.0111	0.0824	0.0052	0.0385
Tillage					
NT	12.25 a	10.31 a	1.56	2.40	3.08 a
MT	2.63 b	1.10 b	1.29	0.99	0.00 b
P>F	0.0240	0.0007	0.7198	0.1030	0.0006
2022					
Time × Tillage					
Pre-NT	0.33	20.83 a	.	2.75 a	0.00
Post-NT	0.00	0.00 b	.	0.00 b	0.02
Pre-MT	0.08	2.85 b	.	0.92 b	0.00
Post-MT	0.00	0.00 b	.	0.00 b	0.00
P>F	0.1834	<.0001		0.0297	0.1444
Time					
Pre-till	0.20	11.84 a	.	1.84 a	0.00
Post-till	0.00	0.00 b	.	0.00 b	0.01
P>F	0.0958	<.0001		0.0001	0.1243
Tillage					
NT	0.17	10.42 a	.	1.38 a	0.01
MT	0.04	1.42 b	.	0.46 b	0.00
P>F	0.1770	<.0001		0.0301	0.1444

[a] Pre=Pre-till, Post=Post-till, NT=No-tillage, MT=Minimal tillage, CG=Cheatgrass, LB=Little barley, HB=Henbit, YM=Yellow mustard, LC=Large crabgrass

[b] Values within a factor within column followed by the same letter are not different at α = 0.05.

Chapter 3 - Soil properties affected by forage rotation and tillage in semi-arid dryland forage cropping systems

Abstract

Annual forages can be grown more intensively than grain crops, which may have positive benefits on soil health. Our objective was to determine the effects of annual forage crop rotations of varying intensity, length, and tillage on soil physical and chemical properties. Soil measurements were done in 2021 and 2022 in a long-term forage study established in 2012 at the Southwest Research-Extension Center near Garden City, KS. Forage crops were winter triticale [×*Triticosecale Wittm*. ex A. Camus (*Secale ×Triticum*)] (T), forage sorghum [*Sorghum bicolor* (L.) Moench] (FS), and spring oat (*Avena sativa* L.) (O). Tillage treatment was reduced tillage (RT) and no-till (NT). There were six treatments: FS-FS (NT), T/FS-FS-O (NT), T/FS-FS-O (RT), T/FS-FS-FS-O (NT), T/FS-FS-FS-O (RT), T-FS-O (NT). The study was a randomized complete block design with four replications. Bulk density (BD), mean weight diameter of water stable aggregates (MWDWSA), dry aggregate MWD (MWDDA), wind erodible fraction (WEF), total nitrogen (TN) stocks, soil organic carbon stocks (SOC), and soil nutrient including soil nitrates (NO_3^--N), phosphorus (P), and potassium (K) concentrations were measured in 2021, and sorptivity and time to runoff (TTR) was measured in 2021 and 2022, and infiltration rate (IR) was measured only in 2022. Analyses of variance was conducted with six treatments, two depths, and their interaction as fixed effects. A second analysis included only the four treatments that include both NT and RT, to examine the effects of tillage and its interaction with depth as fixed effects. Our findings suggest that forage rotations had minimal effects on soil chemical properties and no effects on physical properties. However, they did have minimal effects on water aggregates size distribution and dry aggregates size distribution.

Introduction

Dryland annual forages in the semi-arid Great Plains are known to be productive and are important to the region where many of the cattle industry resides in the region (Carr et al., 2021). Kansas has approximately 1.09 million ha^{-1} of hay and haylage that includes 275,186 ha^{-1} of alfalfa harvested in 2022 ("USDA/NASS 2021 State Agriculture Overview for Kansas," 2023). Nebraska has 0.89 million ha^{-1} of hay and haylage that includes 325,772 ha^{-1} of alfalfa harvested in 2022 ("USDA/NASS 2021 State Agriculture Overview for Nebraska," 2023). Oklahoma has 1.12 million ha^{-1} of hay that includes 89,031 ha^{-1} harvested of alfalfa ("USDA/NASS 2021 State Agriculture Overview for Oklahoma," 2023). Colorado has 0.46 million ha^{-1} of hay and haylage that includes 246,858 ha^{-1} of alfalfa harvested in 2022 ("USDA/NASS 2022 State Agriculture Overview for Colorado,"). Annual forages can also be grown to increase cropping intensity (Holman et al. 2018, 2021, and 2022). However, few studies have reported how combinations of annual forages and tillage affect soil chemical and physical properties. Integrating annual forages into the cropping system by either haying or grazing could increase water infiltration, soil organic carbon (SOC), nutrient cycling, soil structure, and soil aggregation (Obour et al., 2020; Simon et al., 2021). Replacing fallow with annual forages has improved near-surface soil physical factors in previous research. Blanco-Canqui et al. (2013) observed that replacing fallow with cover crops (CC) in a no-till (NT) wheat (*Triticum aestivum* L.) –fallow reduced the potential for wind and water erosion, improved soil aggregation, and increased soil organic carbon (SOC) after 5-yr. in the semiarid central Great Plains (CGP) (Blanco-Canqui et al., 2013).This indicated that growing CCs during the fallow period can improve soil properties. However, they also observed that continuous wheat was as effective or better than most CCs in reducing wind and water erosion, improving soil aggregation, and increasing SOC. This suggests that intensification of the cropping system alone can improve soil properties.

The CGP are known for periods of significant drought and susceptibility for wind-blown soil erosion. The annual precipitation in Kansas gradually increases west to east, ranging from 305 mm to 610 mm per year in western and central Kansas (Robinson and Nielsen, 2015). Crop rotations in the west are less intensive and include more fallow than rotations in the eastern portion of the state. Crop rotations in the water limited regions of the CGP are mostly winter wheat-fallow or winter wheat-summer crop [ex. Corn (*Zea mays subsp.* Mays), grain sorghum (*Sorghum bicolor* Moench.), or sunflower (*Helianthus annuus* L.)]-fallow (Nielsen and Vigil, 2018). Dryland crop production is prevalent in regions where precipitation accounts for only 20 to 35% of potential evapotranspiration and is made possible through increased crop residues resulting from NT and reduced tillage (RT) systems combined with fallow for storing soil water and reducing evaporation. A challenge for dryland crop producers is determining management practices that utilize annual precipitation and soil moisture most effectively to maximize crop yields, manage weeds, and maintain profits.

Annual forages can be hayed or grazed and used in coordination with perennial pasture when pasture productivity or nutrient content is low (Billman et al., 2021). Annual forages can be integrated into grain cropping systems to help increase crop rotation intensity, reduce water loss from evaporation, and could reduce irrigation from declining aquifers with less water use then grain crops (Zilverberg et al., 2015; Holman et al., 2020; Nielsen et al., 2005). Cool and warm season annual grasses and broadleaf forages can be grown across the CGP. These grasses and broadleaves can be highly productive for producers and potentially profitable. Annual forages when harvested correctly have high nutrient value, being high in crude protein (CP), digestibility, and dry matter production (DM production) (Obour et al., 2019; Holman et al., 2019). The most common forages that are grown in the CGP region are triticale [×*Triticosecale Wittm*. ex A. Camus (*Secale* ×*Triticum*)], wheat, forage sorghum, and oats (*Avena sativa* L.) Forage crops, especially annual cool season grasses, are well adapted to temperate semiarid regions, producing good yields with nutritive values suitable for overwintering cattle in the CGP (Obour et al., 2020; Holman et al., 2018; Holman et al., 2021). Forage sorghum is a warm season forage that is well adapted to the GCP region (Holman et al., 2020). A rotation between cool season and warm season forages can contribute to efficient capture of precipitation and resources available during different seasons of the year. A previous study in Garden City Kansas, showed forage productivity, profitability, and overall nutritive value of warm and cool season forages were improved when grown in rotation (Holman et al., 2020). Integrating forages into the crop rotation could increase profitability and sustainability of dryland crop production in the CGP (Holman et al., 2018 ; Nielsen et al., 2016).

