Tillage practices and their effects on crop yield, soil health, and weed abundance in semi-arid dryland cropping systems

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Abstract

Implementing tillage in long-term no tillage (NT) fields in the semi-arid central Great Plains is a concern for producers because soil improvements gained from NT could be lost. However, producers are dealing with herbicide resistant weeds and nutrient stratification, which is forcing them to consider tillage to mitigate these issues. Two experiments were conducted in western Kansas to assess the influence of strategic tillage (ST) and occasional tillage (OT) on crop yields and soil properties. In the current studies, ST is defined as a one-time tillage operation prior to winter wheat (*Triticum aestivum* L.) or grain sorghum (*Sorghum bicolor* L.) planting then the field returns to NT, and OT is defined as a single tillage operation in the fallow phase of a 3-yr winter wheat-grain sorghum-fallow rotation. The objectives of these studies were to investigate the influence of ST and OT on soil physical and chemical properties, crop yields, and weed diversity. A long-term study initiated in 1976 at the KSU Agricultural Research Center – Hays was used to investigate the influence of NT, ST, and reduced tillage (RT) on weeds, crops yields and soil properties. Reduced tillage is defined as two to three tillage operations in the fallow period prior to winter wheat planting and an additional pass before sorghum planting. The experimental design was a randomized complete block with three replications in a split-plot treatment structure with crop rotation as main plots and tillage as sub-plots. The cropping systems compared included continuous wheat (WW), wheat-fallow (WF) and wheat-grain sorghum-fallow (WSF). Subplots were continuous NT, ST, and RT. Results of soil samples collected in 2022 showed soil organic carbon concentration was highest in the soil surface, and RT had 8% less soil organic carbon than ST and NT. There were no differences across tillage treatments in soil bulk density, penetration resistance, or wind erodible fraction. However, mean weight diameter of water stable aggregates in NT was 31% greater than RT, and ST was not significantly different from NT or RT. Reduced tillage and ST increased wheat yields in WW compared to NT. Grain sorghum yields were greater in NT and ST compared to RT. Shannon’s Diversity Index values were greatest in NT and least in RT, so there is greater weed diversity in NT compared to RT. For weed density, the WSF (137 plants m^2) and WF (167 plants m^2) rotations had 50% and 59% greater density than the WW (68 plants m^2) rotation. However, there were no differences across tillage treatments. Overall, this study indicated ST had no negative influence of soil properties or crop yield and could aid in minimizing weed diversity. A second study was initiated in 2013 at Garden City and Tribune, KS and 2014 in Hays, KS, and the tillage treatments were NT, single tillage pass before wheat (STBW), two tillage passes before wheat (2TBW), single tillage after wheat (STAW), and two tillage passes after wheat (2TAW) in a winter wheat-grain sorghum-fallow rotation. Soil sampling occurred pre-tillage in 2022 and post-tillage in 2022 and in 2023. Tillage treatments did not influence soil organic carbon, pH, Mehlich-3 phosphorus, bulk density, mean weight diameter, or wind erodible fraction. However, soil nitrate-N (NO_3-N) concentrations were increased with increased tillage intensity, and the gravimetric water content often depended on the tillage treatment and depth. Tillage tended to increase cumulative water infiltration compared to NT. Winter wheat yields in Garden City increased with tillage in 4 out of 5 years of the study, but tillage had no significant effect on wheat yields in Hays or Tribune. Grain sorghum yields were decreased with tillage in 2019 and 2020 at Hays, but the other locations observed no significant differences. The Shannon’s Diversity Index values were greatest in NT, which was 17% and 33% greater than STBW and 2TBW. However, weed density was not different across tillage treatments, but there was a significant effect of location. Overall, the implementation of OT had minimal negative effects on soil physical and chemical properties. However, there are some soil chemical properties that can

be increased with the use of OT, such as NO_3-N, but some soil physical properties, specifically gravimetric water content, could be influenced with OT. Occasional tillage can increase grain yield but often has no influence. Weed diversity can be lowered with the use of OT. The findings of these studies suggest ST and OT can mitigate the influence of nutrient stratification and herbicide resistant weeds.

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Chapter 1 - Introduction and literature review

Introduction

In semi-arid regions of the central Great Plains (CGP), water availability can be an issue for farmers because of high variability in amount and distribution of precipitation, and due to the high variability in precipitation, this can impact several parts of farming operations, such as tillage operations and crop rotations (Kansas Mesonet; Hansen et al., 2012; Dhuyvetter et al., 1996). Soil conservation practices like no tillage (NT) were developed and broadly implemented in the region to reduce soil erosion and increase precipitation capture and storage (Triplett et al., 2008; Hansen et al., 2012). However, some unintended consequences of long-term NT are stratification of nutrients and organic carbon, soil compaction, and over reliance on herbicides, which has contributed to the development of herbicide resistant (HR) weeds (Schlegel et al., 2020). Therefore, the practice of occasional tillage (OT) has been increasingly investigated as a mitigation option for managing HR weeds such as Palmer amaranth (*Amaranthus palmeri* L.), kochia (*Kochia scoparia* L.) and tumble windmill grass (*Chloris verticillata* Nutt.). In a study conducted in western Kansas, Schlegel et al. (2020) defined OT as a single tillage operation in the fallow phase of a 3-yr wheat (*Triticum aestivum*)-grain sorghum (*Sorghum bicolor* L.)-fallow (WSF) rotation. Obour et al. (2021) investigated the possibility of strategic tillage (ST), which the authors defined as the practice of implementing a tillage pass in an otherwise NT system to manage HR weeds, and after the tillage pass, the field is returned to NT. In a study in Australia, Liu et al. (2016) showed that ST could aid in managing HR weeds but did not influence crop productivity or soil properties. Similarly, Baan et al., 2009 conducted a single tillage pass on a long-term NT soil and concluded that soil properties such as soil organic matter (SOM), aggregation, pH, and water content were unaffected by a single tillage pass. The authors noted there was minimal success in increasing crop productivity with a single pass of tillage. However, there has been research that has observed detrimental effects to soil properties with the use of tillage in an otherwise NT system. For soil physical properties, Grandy et al. (2006) reported a 35% decrease in mean weight diameter (MWD), which is an estimate of aggregate size, within 60 days of tillage. The authors also observed a 12% decrease in organic carbon in 2000- to 8000-μm aggregates. Singh et al. (2006) reported that the wind erodible fraction, which is the susceptibility of aggregates to wind erosion, was smallest under NT and greatest under tillage with straw removal.

While there have been various results on the influence of tillage on soil physical and chemical properties, tillage can help control HR weeds. However, tillage effects on the weed seed bank (WSB) is an area of concern for producers and researchers. Begum et al. (2006) defines the WSB as the reserve of viable weed seeds present along the soil surface and scattered throughout the soil profile, and the WSB can consist of recently shed weed seeds or seeds that have persisted from previous years. Walck et al. (1996) describes transient and persistent seed banks. The authors describe the transient seed bank are the seeds that do not live until the second germination season following maturation, and the persistent seed bank is composed of seeds that live until the second or some subsequent germination seasons. The WSB can be difficult to manage because it contains numerous seeds and a wide array of weed species (Sharshar et al., 2022). Thus, the authors mention it is a key area to assess WSB effect on crop yield. There are several challenges with managing the WSB because weed seeds can survive at different depths, and the seeds can remain dormant for different time periods, which can make them difficult to control (Sharshar et al., 2022). A study conducted in the semi-arid Pacific Northwest compared the WSB under spring wheat-chemical fallow, continuous spring wheat, and spring wheat-spring barley to winter wheat- dust mulch fallow (WWF) (Thorne et al., 2007). The authors reported an initial high density of downy brome (Bromus *tectorum)* was reduced with NT spring crops and in WWF with intensive management strategies, but the authors noted there was an increase in downy brome density in WWF with less management. The authors also reported that a seed bank weed shift occurred where winter annual broadleaf species remained following the reduction of downy brome populations. A study conducted in Georgia investigated the influence of burial depth and burial duration on glyphosate resistance and glyphosate susceptible Palmer amaranth (*Amaranthus palmeri*) (Sosnoskie et al., 2013). The authors reported there were no differences in seed viability between glyphosate resistant and glyphosate susceptible seeds, but the seed viability decreased from 96% at the initiation of the study to 65 to 78% 6 months after burial. Their results also concluded that as burial depth increased Palmer amaranth seed viability did also, which ranged from 9% at 1-cm deep to 22% at 40-cm deep 3 years after initiation. A study conducted in western Canada and the mid-western United States investigated the seedbank longevity of glyphosate resistant kochia (*Kochia scoparia*) (Beckie et al., 2018). The authors concluded that neither site nor depth of burial influenced seed viability, and for seed viability to decrease to 50% and 90% loss, it would take at least 210 and 232 days to accomplish.