The water demand of annual forages is considerably less than grain production due to additional water use during grain fill for grain crops (Holman et al., 2020; Nielsen et al., 2005). Previous research in the southern Great Plains found that forage systems had greater precipitation use efficiency (PUE) than some grain-only crop rotations (Holman et al., 2020; Nielsen et al., 2006). Holman et al. (2021) investigated the water use and water productivity of different forage rotations in southwest Kansas. They observed that forage sorghum productivity was greater in a non-double crop sequence than a double crop forage sorghum after winter triticale (Holman et al., 2021). The greater productivity, water use, and water productivity for forage sorghum also agrees with results of Bhattarai et al. (2020), who observed greater dry matter accumulation and water use efficiency (WUE) of forage sorghum than pearl millet

[*Pennisetum glaucum* (L.) R. Br.] and corn under dryland. Holman et al. (2021) also concluded that forage rotations with better crop diversity (diversity defined as the number of crop species involved in a crop rotation) are more efficient in utilizing resources compared to continuous forage systems, which have similar productivity but are less efficient. Neal et al. (2011) tested seventeen different types of forage under optimal and deficit irrigation to compare WUE of forges. They observed that under optimal irrigation, there was a three-fold difference in mean annual WUE between forages. Corn, wheat, and sorghum had higher WUE then triticale, spring oats, pearl millet, and Japanese millet (*Echinochloa esculenta* (A. Braun)). The ‘harvested’ forages corn, wheat, triticale, and forage pea (*Pisum sativium* L.) had higher mean WUE than the remaining forages which were tested to simulate grazing. Annual forages under deficit irrigation saw the greatest reduction in WUE for warm season forages, while most of the cool season annuals were not significantly affected by deficit irrigation at the levels imposed. However, Zhang et al. (2018) reported lower water use and water use efficiency for oat and legume forages compared with warm season forage crops in Northwest China. These results were likely affected by growing season environment (timing and amount of precipitation).

While WUE is an important criterion for choosing forages, it is only one factor in a complex system. Choice of forages must be considered on a whole farm basis and should include consideration of yield, nutritive value, cost of production, and risk (Neal et al., 2011). The amount of timing of precipitation is also a critical component of forage yield and increasing cropping system diversity reduces the risk of low production (Holman et al., 2020).

Tillage is often an essential practice used in dryland cropping systems for weed control, reducing surface compaction, and reducing nutrient stratification. Tillage affects soil water storage during the fallow period. Full tillage has been shown to reduce soil water and subsequent crop yield, yet occasional tillage and RT during the fallow period has been shown to have no effect on subsequent winter wheat yield or soil aggregates and helped control herbicide resistant weeds (Obour et al., 2021; Schlegel et al., 2020). By preparing the soil for planting with tillage, farmers were able to establish a better stand of winter wheat (Holman et al., 2021). However, Peterson et al. (2020) showed that tillage can increase wind and water erosion, decrease SOC, decrease soil structure, and decrease SOM.

No-till crop production began in the 1970s, made possible with advancements in herbicides and improved planting equipment. No-till initially reduced the weed emergence period because having weed seed near the soil surface resulted in a shorter weed germination period (Anderson, 2005). However, with time, the development of herbicide resistance has increased the duration of weed germination. Furthermore, NT increased soil surface residue and reduced soil erosion compared to tillage (Blanco-Canqui et al., 2009;Merrill et al., 1999; Zuber et al., 2015). However, low residue production can still result in soil erosion, even in NT systems (Schnarr et al., 2022). Reduced tillage and NT increased soil water storage, allowing cropping systems to be intensified from wheat-fallow to winter wheat-summer crop (corn, grain sorghum, or sunflower)-fallow. Increased cropping intensity benefited producers through improved water and fertilizer use efficiency, increased SOC, additional herbicide options for weed control, and improved profitability. However, over intensifying the cropping system can result in crop failure and increased soil erosion (Holman et al., 2018). Dynamic cropping systems that included annual forages in grain-based rotations improved crop production resilience, while providing protection from climate extremes that are likely to come with climate change (Holman et al., 2018).

There is limited research on the effects of annual forage crop rotation and tillage on soil properties. The objective of this study was to identify annual forage rotation components that have positive effects on soil properties and forage productivity in a dryland cropping system under different tillage systems. Our hypothesis is that increasing annual forage cropping intensity and diversity can produce a greater quantity of forage while improving soil properties compared to less intensive and less diverse annual forage rotations. Further, we hypothesized that soils under NT will have improved soil properties compared with reduced tilled systems.

Materials and methods

Experimental Design

This study was conducted from 2021 to 2022 in a long-term study established in 2012 at the Southwest Research-Extension Center near Garden City, KS (37˚ 99′ 07″N, 100˚ 82′ 47″ W). The average annual precipitation at the experiment site was 483 mm, the average temperature was 15.5 ºC, and the soil type was an Ulysses silt loam (fine-silty, mixed, super active, mesic Aridic Haplustolls). Crops in rotation were winter triticale [×*Triticosecale Wittm*. ex A. Camus (*Secale* ×*Triticum*)] (T), forage sorghum [Sorghum bicolor (L.) Moench] (FS), and oats (*Avena sativa* L.) (O). In two of our crop rotations, FS was double cropped after triticale harvest (T/FS). There were six treatments in an incomplete factorial combination of four rotations (FS–FS, T/FS –FS–O, T/FS–FS–FS–O, and T–FS-O). Crop rotation and tillage treatment included FS-FS (NT), T/FS–FS–O (NT), T/FS–FS–O (RT), T/FS–FS–FS–O (NT), T/FS–FS–FS–O (RT), and T-FS-O. All crop phases were present every year such that each rotation treatment existed in all points in its sequence. The study was a randomized complete block design with 4 replications. Individual plot size was 9.1 m by 9.1 m.

Crop management

Tillage was implemented during the fallow period after oat harvest and before triticale planting using a Minimizer sweep plow with 1.8-m blades and trailing pickers (Premier Tillage, Quinter, KS) between July 1st and August 1st. Tillage was a single operation approximately 10-cm deep. The sweep plow is a minimum disturbance equipment commonly used in the region for weed control. Both reduced tillage (RT) and no-till (NT) treatments received the same herbicide applications to control weeds during fallow, which usually consisted of a mixture of glyphosate, dicamba, and 2-4, D. Triticale was planted between September 15th and October 1st at a rate of 82 kg ha^{-1}. Forage sorghum was planted June 1st at a seeding rate 17 kg ha^{-1}. Oat was planted between March 15h and April 1st at a rate of 72 kg ha^{-1}. Each year, winter triticale was harvested by approximately May 15th, spring oat was harvested approximately June 1st, and forage sorghum was harvested approximately the end of August. Forage sorghum regrowth after harvest was minimal and was terminated by drought or killing frost. Forage harvesting occurred at early heading to optimize forage yield and nutritive value.