Cropping systems: history and evolution

After the Dust Bowl, there were several technological advances, such as more powerful tractors that allowed for deeper plowing and sand fighters to increase surface roughness (Fryrear, 1969; Lee et al., 1999). Farmers also began to incorporate a fallow period into their cropping systems (Anderson 2005). The author mentioned that the fallow period allows for soil water storage to stabilize the next crop’s yield. After the Dust Bowl, winter wheat followed by summer fallow was the main crop rotation, which prior to the Dust Bowl fallow was uncommon

(Anderson 2005). With herbicides and less tillage, the fallow period increased water storage efficiency (WSE) allowing producers to grow three crops in two years in a winter wheat-summer crop-fallow rotation. In a study conducted in western Colorado, the WSE was reported for wheat-fallow (WF), wheat-corn (*Zea mays*)-fallow (WCF), and wheat-corn-millet (*Panicum miliaceum*)-fallow (WCMF), which were all managed under NT practices (McGee et al., 1997). The authors reported the WSE in the fallow period prior to corn planting in the WCF rotation was 48% compared to the 22% WSE in the 14-month fallow period in the WF rotation. Nielsen et al. (2010) reported precipitation storage efficiency for wheat-fallow systems averaged 20% under CT and 35% under NT, and fallow soil water increased 111 mm under CT and 188 mm under NT. With the use of a fallow period, summer crops that can be grown include corn, proso millet, sorghum, or sunflower (*Helianthus annuus* L.) (Peterson et al., 1993). Recently, other cropping systems that have been investigated are forage millet-forage triticale (*Triticum aestivum x Secale cereale)*-forage sorghum, wheat-flexible crop-flexible crop, wheat-millet-fallow, and wheat-forage sorghum-flexible crop because of the potential for alternative uses as well as increased economic returns (Nielsen et al., 2016).

Cropping systems vary across the CGP, but common rotations involve winter wheat, one or more summer crops, and a fallow period. Not every farmer uses a fallow period, but this can be a mistake during dry years. A study in Akron, CO reported that winter wheat yields decreased 57% when the fallow period was replaced with crop production (Nielsen et al., 2016). There is research being conducted in the semi-arid parts of the CGP investigating different rotations to increase cropping system intensity by adding cover crops or forage crops. Obour et al. (2022) investigated the effects of spring cover crop treatments, which were spring oat (*Avena sativa* L.), spring triticale [×*Triticosecale* Wittm. ex A. Camus (*Secale* × *Triticum*)], oat and triticale mixture (OT, two-species mixture), oat, triticale, and pea (*Pisum sativum* L.) (OTP, three-species mixture), and oat, triticale, pea, radish (*Raphanus sativus* L.), turnips (*Brassica campestris* L.), and buckwheat (*Fagopyrum esculentum* Moench) (six-species mixture), planted in a wheat-sorghum-fallow rotation. The authors reported productivity was 33-35% greater with only triticale and an oat-triticale mixture than the lone spring oat or cocktail, and the multispecies treatments were greater in nutritive value compared to a single species. Holman et al. (2022) investigated increasing crop intensity by adding forages to various rotations. The authors noted the crops incorporated into the rotations in this research were winter wheat (W), grain sorghum (S), forage sorghum (FS), and forage oats (FO, *Avena sativa* L.), which were used to generate six crop rotations. The rotation treatments were integrated into the fallow periods (F) and were W-S-F, W-FS-F, W/FS-S-FO, W/FS-FS-FO, W/FS-S-F, and W/FS-FS-F, and the W/FS rotation is winter wheat with double crop FS in the same year. The authors reported 45-56% greater FS yield with W/FS-FS-FO and W-FS-FS-F compared to W-FS-F, and grain sorghum yield was 52-60% lower with W/FS-S/F compared to W-S-F. However, gross returns were highest with W/FS-FS-FO and W/FS-FS/F.

Tillage: history and evolution

Humans have been farming for thousands of years, and during that time, numerous crops have been domesticated. However, one of the most revolutionary inventions to hit the market in the agricultural industry was the steel moldboard plow of the 1830s, which enabled farmers to farm more acres in less time, because prior to this invention farmers had to walk behind the plow in order to control the depth of tillage (Lee and Gill 2015). In addition to the introduction of the plow, the authors note the farming industry changed when the first tractors and combines reached the market following World War I. The use of the moldboard plow and tractor created an explosion of acres planted into crops, and by 1920, roughly 955 million U.S. acres were considered farmland (Dennehy et al., 2002). The Homestead Act of 1862 allowed millions of acres to be claimed by settlers, so in the late 19th and early 20th century, significant amounts of people moved to the western parts of the CGP with the belief they could farm and plow with the moldboard implement (Dennehy et al., 2002; Augustine et al., 2021). However, not every soil type or region is suitable for the moldboard plow. The consequence of this farming practice was significant soil degradation that cumulated with the Dust Bowl (Lee and Gill, 2015).

Several factors interacted to cause the Dust Bowl. Before and during the Dust Bowl, a moldboard plow was commonly used across the CGP (Lee and Gill, 2015). In the 1920s, the authors noted one-way disk plow was widely adopted to till and break the soil, and it was a common implement used to create dust mulching. Other implements, such as the disk harrow and spike-tooth harrow, also caused soil surface degradation. In addition to the various tillage implements used, the authors noted dryland farming techniques such as “soil mulching,” which left the topsoil exposed to wind erosion, were considered to play some role in causing the Dust Bowl as well. Aside from the use of these implements and farming practices, another key factor in wind erosion was suitcase farmers. The authors mentioned these farmers often planted and harvested their fields, but they spent little time at or between their fields. In addition to the tillage implements used and suitcase farmers, the authors mentioned there were severe droughts and high temperatures, which caused crop fields to fail. The bare, dry soil began to blow away due to the lack of residue and moisture. Once the drought and Dust Bowl hit, these suitcase farmers abandoned their fields, and with no crop residue present, the winds would blow their topsoil as well as their neighbors’ (Lee and Gill 2015). A dust storm in May of 1935 was estimated to carry and translocate 350 million tons of soil across the United States (Lal et al., 2007). The authors stated the Dust Bowl was a life changing event for millions of people because many of them left the CGP, with field abandonment leading to additional loss of topsoil. However, it was also mentioned the Dust Bowl was also revolutionary in how it changed how farmers used and viewed tillage intensity and frequency, tillage implements, and the use of a fallow period (Lal et al., 2007).

Even though the Dust Bowl was an event that changed the course of agriculture in the CGP, there were still areas that continued conventional tillage (CT) (Lal et al., 2007). Conventional tillage was continued especially in the southern states, but since the 1950s, there has been a transition from CT to forms of conservational tillage such as NT or reduced tillage (RT). A key realization during the 1950s was the importance of residue management, so important subsurface tillage implements such as the sweep plow or rod weeder were invented and utilized in stubble mulch systems (Anderson, 2004). The author noted the sweep plow consists of V-shaped blades that separate plant roots at roughly 5-to-8-cm deep, and tillage operations done with a sweep plow buries only 10% of crop residue compared to a moldboard plow that buries 60 to 100% of crop residue. Another key factor in these transition acres was the invention of herbicides such as 2,4-D after World War II. In addition to the invention of helpful chemistries, conservational tillage practices such as NT or RT worked better for semi-arid regions to reduce wind and water erosion. Reduced tillage as a conservation tillage practice uses implements specifically designed to leave crop residue at the soil surface. There have been several types of RT practices implemented, such as “one time tillage,” “strategic tillage,” or “one cycle of tillage” (Blanco-Canqui and Wortmann, 2020). Obour et al. (2021) implemented strategic tillage in an otherwise NT system and used a Quinstar Fallow Master sweep plow with pickers at the depth of 7.5-cm then a second operation was done three days later with the same implement at a depth of 15-cm. The authors also defined RT by the use of implements such as a V-blade and Fallow Master sweep plow, and two to three tillage operations were completed in the fallow period prior to winter wheat planting or sorghum planting depending on the rotation. Thapa et al. (2023) compared the effects of CT, NT, stubble mulch tillage (SMT), and strip tillage (STR) on various soil properties and yields. The authors noted for the CT treatment the tillage implements were a disk harrow, DMI ripper, sweep blades, and a land finisher at depths of 10-cm, 25-cm, 10-cm, and 15-cm. For SMT, the authors defined it at a 15-cm deep tillage operation with a blade plow or sweep openers, and for STR, the authors reported the tillage operation was done at 15-cm deep with a four-row Strip-Cat. However, tillage implements used in other tillage practices (e.g., CT) can influence the amount of crop residue retained. For instance, the moldboard plow retains less than 10% of crop residue, chisel plow and disking retain between 25 and 75%, conservation tillage with a sweep plow can retain 30% or more residue, and ridge-planting and till planting retain 40-60% crop residue (CTIC, 2006). Compared to all these tillage practices, NT maintains the most crop residue with 90% or more of crop residue being conserved (Lal et al., 2007). In areas prone to wind and water erosion, having crop residue on the soil surface aids in limiting erosion (Hansen et al., 2012). Aggressive tillage with certain implements, such as the moldboard plow and disk, can increase the chance of wind and water erosion in semi-arid dryland cropping systems. In the northern grains-growing regions of Australia, farmers typically use tillage implements such as a disc, chisel blade, or a sweep plow (Dang et al., 2015). The authors note that high mixing tillage operations can be helpful in some instances, especially with issues in NT farming operations.

Challenges of long-term no-tillage systems

Although NT can help conserve soil water, long-term it can create a few unintended negative influences. Continuous NT practice can influence stratification of soil nutrients, SOM, acidification in the upper soil surface, and increased bulk density (Obour et al., 2017). Nutrients concentrated at the soil surface can be susceptible to loss through runoff, erosion, and volatilization, particularly nitrogen (Blanco-Canqui and Wortmann, 2020). In addition to these undesirable effects, NT can also influence timely planting of crops. Low surface soil temperatures can postpone planting as well as slow crop germination and emergence (Baan et al., 2009).

In addition to the influence on planting, NT can also allow for varmint holes to form and to go uncorrected, which can cause a rough surface for the various field operations that take place throughout the growing season (Obour et al., 2021). There is also a possibility of having higher populations of HR weeds in long-term NT systems. In Nebraska, there are up to 41 weed species recorded to be resistant to glyphosate (Sarangi et al., 2018). Oreja et al. (2024) investigated HR weeds in dryland agriculture in Argentina and found 24 species have developed herbicide resistance, and of those 24 weed species, 54% were grasses, 88% were annuals, and 63% were cross-pollinated species. When breaking down their rotation, it was found that wheat/barley and fallow had the least number of resistant species with results of 10 and 9 resistant species (Oreja et al., 2024). With rising herbicide prices, developing and implementing plans for managing HR weeds will become more important for farmers to maximize profits.

Weeds

Weeds have been an issue in farming for numerous years, but with increased use and reliance on herbicides, HR weeds are becoming more difficult to deal with. The first thought in combating weeds is to use crop rotation because in NT and OT systems tillage is not consistently used (Weisberger et al., 2019). The authors found that a diversified crop rotation can decrease weed abundance by 49%, and the greatest reductions were found in NT systems. A review completed by Anderson (2015) reported that a complex NT cropping system with various crops instead of a monoculture can reduce weed emergence up to 4-fold in some annual crops, delay weed emergence up to 4 weeks, and reduce yield loss due to weed interference. Another key consideration when building a complex crop rotation is to incorporate annual crops with different growing seasons. For instance, Anderson (2008) reported that arranging the crops in a sequence of two cool season crops (e.g. winter wheat) followed by two warm season crops (e.g. grain sorghum or corn) can reduce weed densities 5- to 6-fold compared to a winter crop followed by a summer crop.

In addition to having a diverse crop rotation, other key considerations for producers would be using various herbicide modes of action and application timing in relation to planting. There are numerous weed species that have developed resistance to herbicides, so avoiding the use of repeated application of chemistry is important. The first case of herbicide resistance in weeds was in 1957, and since then, 255 weed species in 93 crops and in 70 countries have reported HR in weeds (Hossein et al., 2019). Weeds have become resistant to multiple modes of action (MOA), and the modes of action with the highest number of herbicide resistance recorded are inhibition of Acetolactate Synthase (HRAC Group #2), photosystem II inhibitors (HRAC Group #5), and inhibition of Enolpyruvyl Shikimate Phosphate Synthase (HRAC Group #9) (Heap, 1993). Producers typically will apply either or both a pre- and post-emergence herbicide. With the absence of a post-emergence herbicide, Calado et al. (2009) noted a 20% reduction in wheat yield. The authors also reported that wheat yield was influenced by the amount of weed dry matter at wheat heading stage and harvest, so there was a lack of post-emergence control.

In the CGP, the common HR weeds are palmer amaranth (*Amaranthus palmeri*) and kochia (*Bassia scoparia*) (Kumar et al., 2019). In a review on kochia, reported yield losses with HR kochia were 68% in corn, 62% in sorghum, 52% in soybeans (Glycine max), 46% in sugar beet (Beta vulgaris subsp. vulgaris Altissima Group), and 20% in wheat, and these losses only account for when the kochia was allowed to germinate with the crop, which resulted in interference for the whole growing season (Geddes et al., 2022). The authors also noted the crop yield loss are influenced by a few factors, such as kochia density, emergence timing, and the environment (Geddes et al., 2022). Palmer amaranth plays a large role in decreasing yields in the CGP. In double crop sorghum in Kansas, Palmer amaranth seeds can emerge and be established alongside the crop (Hay et al., 2019). However, in NT systems as well as double crop systems, tillage is not an option because producers want to save soil moisture for their next crop. If Palmer amaranth is not controlled in grain sorghum, the yield can be reduced as much as 57% (Moore et al., 2004). To summarize what the previous authors mentioned, both kochia and Palmer amaranth can be detrimental to crop growth and yield because of how competitive they are with crops. When weeds and crops are emerging at the same time, they are both competing for the same resources, such as nutrients, water, and sunlight.

Producers deal with weed emergence before, during, and after the growing season as well as the weed seeds from the WSB. The WSB is one of the keyways crop fields can encounter weed infestations because it has the potential to build up with more weed seeds every growing season. The WSB can range from 4,100 to 137,700 seeds m^{-2} (Maqsood et al., 2020). With such a high density of weeds, the authors note producers cannot always predict what weed species will emerge or when. In addition to a variety of weeds being present, the authors note the weeds may already be resistant to herbicides if the prior generation survived previous applications. A study conducted in Ohio compared continuous corn (C-C-C), corn-soybean (C-S), and corn-oats (*Avena sativa*)-hay (*Medicago sativa*) (C-O-H) rotations under moldboard plow, chisel plow, and NT (Cardina et al., 2002). The authors reported seed density was highest in NT and declined as tillage intensity increased. It was also reported by the authors that weed density was highest in NT-CCC with at least 8,680 seeds m^{-2} and as many as 26, 850 seeds m^{-2}. Tillage impacted seed density with NT C-C-C having 40% greater seed density than NT C-O-H, but the total seed density in C-C-C plots were 72% lower than C-O-H plots under a chisel plow or moldboard plow. However, the authors reported seed density was 45% higher in C-C-C than C-O-H plots under NT. A study conducted using an annual plant model found that crop rotation stacking can reduce the weed seed bank compared to rotation without stacked crops (Garrison et al., 2014).