Soil sampling and Analysis

Soils samples were obtained in June of 2021 after triticale and oat harvest and sorghum planting. For all phases of all treatments, soil bulk density (BD), mean weight diameter (MWD) of water stable aggregates (MWDWSA), MWD of dry aggregates (MWDDA), total nitrogen (TN), soil organic carbon (SOC), nitrate (NO_3^--N), phosphorus (P), and potassium (K) concentrations were measured at two soil depths of 0-5 and 5-15 cm. Water infiltration was measured in 2021 and 2022. Soil samples were collected from 0- to 5-cm and 5- to 15-cm depth with a flat shovel to determine MWDWSA and MWDDA. Samples were passed through sieves with 4.75- to 8.0 mm mesh and then were air dried. The 4.75 to 8.0 mm aggregate samples were used to estimate water-stable aggregates by the wet-sieving method (Nimmo and Perkins, 2002). Sand corrections were completed for each aggregate size, and the data was then used to compute aggregate size distribution of wet aggregates and MWDWSA. Half of each sample was separated and air-dried to determine dry aggregate stability using a system of nested rotary sieves having 19-, 6.3-, 2-, 0.84-, and 0.42-mm diameter openings (Chepil, 1962). Mass of soil in each size class were used to compute aggregate size distribution of dry aggregates as well as wind erodible fraction (WEF) as the percentage of dry aggregates <0.84 mm in diameter.

Ten soil cores of 2.5 cm diameter were randomly collected from the 0-5 and 5-15 cm soil depths for determining BD, pH, nitrogen in NO_3^--N and NH_4-N concentration, TN, and SOC. Samples taken at both depths were dried at 105°C for 48-hr, and BD was determined by the mass of oven-dry soil divided by the volume of the core. Subsamples from each depth were air-dried and ground to pass through a 2 mm sieve and used for determining soil chemical properties. Soil pH was analyzed using a 1:1 (soil/water) ratio using a deionized water and an OAKTON PC 700 benchtop pH meter (OAKTON Instruments, Vernon Hills, IL). Soil organic carbon samples were ground with a mortar to pass through a 0.25 mm sieve and used for the determination of SOC concentration by the dry combustion method (Nelson and Sommers, 1996) after pre-treatment with 10% v/v of HCl to remove carbonates. The SOC stocks were calculated as the product of SOC concentration, soil BD, and depth of the soil layer. Available soil nitrogen was determined by weighing three grams of ground soil and adding 30 mL of 2 M KCl to form a 1:10 soil-KCl solution and shaking at 200 revolutions per minute (rpm) for 1 hour. After thorough shaking, samples were centrifuged for 5 minutes at 1500 rpm. The solutions were filtered using Whatman no. 2 filter paper and stored frozen. Soil NO_3^--N concentrations were determined colorimetrically (Mulvaney, 1996). The SOC N stocks were calculated on a fixed-depth basis as the product of nitrogen concentration, soil BD, and depth of the soil layer. In addition, TN and SOC stocks were calculated on equivalent mass basis using minimal soil equivalent mass (Mikha et al., 2013). In the summer of 2021 and 2022, water infiltration rate (IR), sorptivity (S), and time-to-runoff (TTR) were measured with a Cornell Sprinkle Infiltrometer for 60 minutes (Ogden, van Es, and Schindelbeck, 1997). Infiltration rate (IR) was estimated by measuring how much water infiltrated into the soil for 60 minutes. Soil sorptivity describes the soil's capacity to uptake water rapidly and is a measure of soil water absorption under capillarity forces (Koorevaar et al., 1983). Sorptivity was calculated as S=(2TTR)0.5 * r (r=constant rainfall, 0.5 cm/min). Time to run-off (TTR) was determined as the elapsed time until the first water overflow was recorded. Time to run-off could be an indicator of low water storage capacity or soil compaction.

Statistical analysis

Forage rotation and tillage effects on soil physical and chemical properties were analyzed by ANOVA using PROC GLIMMIX in SAS ver. 9.3 (SAS Institute, 2012, Cary, NC). Two separate analyses of variances were conducted. The first compared the six-forage rotation-tillage treatments, two depths, and their interaction as fixed effects. A second analysis compared the two tillage treatments, soil depth, and their interactions as fixed effects to examine the main effect of tillage and included only those crop rotations that had complimentary NT and RT in the same rotations [T/FS-FS-O (NT), T/FS-FS-O (RT), T/FS-FS-FS-O (NT), T/FS-FS-FS-O (RT)]. To conduct the Type 3 test, each response variable was modeled against the fixed variables of treatment or tillage, depth, and their interactions, and replication was considered a random variable. Interaction and main effect means were separated using Tukey’s honest significant difference (α = .05).

Results

Soil physical properties

The interaction of treatment × depth or tillage × depth effects on MWDWSA was not significant (Table 3.1). The MWDWSA was not affected by treatment or tillage but was 45%

greater at the 0- to 5-cm soil depth than the 5- to 15-cm depth. Dry aggregate MWD was not affected by the interaction of treatment × depth or tillage × depth (Table 3.1). Neither treatment nor tillage affected MWDDA, but aggregates were 18% smaller in the 0- to 5-cm depth compared to the 5- to 15-cm depth. Wind erodible fraction was not affected by the interaction of treatment × depth or tillage × depth (Table 3.1). The wind erodible soil fraction was not affected by treatment or tillage, but the 0- to 5-cm depth was 37% more susceptible to wind erodibility compared to the 5- to 15-cm depth. Bulk density is an indicator of soil compaction. There was no two-way interaction of treatment × depth or tillage × depth. Forage rotation treatment and tillage did not affect bulk density (Table 3.1). Bulk density at the 0- to 5-cm soil depth was 22% less than the 5- to 15-cm soil depth.

The proportion of water stable aggregates (WSA) within the 0.25-2 mm size in FS-FS NT was 50% greater in the 5- to 15 cm depth than 0- 5-cm depth (Table 3.2). There was no two-way interaction of tillage × depth for any aggregate size distribution. Forage rotation FS-FS NT and T/FS-FS-O RT had 5% more 0.25 to 2 mm aggregates than T-FS-O NT. Forage rotation T-FS-O had more < 0.25 mm aggregates than T/FS-FS-FS-O NT and T/FS-FS-O RT, which were not different from each other. The 0- to 5-cm soil depth had a greater proportion of 2-8 mm aggregates and fewer < 0.25 mm aggregates than the 5- to 15-cm depth. Tillage did not affect aggregate size distribution.

Of the aggregate sizes, the 2-6.3 mm and 6.3 to 19 mm were in greater frequency in the 5-15 cm depth than 0-5 cm soil depth (Table 3.3). Forage rotation T/FS-FS-FS-O RT had greater proportion of 2-6.3 mm aggregate size than T/FS-FS-O NT, T/FS-FS-O RT, and T-FS-O NT. In the 0- to 5 cm soil depth, there was a greater frequency of <0.42, 0.42-0.84-, and 0.84-2-mm size, and the 5- to 15 cm soil depth had a greater frequency of 2-6.3- and 6.3-19-mm size distribution. Tillage did not affect aggregate size distribution except for the 2-6.3 mm size was greater in RT than NT.