If the weeds are resistant to various herbicide MOA, a solution to minimize the number of weeds would be a form of tillage. A review by Chauhan et al. (2012) notes that restricting tillage can reduce weed control options and increase reliance on herbicides. However, when implementing tillage, a key consideration is that the type of tillage can influence the next generation of weeds that have the potential to emerge and compete with the growing crop or deplete the soil of nutrients and water. Thomas et al. (2004) found that annual weeds, such as field pennycress (*Thlaspi arvense)*, were more abundant after CT compared to NT and RT. Interestingly, weeds such as redroot pigweed (*Amaranthus retroflexus* L.) were not influenced by a specific form of tillage, and Canada thistle (*Cirsium arvense)* was associated with NT and RT (Thomas et al., 2004). Although previous research characterized how weed species responded to

CT, RT, and NT, minimal work has been done with strategic tillage and its potential effects on weed population and weed density.

Soil properties

Tillage can influence soil properties such as erosion, aggregate stability, compaction, evaporation, and SOM. Tillage increased residue decomposition rate, so CT fields had less SOM compared to NT (Mallory et al., 2011). In addition to CT changing soil properties, it leaves little crop residue on the soil surface, which can increase wind and water erosion (Basir et al., 2017). Although NT maintains or builds SOM and retains crop residue on the soil surface, it can also have some undesired effects on soil properties, such as nutrient stratification and increased soil acidification (Deubel et al., 2011; Mikha et al., 2013; Lopez-Fando and Pardo, 2009; Obour et al., 2017).

Because NT and CT can both have unintended negative effects, conservation tillage practices, such as OT and ST, were developed. In a study conducted by Obour et al. (2021), ST with a sweep plow reduced the presence of HR weeds and reduced the stratification of nutrients. In a study conducted in Australia, the introduction of ST reduced weed populations and improved crop productivity in the first year, yet there was no effect on crop productivity in the subsequent 4 years (Dang et al., 2017). While there aren’t consistent findings using ST, it can reduce the potential for wind and water erosion compared to CT, and it also allows for the control of HR weeds as well as reducing nutrient stratification.

Compaction

A concern with NT, OT, and RT is the possibility for increased soil compaction. Excess soil compaction can cause a decrease in soil aeration, root development, water uptake, and overall crop growth. Grant and Lafond (1993) found that both penetration resistance and bulk density were increased in the top 10 cm of the soil in NT in comparison to CT in heavy clay soils. However, they also concluded that the reported bulk densities were not large enough to have hindered crop growth. In a study conducted in western Kansas, Obour et al. (2021) found that ST or RT could lead to reduced soil bulk density in the top 0-to-15 cm of the soil when compared to long-term NT. However, ST in an otherwise NT system did not affect aggregate size distribution or mean weight diameter (MWD) of aggregates (Obour et al., 2021). Blanco-Canqui et al. (2020) reviewed nine studies comparing NT and OT bulk density values, which did not change in five, decreased in three, and increased in one with OT. The authors indicate that effects of OT on soil bulk density can fluctuate and vary. Blanco-Canqui et al. (2009) found tillage intensity and equipment can have an influence on soil compaction, and their results concluded that soil compaction was found to be higher when the soil is tilled with a moldboard plow compared to a chisel plow and disk. MacLaren et al. (2020) concluded that the best management practices to achieve soil health are adopting NT and diversified crop rotations.

On the other hand, OT can be correlated to a variety of results regarding hydraulic conductivity (HC). Díaz-Zorita et al. (2004) concluded that chisel plow-disk tillage in a 20-yr NT soil every other year for 8 yr caused a reduction in mesopore volume by 18% and HC by 69% compared to NT. While HC can be decreased with tillage, total porosity (TP) can be reduced under NT practices compared to CT. In dry soil, the soil TP, which is the measure of overall pore space in the soil, increased 5% with tillage compared to when the soil was undisturbed (Kay et al., 2002). The conversion from CT to NT can also cause a reduction in porosity, but this can be attributed to a change in pore size distribution. The authors noted there is potential for an increase in pore sizes of 100-to-500 µm and a decrease in the 30-to-100 µm pore sizes. These different pore sizes can be created by various abiotic (tillage, traffic, freezing and thawing) and biotic (root growth, earthworms) factors. In a short timeframe, pores near the base of a tillage zone could change because of consistent tillage at the same depth, which would begin the formation of a plow pan. In addition to the formation of a plow pan, pore characteristics could also change because of soil microorganism presence and activity (Kay et al., 2002). Kirkegaard et al. (2020) studied the effects of ST on long-term NT soils using a rotary hoe. The authors found that the bulk density at the 0-to-5cm depth in the ST treatments reconsolidated after the first disturbance, and there was lower bulk density in the ST treatments in the 5-to-10cm layer. The difference was largest in the 5-to-10cm depth but disappeared after 2 years.

Increase water infiltration & storage

Water storage and infiltration are key concerns in the CGP because water is the most limiting factor in crop production in this region. The use of tillage can cause increased water evaporation resulting in lower water storage. Blanco-Canqui et al. (2018) found that NT management can increase water content by 17 to 32% compared to CT practices at the 0-to-15-cm depth. However, when NT was compared to RT, NT increased water content from 5% to 32% in two soils and had no effect in two, which shows that results between RT and NT can be mixed. However, in a review, Blanco-Canqui and Wortmann (2020) reported that in most cases OT did not reduce soil water content. A key factor to consider in NT and tillage systems is residue, and the authors mentioned crop residue accumulation can lead to reduced infiltration and delayed residue decomposition. Schlegel et al. (2020) investigated the effect of occasional tillage in a winter wheat-grain sorghum-fallow rotation with the tillage treatments of a complete NT system, a single tillage pass in May or June during fallow period ahead of wheat planting (STBW), and a single tillage pass after wheat harvest in July (STAW) at Garden City and Tribune, KS. In Garden City, available soil water at planting (ASWP) was measured from 0-to-

90-cm, and it was also reported that available soil water (ASW) was greater below 90-cm compared to the 0-to-90-cm depth at Garden City. In Tribune, the authors reported the key difference was the upper soil profile had greater ASW compared to the lower soil profile. However, the authors reported there were no significant differences in the tillage treatments for either crop at the respective locations for ASWP. For available soil water at harvest (ASWH), the authors reported Garden City had greater ASW deeper in the soil profile, but the ASW at Tribune was greater in the upper soil profile compared to the lower soil profile. However, similarly to ASWP, tillage treatment had no effect on ASWH. For the ASW in the whole soil profile, the authors noted ASW at planting and harvest for both crops were similar in all treatments at both locations, and the total profile ASW was greatest at planting compared to harvest due to evapotranspiration.

To enhance the NT practice, additional management techniques may need to be added. For example, the addition of cover crops (CC) can aid in improving soil hydraulic properties, and Courtland et al. (2021) observed a trend that CC treatments had greater soil water recharge following termination compared to a normal fallow period. Holman et al. (2021) investigated replacing the fallow period in a winter wheat-grain sorghum-fallow rotation with CC. The authors reported the ASWP for CC was greatest for spring CC compared to fall or winter CC. The authors also investigated the influence of leaving the CC standing or haying the CC, and it was reported that ASWP for winter wheat was 4-27% greater for CC left standing compared to hayed CC. Another management technique would be introducing OT to increase water infiltration. Tillage can aid in infiltration because it can create large pores, which can also allow for deep water infiltration. However, creating large pores can increase water evaporation from the deeper soil layers (Lampurlanes et al., 2006). Singh et al. (2006) reported there was 33%

lower water infiltration under NT compared to tilled treatments. In the CGP region, water evaporation from the soil can be harmful to overall yield. Blanco-Canqui et al. (2020) noted that, while OT disturbs the soil and can alter surface-connected macropores, it also loosens the soil and creates large voids or channels, which can help increase water infiltration. Schlegel et al. (2020) reported water use and crop water productivity in response to OT. At Garden City and Tribune, grain sorghum and winter wheat water use varied year to year, but the tillage treatments had no influence on water use for either crop. Similarly to the results of water use, crop water productivity for grain sorghum and winter wheat varied by year, but there were no differences across tillage treatments within a year.

Erosion Potential

Since soil aggregates are very important to soil structure, they can be classified into a few different categories. Biogenic aggregates are formed by decomposing plants and faunal excrements, and thus, biogenic aggregates can be associated with a diverse soil community (Ferreira et al. 2020). Physiogenic aggregates are formed by physical and chemical processes, such as wetting and drying cycles, physical soil compression, and organo-mineral interactions (Pulleman et al., 2005). Intermediate aggregates are formed by both physiochemical and biological pathways, so interactions with soil microorganisms and organo-minerals can form these aggregates. Ferreira et al. (2020) reported that physiogenic and biogenic aggregates differed in their sensitivity to various soil management techniques. They found that a high concentration of physiogenic aggregates was found in long-term NT soil compared to tilled soil, which could be associated with the lack of soil disruption. However, with NT, a smaller concentration of biogenic aggregates was found, and with a higher presence of physiogenic aggregates, the authors mention this indicates soil compaction. Thus, long-term NT soil can be associated with forming more physiogenic aggregates but decreasing the number of biogenic aggregates, and with the reduction of biogenic aggregates, this indicates a reduction in soil biological activity.

In the CGP, wind and water erosion are two factors contributing to loss of soil, and there is an extreme importance of maintaining soil structure in semi-arid regions (Blanco-Canqui and Wortmann, 2020). Dry aggregate stability is a key characteristic of soil and is linked to a strong correlation of a soil's resistance to wind erosion and degradation, and dry aggregate stability can also be used to indicate soil structure. A common index of dry aggregate stability is dry mean weight diameter (DMWD). High DMWD values can depict high water permeability and air capacity and low erodibility of soil (Ciric et al. 2012). On the other hand, wet aggregate stability is how susceptible soil aggregates are to water erosion. Blanco-Canqui et al. (2018) summarized the dry aggregate stability of CT and NT fields in seven studies and found NT can increase dry aggregate stability by 19 to 81%. However, in seven other studies, the authors found NT did not influence dry aggregate stability. However, NT has been found to have greater dry and wet aggregate stability compared to CT. In a study conducted by Pi et al. (2019), dry aggregate stability was found to be 24 to 114% higher in NT summer fallow fields compared to CT fallow treatments. A review by Blanco-Canqui et al. (2018) reported that NT can increase wet aggregate stability in 74% of cases. In the upper 30 cm of the soil, NT can increase wet aggregate stability by 1 to 97%. However, the authors also reported that NT has the possibility to not improve aggregate stability in 24% of cases (Blanco-Canqui et al. 2018). The largest difference in aggregate stability between NT and CT was found in the 0-to-5 cm depth. These studies show that NT can have mixed effects on dry aggregate and wet aggregate stability.

However, while OT can increase erodibility compared to NT, Blanco-Canqui et al. (2020) compared dry and wet aggregate stability in three studies and found that aggregate stability did not change in two studies and decreased in one following OT. This suggests that soil health parameters can still be maintained with OT. Maintaining stable aggregates is important for soil health. Improving the aggregate stability can reduce water and wind erosion, increase porosity, increase water infiltration, and improve other soil physical characteristics.

Soil Organic Carbon (SOC) and Soil Organic Matter (SOM)

Soil organic matter (SOM), which is affiliated with plant and animal decomposition, influences and stabilizes different pore sizes and affects several soil biological, chemical, and physical processes (Kay et al., 2002). When soil is exposed to stress, the authors note SOM can increase the amount and diversity of pore sizes because of its role in the stabilization of the pores. Changes in SOM and its characteristics can take years before a noticeable difference is observed, and the SOM distribution through the soil profile can influence soil porosity and pore characteristics (Kay et al., 2002).

In addition to SOM, soil organic carbon (SOC), which is the carbon component of organic compounds within the soil, also has many roles in crop growth. For numerous plants, up to 50% of the carbon fixed during photosynthesis is translocated below-ground (Buyanovsky and Wagner, 1997). Soil organic carbon can be used for structural growth of the root system, autotrophic respiration, and it can be lost to surrounding soil through rhizodeposition (Baker et al. 2007). Due to the lack of soil disturbance, it is common to see that SOC in NT systems has been stratified compared to CT or RT systems. Hernanz et al. (2009) found that SOC measured in CT and minimum tillage were less stratified compared to NT. However, Kirkegaard et al.

(2020) found that ST had the effect of redistributing SOM rather than reducing it. Surface-retained SOM can be subject to decomposition and loss over time from the system.

During erosion related processes, up to 26% of SOC can escape from the soil to the atmosphere (Oost et al. 2007). Therefore, limiting tillage passes or practices can aid in minimizing wind erosion losses of SOC. In a study conducted by Chowaniak et al. (2020), SOC in NT plots was found to be 8.7% to 11.1% higher than in CT plots. The added crop residue on the soil surface may have allowed for an increase in carbon accumulation. Interestingly, Obour et al. (2021) found that SOC concentration was affected by the interaction of Rotation × Depth as well as the interaction of Tillage × Depth. Soil organic carbon was 27% greater in the 0-to-5 cm depth in a continuous wheat rotation compared to wheat-fallow and wheat-sorghum-fallow, and SOC was 17% less in RT compared to ST and NT (Obour et al., 2021). However, with ST, Obour et al. (2021) found that SOC concentration was not influenced below the 5-cm depth.

Stratification of soil nutrients and pH

While NT has several positive effects on soil conservation, there are a few negatives, and one of those is the stratification of soil nutrients. With the introduction of ST in long-term NT systems, Obour et al. (2021) found that the mean soil pH measured at the 0-to-5-cm depth was unaffected by Tillage as well as the Tillage × Rotation interaction, and the soil pH in the upper 0-to-5-cm was lower than the 5-to-15 cm or 15-to-30 cm depth. There have also been interesting results regarding nutrient stratification as well. The authors reported the Tillage × Depth interaction influenced NO_3-N concentration, so concentrations of NO_3-N at the 0-to 5-cm depth was greater in ST compared to NT or RT. However, the authors noted NO_3-N was unaffected by tillage in the 5-to-15-cm or 15-to-30-cm depths, but NH_4-N in the 0-to-5-cm depth was less in ST and RT compared to NT. The authors also noted soil P was unaffected by tillage or crop rotation, but it was greater in the 0-to-5-cm depth compared to the 5-to-15-cm and 15-to-30-cm depths. Conyers et al. (2019) found soil pH, phosphorus, carbon, and nitrogen to be stratified in the soil surface in on-going NT compared to ST, which was done with a scarifier or offset discs. However, research by Wortmann et al. (2010) reported that stratification of soil P and SOC 5 years after one-time tillage was similar to continuous NT, and the tillage treatments that were compared to NT were: chisel plow with four-inch-wide twisted shanks at 30-cm depth, chisel at 20-cm depth, dish at 10-cm depth, and moldboard plow at 20-cm depth. Obour et al. (2017) also reported significant accumulation of soil P in the upper 7.5-cm under NT compared to CT or RT. The authors described CT as tillage with a tandem disk at 15-cm deep as well as a field cultivator, and the tillage occurred 3 to 4 times in the fallow phase prior to winter wheat planting. The authors also described the RT treatment as tillage being done a sweep plow, and it was noted that 2 tillage operations were completed prior to wheat planting and 1 operation prior to sorghum planting.