Soil chemical Properties

Total nitrogen (TN) was greater in the T/FS-FS-O (RT) (1.06 Mg ha^{-1}), T/FS-FS-FS-O (NT), and T/FS-FS-FS-O (RT) forage rotations compared to the other rotations, which were not different among each other (Table 3.4). The TN measured in the 0- to 5-cm soil depth was 104% less than the 5- to 15-cm soil depth. Tillage treatments did not affect TN stocks.

Soil organic carbon (SOC) is an important soil health indicator of nutrient cycling, soil structure, water holding capacity, carbon sequestration, and biological activity. Soil organic carbon was not affected by forage rotation or tillage (Table 3.4). However, SOC was 90% less at the 0- to 5- cm soil depth than the 5- to 15-cm soil depth.

Soil NO_3^--N was greatest in T/FS-FS-FS-O (NT), which was not different from FS-FS (NT) or T-FS-O (NT), and those two rotation treatments were similar to all other rotation treatments (Table 3.4). Soil NO_3^--N was 59% greater in the 0- to 5-cm soil depth compared to the 5- to 15-cm depth. Soil NO_3-N concentration was not affected by tillage treatment.

Soil P concentration was 47% greater in the 0- to 5-cm soil depth than the 5- to 15-cm depth (Table 3.4). Forage rotation treatment and tillage did not affect soil P concentration (Table 3.8).

The interaction of treatment × depth and tillage × depth was not significant for soil potassium (K) (Table 3.4). Soil K concentration was greatest in the T/FS-FS-FS-O (NT) and T-FS-O (NT) rotations. The forage rotation treatment T/FS-FS-FS-O (NT) had 9% more K concentration than FS-FS (NT). Potassium concentration measured in the 0- to 5-cm soil depth was 28% greater compared to 5- to 15-cm soil depth (Table 3.7). Averaged across forage rotations, there was no significant difference in soil K concentration between tillage practices.

Sorptivity, Infiltration rate, and Time to run-off

Soil sorptivity describes the soil's capacity to uptake water rapidly and is a measure of soil water absorption under capillarity forces (Koorevaar et al., 1983). In this study, there was no significant two-way interaction of treatment × year for sorptivity (Table 3.5). Sorptivity was 30% greater in NT in 2021 compared to NT in 2022. Sorptivity in RT was similar across years. Forage rotation treatment, year, and tillage did not affect sorptivity.

Infiltration rate (IR) in this study measured how much water infiltrated into the soil for 60 minutes. A high IR is preferred to capture moisture and reduce run-off. Infiltration rate in 2021 was 32% greater in NT compared to RT (Table 3.5). However, in 2022, IR was 45% greater in RT compared to NT. Forage rotation, year and tillage did not affect IR.

Time to run-off can be used as an indicator of low water storage capacity or soil compaction. In this study, there was a significant treatment × year interaction on time to run-off (Table 3.5). In 2021, T/FS-FS-O in NT had the longest time to runoff and was 284% longer than T-FS-O NT. All other forage rotations in 2021 were not significantly different from each other. In 2022, T/FS-FS-FS-O in RT had the longest time to runoff and was 177% longer than T/FS-FS-O in RT. All other forage rotations were not significantly different from each other in 2022. There was a significant two-way interaction of tillage × year for TTR. The TTR for NT in 2021 was 32% slower compared to RT in 2021. However, NT in 2022 was 43% faster compared to RT in 2022. Time to run-off was 39% faster in 2021 than 2022. The main effects of tillage or forage rotations were not different.

Discussion

The MWDWSA is a measurement of soil aggregate stability and an important physical indicator of soil health. Stable aggregates protect SOM, improved soil porosity, drainage, and water availability, decreased soil compaction, and supports biological activity, and nutrient cycling. It provides insights into the physical properties of the soil and its ability to support plant growth, nutrient availability, and water movement. Monitoring MWDWSA assists in evaluating soil management practices, identifying soil degradation risks, and promoting sustainable soil ecosystems. In this study, we did not observe any significant differences in MWDWSA among forage rotation nor tillage. This is contrast to what Obour et al. 2021 observed between tillage practices where NT and strategic tillage (ST) maintained a higher MWD compared to RT near Hays, Kansas. They also measured a significant difference between crop rotations with continuous wheat maintaining high aggregate stability compared to wheat-sorghum-fallow and wheat-fallow. A study in western Illinois reported similar results in the 0- to 20-cm soil depth with NT having larger aggregates compared to conventional tillage (CT) (Zuber et al., 2015). Crop rotations also were significantly different with corn-soybean-wheat maintaining the highest aggregate stability while continuous soybean and corn-soybean having the lowest aggregate values across tillage treatments. Angers et al. 1993 investigated MWDWSA under two different rotations (continuous barley (*Hordeum vulgare* L.), and barley-red clover (*Trifolium pratense* L.), and three tillage treatments (fall moldboard plowing with spring secondary tillage, fall chisel plowing followed by spring secondary tillage, and NT). They observed similar results as our study that crop rotation had no effect on water stable aggregates (Angers et al., 1993). However, they observed significant differences in MWDWSA in tillage practices with NT having greater MWDWSA compared to moldboard plow and chisel plow. This could be due the differences of tillage systems between NT and moldboard plow. A similar study by Kibet et al. 2016 investigated long-term tillage impacts on soil physical properties in Typic Argiudoll near Lincoln, Nebraska. This study evaluated the impacts of 33 years of NT, double disk, chisel, and plow tillage under corn–soybean rotation. Both crop phases of the two-year crop rotation were present each year. Although Kibet et al. 2016 did not test crop rotation, they showed double disk and NT had significantly higher MWD than chisel and plow tillage. No-till had 2.1-fold higher MWD than plow tillage and 1.6 times higher than chisel treatments, while double disk had 2.4 times greater MWD than plow tillage and 1.8 greater than chisel at the 0- to 10-cm soil depth but no significant differences were measured at deeper depths (Kibet et al., 2016). This is like what we observed at soil depth, however, we did not observe a significant tillage effect.

Water stable aggregate size distribution is an important measure for assessing soil health that can lead to enhanced productivity and sustainability. In our study, tillage had no effect on aggregate size distribution. However, we did observe that forage rotations that were more productive (produced more biomass) had more aggregates in the 0.25-2.0-mm and fewer in the <0.25-mm. The forage data for this study comes from Holman et al., 2021, where they observed that T/FS-FS-O (NT and RT) and T/FS-FS-FS-O (NT and RT) had greater forage productivity compared to FS-FS (NT) and T-FS-O (NT). This is similar to another study (Obour et al., 2021). They observed that a one-time strategic tillage had no effect on water stable aggregate size distribution compared to NT. They also noted that continuous wheat crop rotation improved proportions of large macroaggregates near the soil surface compared to wheat-fallow and wheat-sorghum-fallow. This could be attributed to differences in SOC. Although there were no differences in SOC between forage rotations, the higher forage productivity rotations tended to have greater average SOC compared to less productive forage rotations.