Soil microbes and biological activity

Soil biota and the processes associated with them have numerous direct and indirect effects on several soil properties and crop growth. A couple of the most important soil microorganisms are earthworms and collembola, which both help with soil structure and nutrient cycling. However, in tilled fields, there tend to be less earthworms because of the physical damage from the plow (Coulibaly et al. 2022). On the other hand, collembola can be affected because the soil can become inverted and influence their environment. Both earthworm and collembola abundance were higher in NT systems compared to RT and CT systems (Coulibaly et al. 2022). Converting from CT to NT can result in several changes in the soil, but one of the key changes would be a change in fungi and bacterial presence. One key fungus that can be seen to increase in a conversion from CT to NT is arbuscular mycorrhizal fungi (Jha et al. 2022). In addition to an increase in arbuscular mycorrhizal fungi, glomalin, which is a glycoprotein, is produced by these mycorrhizal fungi and is associated with improved soil aggregation (Jha et al. 2022).

In a study conducted in New South Wales, Australia, the effect of ST on species richness within the soil was investigated (Fang et al., 2022). Interestingly, the authors reported ST did not affect the bacterial richness or diversity, and the fungal community within the soil also was not affected by tillage. Strategic tillage also had interesting effects on soil bacteria. The authors reported ST aided in the increase abundance of bacterial *Blastococcus* (genus of *Geodermatophilaceae), Geodermatophilaceae* (family of Actinomycetales, Actinobacteria phylum), and *Sporosarcina* (genus of *Planococcaceae,* Firmicutes phylum), but strategic tillage decreased the overwhelming number of Solirubrobacterales (order of Actinobacteria, Actinobacteria phylum), class Spartobacteria (Verrucomicrobia phylum), and unidentified bacteria (Fang et al., 2022). Regarding fungi, ST had varying effects. Strategic tillage increased the abundance of fungal taxa *Auriculariaceae* (a family in Agaricomycetes class, Basidiomycota phylum), but it also decreased Pezizales (order in Ascomycota phylum) (Fang et al., 2022).

Summary, Objectives, and Hypothesis

The use NT systems has increased in recent years due to the benefits that can be seen in dryland crop production in the semiarid areas of the CGP. Some benefits are improvements to soil health, increased retention of soil moisture, improved crop yields, and reduced wind and water erosion. However, there have been some drawbacks associated with long-term NT as well, and these are HR weeds, nutrient and pH stratification, and compaction of the field. Due to these issues producers are experiencing, the incorporation of tillage in cropping systems has become more prominent because it is a way to save money due to the high costs of controlling HR weeds. Research from Obour et. al (2021) showed strategic tillage (ST) with a sweep plow in an otherwise NT cropping system has the potential to manage HR weeds and results in no negative impact on crop yields. However, the long-term effect of ST on soil properties and crop yields are unknown in water-limited environments of the CGP. Previous research by Schlegel et al. (2020) highlight aspects of OT on available soil water, water use efficiency, and crop yields. However, there was no investigation on the influences of OT on soil physical and chemical properties, and there is minimal information available on the long-term effect of OT on soil properties and crop yields.

The objectives of this research are to:

1. Determine the effect of strategic tillage and occasional tillage on soil properties
    a. Strategic tillage hypothesis: Soil properties will not be different among tillage practices 6 years following implementation of ST in an otherwise NT soil.
    b. Occasional tillage hypothesis: Increased tillage will cause a negative effect on soil properties
2. Assess the effect of strategic tillage and occasional tillage on crop yields
    a. Strategic tillage hypothesis: Crop yields will not be different among tillage treatments
    b. Occasional tillage hypothesis: Increased tillage intensity will negatively impact crop yields
3. Investigate the effect of strategic tillage and occasional tillage on weed abundance and diversity

a. Weed diversity and abundance will be less with the use of tillage for both strategic tillage and occasional tillage
b. Weed diversity will be greatest under no-tillage compared to other tillage treatments.

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Chapter 2 - Strategic tillage effects on soil properties and crop yields in semi-arid dryland cropping systems

Abstract

In the semi-arid central Great Plains (CGP) of the United States, long-term no-tillage (NT) systems struggle with herbicide-resistant (HR) weeds as well as nutrient and pH stratification. Strategic tillage (ST) in long-term NT systems could aid in solving these issues, but there is little information on the effect of ST in traditional crop rotations of the CGP region. This study investigated the effect of one-time ST (6 years ago) on HR weeds, soil properties, and crop yields in an otherwise long-term NT. The experiment design was a randomized complete block with three replications in a split-plot treatment structure with crop rotation as main plots and tillage as sub-plots. The cropping rotations were continuous wheat (*Triticum aestivum* L.) (WW), wheat-fallow (WF) and wheat-grain sorghum (*Sorghum bicolor* L.)-fallow (WSF). Subplots were continuous NT, ST, and reduced tillage (RT). Tillage was implemented using a sweep plow, which allows for minimal residue disturbance. Data was collected one time in July of 2022 to determine the effects of ST and RT compared to NT on grain yield (over 6 years), weed density and diversity, and soil properties in the crop rotations. Rotation and tillage had no significant effect ($P < 0.05$) on soil bulk density. However, bulk density was less in the 0- to-5-cm soil depth compared to the 5-to-15-cm and 15-to-30-cm depths, with values of 1.16, 1.44, and 1.39 g cm^3, respectively. Soil organic carbon (SOC) concentration was greatest in the 0-to-5-cm soil depth. The SOC concentration in ST was not different than NT or RT, whereas soils under RT had 8% less SOC than NT. Wind erodible fraction (WEF) was not different among tillage treatments. However, mean weight diameter (MWD) differed among tillage treatments, with NT having greater MWD compared to RT but not different from ST. Winter wheat yield was greatest in RT across the crop rotations. Strategic tillage increased wheat yields in WW compared to NT, which is partly due to improved weed control. Grain sorghum yield was not different between ST and NT, but the ST and NT treatments had 12% and 13% greater yields than RT. Across rotations, WF had 59% greater weed abundance compared to WW or WSF. Shannon's Diversity Index (SDI) was greatest in NT particularly in WSF (1.07) and WF (1.06) rotations compared to WW (0.33). Values for SDI were smallest for RT compared to the other tillage treatments in all rotations. The SDI values under ST were most in the WF and WW rotations compared to WSF rotation under ST. Overall, ST had no negative effect on soil properties or crop yield and can be a mitigation option to control herbicide resistant weeds and increase profitability of dryland crop production.

Introduction

Historically, no-tillage (NT) farming has been known to store more soil water and can allow cropping intensification in dryland environments across the semi-arid CGP of the United States due to the maximization of crop residue on the soil surface (Anderson 2004). However, Holman et al. (2021) found that RT can increase soil water compared to NT ahead of winter wheat or winter triticale (*Triticosecale Wittm. ex A. Camus* (*Secale* ×*Triticum)* planting. Overall, NT is known to have several soil health benefits including reductions in soil erosion from wind and water, accumulation of soil organic carbon (SOC), and improvement of soil structure (Baumhardt et al., 2017; Blanco-Canqui and Ruis, 2018; Hansen et al., 2012). However, NT relies heavily on herbicides such as atrazine and glyphosate for weed control during fallow and in-crop. This has resulted in the development of herbicide-resistant (HR) weed species such as kochia [*Kochia scoparia* (L.)], green foxtail [*Setaria viridis* (L.)], redroot pigweed (*Amaranthus retroflexus* (L.), and barnyardgrass [*Echinochloa crus-galli* (L)] (Anderson 2004; Dille et al., 2017). With the increase in HR weeds, some producers are incorporating other weed management practices. One practice that has gained popularity in weed control is cover crops, and the review by Kumar et al. (2020) highlights the reduction in costs of managing HR weed populations with the use of cover crops.

With long-term NT, stratification of soil properties can build up over time and cause issues for producers, so a tillage pass could help mitigate some of these problems. For example, soil compaction, stratification of pH and nutrients, and the increased loss of nutrients to runoff could be mitigated with the use of ST (Dang et al., 2015; Obour et al., 2017). In addition to these soil chemical properties, long-term NT can also negatively affect soil physical properties. A study conducted in a semi-arid agroecosystem reported greater bulk density and penetration resistance values in NT soils (Amami et al., 2022). In their study, penetration resistance increased by 149% with NT, and bulk density was 16.4% more compared to conventional tillage (CT) treatments (Amami et al., 2022). These issues caused by long-term NT farming are forcing producers to rethink their current management practices and adjust to techniques that are more flexible without losing the soil health benefits that have built up over time with NT.

Introducing tillage in NT farming systems could cause negative effects on the soil. For instance, research has demonstrated that soil biological communities and soil aggregates could be disrupted by tillage operations (Mitchell et al., 2015). Tillage also has been shown to lead to a decline of SOC (Six et al., 2004). Dobrzeniecki et al. (2012) compared various soil properties across tillage treatments of conventional tillage (CT), RT, and NT, and their results showed NT had the highest volumetric water content followed by RT then CT. In addition to the negative effects on the soil, another issue with introducing a pass of tillage to a long-term NT field is the changes and seed increases in weed seed bank. Young et al. (2014) investigated postharvest tillage in a winter wheat-fallow system with four different types of tillage, which were a disk, sweep plow, harrow, and skew treader. Due to more soil inversion, the authors noted the sweep plow and disk led to an increased movement of downy brome (Bromus *tectorum*) seed deeper in the soil profile compared to the NT treatment. However, the disk and sweep plow were able to decrease the downy brome seed near the soil surface in the depth when contrasted to NT and harrow treatments (Young et al., 2014). A concern is that a second tillage operation would then reinvert the buried seed back to the soil surface where it could germinate.

There are several types of tillage practices, such as occasional tillage (OT) and strategic tillage (ST). Occasional tillage (OT) is defined as a single tillage operation in the fallow phase of a 3-yr winter wheat-grain sorghum-fallow rotation (Schlegel et al., 2020). Vandeveer et al. (2023) reported the economics on OT in a winter wheat-grain sorghum-fallow rotation. The authors reported net returns between NT and OT were not different. Additionally, the authors found that crop yields were not affected in the first five years following the implementation of OT. Another emerging type of tillage is ST, which refers to the practice of a one-tillage tillage operation in an otherwise NT cropping system to manage HR weeds and nutrient stratification issues. After the one-time tillage operation, the field would go back to NT production (Obour et al., 2021). Strategic tillage with a sweep plow should be timed when soil erosion risk is lowest. This ST approach could increase productivity and profitability of dryland cropping systems. Obour et al. (2021) found that incorporating ST can mitigate a few problems associated with NT farming systems. Their findings concluded that ST could reduce the presence of HR weeds in NT fields with little effect on crop yield, soil organic carbon (SOC), and aggregate stability. In their study, SOC with ST was similar to long-term continuous NT, but both tillage treatments were 17% greater than RT.

In a study in Australia, Kirkegaard et al. (2020) found that ST can significantly aid in the redistribution of pH, SOC, and nitrogen. In the 0-to-5 cm layer, a decrease was observed in these parameters, but in the 5-to-10 cm and 10-to-15 cm layers, an increase was observed. The authors noted the soil C and N concentrations were similar following the initiation of ST, however, the effects of ST on pH declined over time throughout the soil profile. Interestingly, Obour et al. (2021) found pH in the 0-to-5-cm depth to be lower than that measured in the 5-to-15-cm or 15-to-30-cm depths. Reduced tillage had 17% less SOC compared to ST and NT. In a wheat-fallow rotation study in western Nebraska, declines of SOC in the 0-to-7.5-cm depth were 27 and 40% for CT with a moldboard plow compared to sub-tillage and NT (Doran et al. 1998). Kettler et al. (2000) conducted a similar study in western Nebraska and found there was 5% greater pH and 20% higher soil nitrogen with ST, which could benefit plant growth and productivity. In addition to the research conducted on soil physical and chemical properties, there has also been researched that reported soil biological factors. Rincon-Florez et al. (2020) investigated the effects of one-time ST after 44 years of continuous NT or CT on soil microbial diversity, biomass, and enzymatic activity at two depths. The authors found one-time ST had no significant effect on bacterial or fungal community composition regardless of previous tillage management or depth.

In addition to soil physical, chemical, and biological properties being investigated and reported, studies have also reported crop yield in response to ST. Kettler et al. (2000) reported up to an 18% increase with ST on winter wheat grain yield. Obour et al. (2021) observed an increase with ST and RT in winter wheat yields compared to NT, but in grain sorghum yield, ST and NT yielded more than RT. Schlegel et al. (2020) investigated the influence of OT on soil water, total profile water, water use, crop water productivity, biomass, and grain yields, and the authors reported none of these parameters were influenced by OT. However, in Australia, Dang et al. (2017) observed no significant differences in grain yield between NT and ST. In another Australian study, Conyers et al. (2019) reported similar results to the previous authors mentioned and observed neutral or minor effects on crop dry matter and grain yield. There appears to be varying effects of ST on crop yields.

Overall, there is minimal information on the long-term (>5 years) effects of ST on various indicators of soil health and crop yields in the CGP. The objective of this study was to evaluate soil properties and crop yields 6 years after one-time ST. Specifically, this study investigated the i) direct effects of one-time ST (6 years ago) on soil physical and chemical properties and crop yield, and ii) how tillage practices affected weed abundance and diversity 6 years after ST. Our hypotheses were that soil properties and crop yields would not be different among tillage practices 6 years following a ST event in an otherwise NT soil. Furthermore, we hypothesized that weed diversity and abundance will be greater in NT compared to ST.

Materials and Methods

Experimental layout

This study used long-term experimental plots initiated in 1976 at the Agricultural Research Center - Hays near Hays, KS (38°52′46″N 99°19′20″W). However, in 2016, the experiment was modified to add ST in existing NT plots. The soil at the location of the study was a Crete silty clay loam (Fine, smectitic, mesic Pachic Udertic Argiustolls) formed from loess material at an elevation of 607 meters above sea level. The annual precipitation of Hays is 560 mm and has an open-pan evaporation (April-June) of 1741 mm.

The design of the study was a randomized complete block design with three replications in a split-plot treatment structure. Each split-plot was 12.2 m wide and 24.4 m long prior to the addition of ST, but in 2016, the long-term NT plots were split equally into two plots with dimensions of 6.1 m wide by 24.4 m long. One half was left in continuous NT and the other half was tilled. Main plots were three crop rotations [continuous winter wheat (WW), wheat-fallow (WF), and wheat-sorghum-fallow (WSF)] with each phase of the rotation present every year, and subplots were no-tillage (NT), strategic tillage (ST), and reduced tillage (RT).

For tillage of the ST plots, the first pass was done with a Premier Tillage Minimizer (Premier Tillage Implements, Quinter, KS) at the depth of 7.5 cm, equipped with pickers to aid in controlling herbicide resistant weeds, such as kochia and tumble windmill grass. A second tillage pass was done 3 days later with a Quinstar Fallow Master sweep plow (Quinstar Equipment Company, Quinter, KS), but the depth was 15 cm to allow for adequate soil mixing and help with redistributing nutrients and pH in the soil profile. All tillage operations were performed in July prior to winter wheat planting in wheat-based rotations. For the crop rotations with grain sorghum (WSF), the tillage operations were conducted in May prior to sorghum planting in June. In the RT treatment, tillage was done with a V-blade implement (Premier Tillage, Quinter, KS) as well as Fallow Master sweep plow to aid in residue conservation. Two to three tillage operations at 15-cm deep were done in the RT plots during the fallow period, which takes place before winter wheat planting in the WF or WSF crop rotation. However, only one tillage operation occurs in the RT plots prior to sorghum planting in the WSF plots or wheat in the WW plots.