Monitoring MWDDA helps evaluate different soil management practices that can decrease soil degradation from wind erosion. Wind erosion is a major concern for this region due to its susceptibility to wind erosion in the past**.** In our study, we did not observe any significant differences between forage rotations and tillage. However, there was a significant difference between soil depth. This was similar to Blanco-Canqui et al. 2009, who reported in their study at four different locations across the Great Plains including Akron, CO, Sidney, NE, Hays, KS, and Tribune, KS (Blanco-Canqui et al., 2009). They observed that MWDDA was not affected by tillage practice in three out of the four locations. At Akron CO, MWDDA in moldboard plow was 1.5 times greater than NT in the 0- to 2-cm soil depth. Previous work shows that impact of tillage systems on MWDDA can vary, depending on soil type, cropping systems, and climate. Another study investigated tillage and crop rotation effects on MWDDA in northeastern Saskatchewan (Malhi et al., 2008). They observed no significant difference between crop rotation throughout the study. However, MWD was significantly larger under NT than CT. This is contrast to what we observed in our study. The results of MWDDA in our study indicate that RT had minimal effects on soil properties compared to NT. This could be due to our tillage intensity of RT being very low in our forage rotations, since they were only tilled every 4-5 years depending on the rotations. This could explain why we saw no differences between tillage systems.

Dry aggregate size distribution is useful to assess possible soil erosion from wind. In our study, we observed that the 2.0-6.3 mm aggregate size were greater in the RT compared to NT. However, the aggregates above 6.3 mm tended to be greater in the NT compared to RT. All other size distributions were not different in tillage practices. This is similar to what Blanco-Canqui et al. 2009 reported. They observed that NT did not induce any significant differences in dry aggregate-size distribution and stability except at Akron, Colorado where MWDDA in moldboard plow was greater by about 1.5 times than RT and NT management in the 0- to 2-cm depth (Blanco-Canqui et al., 2009). In our study, the forage rotations T/FS-FS-FS-O (RT and NT) and FS-FS (NT) had more 2.0-6.3 mm size aggregates compared to other forage rotations. These more intensive and diverse forage rotations provided soil cover to protect the soil against potential erosion from wind and water compared to less intensive systems. In Holman et al. 2021, the forage rotations T/FS-FS-FS-O (RT and NT) and FS-FS (NT) also produced the most forage accumulation. This could suggest that more productive forage yielding rotations had more aggregates in this size distribution and tended to have fewer smaller aggregates.

Measuring WEF is important for assessing the risk of wind erosion, identifying areas vulnerable to erosion, managing soil organic matter and moisture, protecting crop productivity, and evaluating overall soil health. By understanding the WEF percentage, farmers and land managers can implement targeted erosion control measures, improve soil management practices, and protect soil resources from the detrimental effects of wind erosion. In this study, WEF was not affected by forage rotation or tillage. The results from Colazo and Buschiazzo. 2010 were similar to findings of present study. In their study, they observed that under certain soils, there was a significant tillage effect, yet, other soil types, WEF was not difference between tillage and no-tillage (Colazo and Buschiazzo, 2010). Reducing soil residue cover in CT and RT by incorporation into soil made the soil more susceptible to wind erosion (He et al., 2018). Malhi et al. 2006 observed similar results (Malhi et al., 2006) that the proportion of wind-erodible aggregates was significantly greater in surface soil of CT compared to NT(Malhi et al., 2006). On the other hand, the proportion of large aggregate (>12.7 mm) under NT compared to CT was about three times greater for the >38 mm size and 37% greater for the 12.7-38.0 mm size. Since tillage did not affect MWDDSA in our study, we would not expect to observe a difference in WEF.

Measuring bulk density is important for assessing soil compaction, porosity, nutrient availability, water retention, root growth, and overall soil health. By understanding BD values, farmers and land managers can make informed decisions to address soil compaction issues, improve soil structure, enhance nutrient availability, optimize water management, and promote healthy and productive soils. In this study, BD was unaffected by forage rotation nor tillage. This is in contrast to NT having higher BD compared to ST and RT in the 0- to 15-cm soil depth near Hays, KS (Obour et al., 2021). However, there were no observed differences between tillage treatments in the 15- to 30-cm soil depth. This could be due to ST and RT breaking up possible surface compaction. Bulk density was also affected by crop rotation and was higher in wheat-sorghum-fallow than continuous wheat in the 0- to 15-cm soil depth. However, in the 15-cm to 30-cm soil depth, there was no significant difference in BD between crop rotations. This could be due the difference of rooting depths between wheat-sorghum-fallow rotations compared to continuous wheat rotations. Another study observed the rotation and tillage effects on BD. (McVay et al., 2006). They observed variability across Kansas with only one of four sites being affected by rotation and tillage. The reason we did not see any differences between tillage could be due to the RT intensity and regularity when tillage occurred. Tillage only occurred at the end of oat harvest. The crops in our forage rotations were all the same besides FS-FS and could explain why there was no difference between forage rotations.

Measuring TN stocks is crucial for evaluating nitrogen levels in soils to be a more efficient in our soil fertility management practices. Optimizing our fertilizer amounts can reduce the risk of contamination and can become more efficient in fertilizer use. In this study, TN was affected by rotation but not tillage. This could be due to high crop residue in our forage rotations and the different types of residues left in our rotations. Similar to our study, in a rotation study of wheat, corn, and soybean with NT and CT, TN was greatest in corn-soybean-wheat (9.27 Mg ha^{-1}) and the least in corn-soybean (8.56 Mg ha^{-1}) and continuous soybean (8.04 Mg ha^{-1}) (Zuber et al., 2015). Although TN was not affected by tillage in our study, TN was greater in NT (8.87 Mg ha^{-1}) than CT (8.40 Mg ha^{-1}) (Zuber et al., 2015). It is likely the return of greater crop residue from corn and wheat compared to soybean is an important factor in the greater TN under rotations that incorporate these crops more frequently. A tillage and rotation study in Ontario observed TN was greater in NT than CT, and TN was greater in crop rotations that included winter wheat than crop rotations without winter wheat (Van Eerd et al., 2014). These results are comparable to our results that observed rotations with double crop triticale/forage sorghum observed higher TN compared to rotations that did not have a double crop triticale/forage sorghum.

Measuring SOC is important for assessing soil fertility, structure, nutrient cycling, water retention, and climate change mitigation. It provides insights into nutrient availability, soil structure stability, water-holding capacity, and the potential for carbon sequestration. In this study, SOC was not affected by forage rotation or tillage. Similar to our study, others have also observed no difference in SOC between rotations or tillage systems (Zuber et al., 2015). Yet another study observed that SOC was less in CT than NT (Van Eerd et al., 2014). In another study, SOC was not different between NT and CT in the 0- to 5-cm soil depth but was different at the 5- to 10-cm soil depth (Tarkalson et al., 2006). However, 14 years later, after converting CT to NT, there were no longer differences in SOC compared with the long-term NT of 41 years. This could be due the converted CT to NT being able to build SOC for over a decade. The possible reason we did not observe differences between tillage practices could be due to the lack of tillage intensity and regularity of tillage.

Measuring soil NO_3^--N concentrations is important for optimizing nutrient management practices and minimizing environmental impacts. In this study, soil nitrate varied by forage rotation and depth but not tillage. Although tillage was not significantly different, forage rotations with NT tended to have higher NO_3^--N concentrations compared to forage rotations under RT. This could be due to NT systems retaining more crop residue than RT systems. Fertilizer applications could have also contributed to different NO_3^--N level. A similar study showed soil NO_3^--N was greater in continuous corn compared to corn-soybeans, which was attributed in part to applying fertilizer every year compared to every other year in corn-soybean (Obour et al., 2016). Contrast to our study, a study in southern Spain observed CT had greater NO_3^--N concentrations than NT (López-Bellido et al., 2013). Although it was not observed in our study, others have reported a lower net N mineralization under NT due to slower decomposition than tillage systems (Soon and Clayton, 2002; McConkey et al., 2002; Grant and Lafond, 1994). However, in the semi-arid central Great Plains, higher temperatures increased crop decomposition rate compared to cooler environments such as southern Spain or northern Great Plains. López-Bellido et al. 2013 also observed nitrates were higher in the wheat-faba bean (*Vicia faba* L.) rotation followed by continous wheat, wheat-fallow, wheat-chickpea (*Cicer arietinum*), and wheat-sunflower (*Helianthus annuus* L.). Soil NO_3^--N concentration was greater in the wheat–faba bean rotation likely due to higher rhizodeposit mineralisation of legumes and lower utilisation of nitrates by the faba beans compared with wheat.

Phosphorus is an important nutrient in plant health and growth. It is essential in many plant processes including photosynthesis, flowering and seed production and crop yield.

Maintaining optimal soil P levels is crucial for promoting healthy plant growth, maximizing agricultural productivity, and sustaining ecosystems. In this study, P concentration was not affected by forage rotation or tillage treatment. These results are similar to no rotation or tillage affect observed by others (Hickman, 2002; Zuber et al., 2015). The possible reason we see no difference between forage rotation and tillage is that we applied the same rate of phosphorus fertilizer across all treatments.

Soil K is an essential nutrient for plant growth, development, and overall crop productivity. Potassium plays a vital role in various physiological processes, including enzyme activation, photosynthesis, and protein synthesis. Maintaining good soil K helps crops with drought and cold stress. In this study, soil K levels were affected by forage rotation and soil depth, however, tillage did not affect soil K levels. This could be due to forage rotations with higher biomass had lower K concentrations compared to rotations with lower biomass production. Similar to this study, a study in Illinois measured greater K at shallow soil depth, no difference between tillage systems, but differences between crop rotations (Zuber et al., 2015). Continuous soybean had less K compared to corn-soybean-wheat and continuous corn, while corn-soybean was intermediate. The lower soil concentration of K under continuous soybean was likely due to greater uptake of K by soybean compared to corn (Russell et al., 2006). This is similar to our study with continuous forage sorghum that observed the lowest levels of K concentration. However, other studies have observed significant differences in K. In Tarkalson et al. 2006, they observed that CT had higher K values compared to NT in the 0- to 5-cm and 5- to 10-cm soil depth. The reason we see differences between potassium levels in forage rotations could be from biomass removal. This could explain why continuous forage sorghum saw the lowest soil K (671 ppm) and T-FS-O had one of the highest levels of K (736 ppm).

Soil sorptivity is a measure for assessing soil health, particularly in relation to water infiltration and retention capabilities. Soil sorptivity refers to the ability of the soil to absorb and transport water through capillary action. By understanding soil sorptivity, farmers and land managers can make informed decisions to optimize irrigation practices, enhance water use efficiency, prevent erosion, and promote sustainable agricultural practices. In this study, no significant differences were observed for the main effects of treatment, year, or tillage. However, tillage by year was significantly different where NT was higher in sorptivity in 2021 compared to RT, but NT and RT were not different in 2022. The reason we see a difference between the years could be the difference soil moisture at testing. It is well noted that dry soil with low moisture content hampers water absorption, while adequately moist soil facilitates faster water infiltration. Bulk density is also affected by soil water content which can affect soil water absorptivity.

Measuring soil infiltration rate provides information about the ability of the soil to absorb and retain water. By understanding soil infiltration characteristics, farmers and land managers can make informed decisions to improve water management, prevent erosion, enhance nutrient availability, and promote sustainable agricultural practices that support soil health and overall ecosystem functioning. In this study, there was a significant two-way interaction of tillage × year with 2021 NT having greater IR compared to RT. However, in 2022 RT had greater IR compared to NT. There was no significant main effects of forage rotation, year, or tillage for IR. Similar to our findings, others reported no difference in IR between tillage systems (Baumhardt et al., 2017; Franzluebbers and Stuedemann, 2008). The variation in IR between tillage and year could be from differences in soil moisture content at infiltration testing (Blanco, 2011). It is plausible that soil moisture conditions between years affected IR in NT more than RT in our study.

Measuring soil TTR is important for assessing soil health because it provides valuable information about the ability of the soil to retain and manage water. Time to run-off is important for assessing water infiltration and retention, preventing erosion, optimizing water use efficiency, evaluating soil structure, and overall soil health. By understanding soil TTR, farmers and land managers can make informed decisions to improve water management, prevent erosion, enhance water use efficiency, and promote sustainable agricultural practices that support soil health and overall ecosystem functioning. In this study, TTR was longer in 2022 than 2021. This could result from dry soils in 2022, taking longer to reach soil saturation compared to 2021. Plot variability also could have played a role in the differences in TTR.

Conclusions

Crop rotation and tillage had limited effects on soil physical and chemical properties in our study. Tillage did not influence soil physical or chemical properties. Forage rotation did effect water aggregate size distribution in the 0.25- to 2.0-mm, with forage rotations with more productive forage yielding rotations having more aggregates in this size distribution and tended to have less smaller aggregates. Similarly, forage rotations with the greater forage yield had more aggregates in the dry aggregate size distribution in the 2.0- to 6.3-mm and tended to have fewer smaller aggregate$_s$. This suggests that diverse, highly productive forage rotations can help improve soil aggregate size and decrease wind and water erosion . Forage rotation had effects on TN, NO_3^--N concentrations, and K concentration with T/FS-FS-FS-O (NT) having greater concentrations of all three nutrients. Tillage and year had significant impacts on sorptivity, IR, and TTR. This could indicate weather variability as well as plot variability. Our more intensive and diverse forage rotations [T/FS-FS-O (NT), T/FS-FS-O (RT), T/FS-FS-FS-O (NT), T/FS-FS-FS-O (RT)] provided soil cover to protect the soil against potential erosion from wind and water compared to less intensive system T-FS-O (NT). No-tilled systems were not significantly greater in terms of soil health compared to RT systems. The reasons we did not observe any difference between tillage systems could be from the minimal disturbance and infrequent tillage (one tillage operation every 3 or 4 years) in the RT treatment compared to more intensive tillage systems. The significance of this study to note is that diverse and productive forage rotations can help maintain soil physical and chemical properties, and that occasional RT had limited effects on soil physical and chemical properties.

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Tables

Table 3.1 Forage rotation and tillage effects on water stable aggregate mean weight diameter (MWDWSA), dry aggregate mean weight diameter (MWDDA), dry aggregate stable wind erodible fraction (WEF), and bulk density in the 0-5 cm and 5-15 cm soil depths in 2021 at the Southwest Research Center near Garden City Kansas.

Factor[a]	**MWDWSA**	**MWDDA**	**WEF**	**Bulk density**
Treatment × Depth	mm	mm	%	g cm^{-3}
FS-FS (NT) – 0-5	0.86	6.15	24.71	1.16
FS-FS (NT) – 5-15	0.51	7.33	14.52	1.57
T/FS-FS-O (NT) – 0-5	0.88	6.49	24.58	1.23
T/FS-FS-O (NT) – 5-15	0.54	7.39	16.35	1.47
T/FS-FS-O (RT) – 0-5	1.11	6.22	25.78	1.23
T/FS-FS-O (RT) – 5-15	0.57	7.35	15.85	1.45
T/FS-FS-FS-O (NT) – 0-5	1.04	6.25	24.21	1.21
T/FS-FS-FS-O (NT) – 5-15	0.47	7.48	15.12	1.47
T/FS-FS-FS-O (RT) – 0-5	0.97	5.96	25.06	1.25
T/FS-FS-FS-O (RT) – 5-15	0.56	7.07	16.34	1.48
T-FS-O (NT) – 0-5	0.81	6.04	27.75	1.24
T-FS-O (NT) – 5-15	0.44	7.12	17.14	1.48
P>F	0.4991	0.9918	0.9691	0.1868
Tillage × Depth				
NT - 0-5	1.01	6.36	24.37	1.21
NT - 5-15	0.48	7.44	15.70	1.47
RT - 0-5	1.06	6.09	25.38	1.24
RT - 5-15	0.57	7.21	16.11	1.46
P>F	0.6526	0.8837	0.7583	0.2564
Treatment				
FS-FS (NT)	0.69	6.74	19.61	1.36
T/FS-FS-O (NT)	0.71	6.94	20.46	1.35
T/FS-FS-O (RT)	0.84	6.79	20.81	1.34
T/FS-FS-FS-O (NT)	0.76	6.86	19.67	1.34
T/FS-FS-FS-O (RT)	0.77	6.52	20.70	1.36
T-FS-O (NT)	0.63	6.58	22.45	1.36
P>F	0.0980	0.4597	0.5162	0.8332
Depth				
0-5 cm	0.95 a[b]	6.18 b	25.35 a	1.22 b
5-15 cm	0.52 b	7.29 a	15.89 b	1.49 a
P>F	<.0001	<.0001	<.0001	<.0001
Tillage				
NT	0.75	6.90	20.04	1.34
RT	0.82	6.65	20.74	1.35
P>F	0.1766	0.1283	0.4725	0.5696

[a] NT= No-till, RT= Reduced tillage, FS= Forage sorghum, T= Winter triticale, O= Oats, T/FS= winter triticale double cropped with forage sorghum

[b] Values within a factor within column followed by the same letter are not different at α = 0.05.

Table 3.2 Forage rotation and tillage effects on aggregate size distribution of water stable aggregates in 2021 at the Southwest Research Center near Garden City Kansas.

Factor[a]	<0.25-mm	0.25- to 2.0-mm	2.0- to 8-mm
		%	
Treatment × Depth			
FS-FS (NT) – 0-5	67.90	20.76 b	12.51
FS-FS (NT) – 5-15	64.70	31.31 a	3.76
T/FS-FS-O (NT) – 0-5	64.15	23.73 b	12.15
T/FS-FS-O (NT) – 5-15	70.76	24.21 b	5.41
T/FS-FS-O (RT) – 0-5	56.04	26.81 ba	16.30
T/FS-FS-O (RT) – 5-15	68.95	25.20 ba	5.71
T/FS-FS-FS-O (NT) – 0-5	58.43	26.52 ba	14.95
T/FS-FS-FS-O (NT) – 5-15	73.17	22.59 b	4.22
T/FS-FS-FS-O (RT) – 0-5	63.14	22.91 b	14.02
T/FS-FS-FS-O (RT) – 5-15	72.67	21.08 b	5.90
T-FS-O (NT) – 0-5	68.53	20.92 b	11.39
T-FS-O (NT) – 5-15	74.55	22.10 b	3.65
P>F	0.0733	0.0400	0.6548
Tillage × Depth			
..NT - 0-5	60.52	25.04	14.70
..NT - 5-15	73.10	22.90	4.36
RT - 0-5	59.82	24.46	15.59
RT - 5-15	70.78	22.94	5.92
P>F	0.6296	0.7786	0.7429
Treatment			
FS-FS NT	66.30 bac[b]	26.03 a	8.13
T/FS-FS-O (NT)	67.45 ba	23.97 b	8.78
T/FS-FS-O (RT)	62.50 c	26.00 a	11.01
T/FS-FS-FS-O (NT)	65.80 bc	24.56 b	9.59
T/FS-FS-FS-O (RT)	67.90 ba	21.99 b	9.96
T-FS-O (NT)	71.54 a	21.51 c	7.52
P>F	0.0106	0.0273	0.2406
Depth			
0-5 cm	63.03 b	23.61	13.55 a
5-15 cm	70.80 a	24.42	4.77 b
P>F	0.0020	0.5449	<.0001
Tillage			
NT	66.81	23.97	9.53
RT	65.30	23.70	10.76
P>F	0.3689	0.8050	0.2249

[a] NT= No-till, RT= Reduced tillage, FS= Forage sorghum, T= Winter triticale, O= Oats, T/FS= winter triticale double cropped with forage sorghum

[b] Values within a factor within column followed by the same letter are not different at α = 0.05.

Table 3.3 Forage rotation and tillage effects on aggregate size distribution of dry aggregates in 2021 at the Southwest Research Center near Garden City Kansas.

Factor[a]	<0.42 mm	0.42- to 0.84-mm	0.84- to 2.0-mm	2.0- to 6.3-mm	6.3- to 19-mm
			%		
Treatment × Depth					
FS-FS (NT) – 0-5	17.00	7.67	12.01	25.06	38.53
FS-FS (NT) – 5-15	9.93	4.58	10.33	27.76	47.34
T/FS-FS-O (NT) – 0-5	17.75	6.83	10.84	22.73	42.03
T/FS-FS-O (NT) – 5-15	11.72	4.65	9.93	24.90	48.64
T/FS-FS-O (RT) – 0-5	19.08	6.70	11.46	23.63	39.65
T/FS-FS-O (RT) – 5-15	11.59	4.27	9.49	26.48	47.89
T/FS-FS-FS-O (NT) – 0-5	17.19	7.02	11.81	24.53	39.35
T/FS-FS-FS-O (NT) – 5-15	10.48	4.62	9.97	26.00	49.11
T/FS-FS-FS-O (RT) – 0-5	18.06	7.00	12.26	26.16	36.47
T/FS-FS-FS-O (RT) – 5-15	11.48	4.85	10.42	28.21	45.08
T-FS-O (NT) – 0-5	19.63	8.12	12.00	21.02	38.56
T-FS-O (NT) – 5-15	12.23	4.91	10.63	26.22	46.12
P>F	0.9855	0.8259	0.9540	0.6262	0.9872
Tillage × Depth					
..NT - 0-5	17.44	6.92	11.35	23.64	40.62
..NT - 5-15	11.08	4.62	9.93	25.50	48.95
RT - 0-5	18.52	6.85	11.84	24.81	37.99
RT - 5-15	11.54	4.56	9.93	27.32	46.52
P>F	0.6792	0.9923	0.5485	0.6579	0.9475
Treatment					
FS-FS (NT)	13.47	6.13	11.17	26.41 ba	42.94
T/FS-FS-O (NT)	14.73	5.74	10.39	23.81 b	45.33
T/FS-FS-O (RT)	15.34	5.48	10.47	25.05 b	43.77
T/FS-FS-FS-O (NT)	13.83	5.82	10.89	25.27 ba	44.23
T/FS-FS-FS-O (RT)	14.77	5.93	11.34	27.19 a	40.78
T-FS-O (NT)	15.93	6.51	11.31	23.62 b	42.34
P>F	0.3944	0.2948	0.4776	0.0125	0.3641
Depth					
0-5 cm	18.12 a[b]	7.22 a	11.73 a	23.86 b	39.10 b
5-15 cm	11.24 b	4.65 b	10.13 b	26.59 a	47.36 a
P>F	<.0001	<.0001	0.0003	0.0016	<.0001
Tillage					
NT	14.26	5.77	10.64	24.57 b	44.78
RT	15.03	5.70	10.89	26.06 a	42.25
P>F	0.2970	0.8097	0.5478	0.0435	0.0911

[a] NT= No-till, RT= Reduced tillage, FS= Forage sorghum, T= Winter triticale, O= Oats, T/FS= winter triticale double cropped with forage sorghum

[b] Values within a factor within column followed by the same letter are not different at $\alpha = 0.05$.

Table 3.4 Forage rotation and tillage effects on total nitrogen (Total N) stocks, soil organic carbon (SOC) stocks, nitrate (NO_3^--N) concentrations, phosphorus (P) concentrations, and potassium (K) concentrations in the 0-5 cm and 5-15 cm soil depths in 2021 at the Southwest Research Center near Garden City Kansas.

Factor[a]	Total N	SOC	NO_3^--N	P	K
Treatment × Depth	Mg ha^{-1}	Mg ha^{-1}	ppm	ppm	ppm
FS-FS (NT) – 0-5	0.67	6.85	30.9	100.3	758
FS-FS (NT) – 5-15	1.31	12.45	15.4	47.8	583
T/FS-FS-O (NT) – 0-5	0.69	6.82	29.2	113.9	828
T/FS-FS-O (NT) – 5-15	1.42	12.71	10.3	51.0	563
T/FS-FS-O (RT) – 0-5	0.67	6.68	28.2	113.4	809
T/FS-FS-O (RT) – 5-15	1.45	13.41	11.2	63.4	581
T/FS-FS-FS-O (NT) – 0-5	0.70	6.89	30.6	119.1	860
T/FS-FS-FS-O (NT) – 5-15	1.42	12.96	16.5	64.5	617
T/FS-FS-FS-O (RT) – 0-5	0.69	6.84	29.1	103.0	794
T/FS-FS-FS-O (RT) – 5-15	1.43	12.69	9.5	63.5	592
T-FS-O (NT) – 0-5	0.65	6.20	32.0	113.8	878
T-FS-O (NT) – 5-15	1.33	12.28	11.6	58.7	594
P>F					
Tillage × Depth					
NT – 0-5	0.70	6.86	30.0	116.3	846
NT – 5-15	1.42	12.85	13.7	58.8	594
RT – 0-5	0.68	6.77	28.5	107.9	802
RT – 5-15	1.44	13.00	10.2	63.5	587
P>F	0.2711	0.5429	0.4317	0.0834	0.1774
Treatment					
FS-FS (NT)	0.99 b[b]	9.65	23.2 ab	74.1	671 c
T/FS-FS-O (NT)	1.05 ba	9.76	19.8 b	82.5	695 c
T/FS-FS-O (RT)	1.06 a	10.05	19.7 b	88.4	695 c
T/FS-FS-FS-O (NT)	1.06 a	9.93	23.6 a	91.8	739 a
T/FS-FS-FS-O (RT)	1.06 a	9.76	19.3 b	83.2	693 c
T-FS-O (NT)	0.99 b	9.24	21.8 ab	86.2	736 ab
P>F	0.0088	0.0653	0.0418	0.1431	0.0172
Depth					
0-5 cm	0.68 b	6.71 b	30.0 a	110.6 a	821 a
5-15 cm	1.39 a	12.75 a	12.4 b	58.1 b	588 b
P>F	<.0001	<.0001	<.0001	<.0001	<.0001
Tillage					
NT	1.06	9.86	21.9	87.5	720
RT	1.06	9.88	19.4	85.7	694
P>F	0.9461	0.8790	0.0540	0.6291	0.0700

[a] NT= No-till, RT= Reduced tillage, FS= Forage sorghum, T= Winter triticale, O= Oats, T/FS= winter triticale double cropped with forage sorghum

[b] Values within a factor within column followed by the same letter are not different at α = 0.05.

Table 3.5 Forage rotation and tillage effects on sorptivity, infiltration rate, and time-to-runoff (TTR) in 2021 and 2022 at the Southwest Research Center near Garden City Kansas.

Factor[a]	Sorptivity	Infiltration Rate	TTR
	— cm min$^{-0.5}$—	cm hr^{-1}	min
Treatment × Year			
FS-FS (NT) 2021	1.31	8.07	4.08 cd
T/FS-FS-O (NT) 2021	1.85	12.63	7.44 abc
T/FS-FS-O (RT) 2021	1.58	9.13	5.30 abcd
T/FS-FS-FS-O (NT) 2021	.	.	.
T/FS-FS-FS-O (RT) 2021	1.28	8.33	4.99 bcd
T-FS-O (NT) 2021	1.28	9.57	2.62 d
FS-FS (NT) 2022	1.26	8.17	6.33 abcd
T/FS-FS-O (NT) 2022	1.26	5.42	5.73 abcd
T/FS-FS-O (RT) 2022	1.32	9.41	4.87 bcd
T/FS-FS-FS-O (NT) 2022	1.32	4.85	5.50 abcd
T/FS-FS-FS-O (RT) 2022	1.30	9.50	8.63 a
T-FS-O (NT) 2022	1.35	6.56	8.56 ba
P>F	0.1591	0.0604	0.0330
Tillage × Year			
2021 – NT	1.85 a[b]	12.63 a	7.44 a
2021 – RT	1.38 b	8.60 b	5.09 b
2022 – NT	1.29 b	5.17 c	5.15 b
2022 – RT	1.31 b	9.46 ba	7.39 a
P>F	0.0384	0.0011	0.0315
Treatment			
FS-FS (NT)	1.28	8.12	5.20
T/FS-FS-O (NT)	1.56	9.02	6.15
T/FS-FS-O (RT)	1.45	9.27	5.52
T/FS-FS-FS-O (NT)	.	.	.
T/FS-FS-FS-O (RT)	1.29	8.91	6.81
T-FS-O (NT)	1.31	8.07	5.59
P>F	0.3731	0.6145	0.7310
Year			
2021	1.46	9.34	6.26
2022	1.30	7.83	6.27
P>F	0.0985	0.0951	0.0288
Tillage			
NT	1.57	8.90	6.29
RT	1.34	9.03	6.24
P>F	0.0556	0.9096	0.9576

[a] NT= No-till, RT= Reduced tillage, FS= Forage sorghum, T= Winter triticale, O= Oats, T/FS= winter triticale double cropped with forage sorghum

[b] Values within a factor within column followed by the same letter are not different at α = 0.05.