Soil sampling and analysis

Soil sampling first occurred in fall of 2016, three months after ST operations and before winter wheat planting [as previously reported by Obour et al. (2021)]. During the summer of 2022, soil sampling occurred again, with samples taken from all plots in each of the crop rotation phases. To assess bulk density, two soil cores (5-cm diameter) per plot were randomly taken from the 0-to-30-cm depths. The samples were dried at 105 °C for 48 hr, and bulk density was determined by mass of oven-dry soil divided by volume of the core. For the assessment of soil chemical properties, ten soil cores (2.5-cm diameter) were randomly taken from the 0-to-5, 5-to-15 and 15-to-30-cm depths with each depth composited before subsequent analysis for pH, nitrogen (NO_3-N and NH_4-N), Mehlich-3 phosphorus (M3-P), and soil organic carbon (SOC). These soil samples were air-dried and ground to pass through a 2 mm sieve. The Kansas State University Soil Testing Laboratory, following standard procedures, analyzed the soil samples for pH and extractable nutrients.

Briefly, the soil pH was determined potentiometrically by an electrode (Thomas, 1996). Soil nitrate-N (NO_3-N) and ammonium-N (NH_4-N) concentrations were determined colorimetrically once the samples were extracted with 2 M KCl. Soil available P was measured using the Mehlich-3 extraction method (Mehlich, 1984), and following the extraction, the M3-P concentration was measured using inductively coupled plasma-optical emission spectrometry (ICP-OES). The exchangeable Calcium (Ca), magnesium (Mg), and potassium (K) concentrations were determined by the ICP-OES after NH_4OAc extraction (Knudsen et al., 1982), and iron (Fe), manganese (Mn), and zinc (Zn) concentrations were determined by the DTPA extraction method (Lindsay and Norvell, 1978). The nutrient concentrations in the DPTA extract were measured using atomic absorption spectrometry. A portion of the soil samples from each plot were ground to pass through a 0.25 mm sieve, and SOC concentration was determined by dry combustion using a CN analyzer after pretreating samples with 10% (*v/v*) HCl to remove carbonates (Nelson and Sommers, 1996).

In addition to bulk density and nutrient samples, additional soil samples were collected from the 0-to-5-cm soil depth using a flat shovel for determining dry and wet aggregate stability. The samples were split into two, and half of the samples were passed through 8.0-mm mesh sieves and were allowed to air-dry and used for wet aggregate stability analyses. The 8.0-mm aggregate samples were used to estimate water-stable aggregates (WSA) using the wet-sieving method (Nimmo and Perkins, 2002). Sand corrections were conducted for each aggregate size fraction to remove sand particles, and then the data was used to compute aggregate size distribution and mean weight diameter (MWD) of water stable aggregates. The remaining half of the air-dried samples were used to determine dry aggregate stability with a system of nested rotary sieves with 19-, 6.3-, 2-, 0.84-, and 0.42-mm diameter openings (Chepil, 1962). Samples were shaken for 5 minutes using a portable sieve shaker (W.S. Tyler Model RX-812, Mentor, OH). The soil particles remaining on each sieve was weighed and the data was used to compute dry aggregate size distribution (ASDDA) and mean weight diameter of dry aggregates (MWDDA) as well as wind-erodible fraction (WEF).

Crop management

Winter what was planted in early October and harvested in the following July. After an eleven-month fallow period, grain sorghum was planted in June and harvested in mid-October. Winter wheat and grain sorghum yields over the study period were determined by harvesting an area 1.5 m wide by 24.4 m long from the center of each plot using a Kincaid 8XP single plot combine harvester (Kincaid, Haven, KS). Grain moisture content was determined using a DICKEY-john grain moisture tester (DICKEY-john Inc., Auburn, IL), and yield of both wheat and grain sorghum were adjusted to 13.5% moisture content.

Weed density analysis

Weed counts were conducted for all plots in June of 2023 prior to a POST emergence application of herbicides. Two quadrat (1 m × 1 m) counts per plot were taken and consisted of number of individuals of each weed species identified in the quadrat. The Shannon's Diversity Index is a measure of species diversity. Using the numbers from the June 2023 sampling, the weed species and quantity were then used to compute the Shannon's Diversity Index (SDI) to quantify the influence of rotation, tillage, and crop phase on weed diversity. Each crop phase (i.e. fallow, wheat, and sorghum) was analyzed individually. The equation used for SDI was:

$$H = -\Sigma pi * \ln (pi)$$

where Σ is the sum of the weeds emerged, pi is the proportion of the community made up of species *i*, and ln is the natural log (Ortiz-Burgos, 2016).

Statistical analysis

The data was tested for normal distribution and equal variance using the Shapiro-Wilk Test and Levene's Test to fulfill the assumptions for ANOVA. Data analysis for soil physical and chemical properties were performed using PROC GLIMMIX in SAS ver. 9.3 (SAS Institute, 2012, Cary, NC). Response variables were modeled against fixed-effect variables of rotation, tillage, depth, and their interactions. Replication and its interaction with fixed effects were considered random. Effects were considered significant at $P \leq 0.05$. Correlation analyses across variables were conducted using the PROC CORR procedure of SAS. Similar to soil properties, winter wheat grain yield response variables were modeled against fixed effects of rotation, tillage, year, and their interactions. However, grain sorghum yield response variables were modeled against tillage, year, and their interactions because sorghum was present only in the WSF rotation. Weed count and diversity data were evaluated using PROC GLIMMIX in SAS ver 9.3 (SAS Institute, 2012, Cary, NC). Response variables were modeled against the fixed-effect variables of tillage, phase, and their interaction.

Results

Long-term weather patterns

The precipitation received in western Kansas can vary year to year with there being some years with sufficient precipitation and others with significantly less, which can influence soil properties and crop yield. Annual precipitation from 2010 to 2015 averaged 490 mm, which was 81% of the 30-year average (Table 2.1). Adequate spring precipitation (March-May) allowed for winter wheat to continue growing and recharge the subsurface soil moisture. The average annual precipitation for 2014 to 2020 was 123% of the 30-year average. Although most years from 2014 to 2020 had above-average precipitation, 2010 to 2013 had 73% of the 30-year average. From 2017 to 2021, average precipitation was 162 mm less than the 30-year average. However, in 2022, precipitation was 161 mm less than the 30-year average. The lower precipitation in the past few years influenced winter wheat and grain sorghum yields as well as subjecting the soil to more shrinking cycles, which can have implications for soil physical properties such as bulk density and penetration resistance.

Soil organic carbon

There was not a significant 3-way interaction of Crop Rotation × Tillage × Depth for SOC, however, the SOC concentration was significantly affected by the interaction of Tillage × Depth and the main effects of Depth, Crop Rotation, and Tillage (Table 2.2). No-tillage at the 0-to-5-cm depth was 7% and 13% greater in SOC than ST and RT, respectively. However, SOC concentrations at the 5-to-15-cm and 15-to-30-cm depths were not different among tillage practices (Figure 2.1a). For the main effect of Depth, the 0-to-5-cm depth was 35% and 46%

greater than the 5-to-15-cm and 15-to-30-cm depths. Among rotations, the WW rotation had the greatest SOC concentration, which was 6% and 7% greater than the WSF and WF rotations, but the WSF and WF rotations were not significantly different from each other. When comparing Tillage treatments, the SOC in soils under NT and ST were not significantly different, and the values were 5% and 8% greater with ST and NT compared to RT.

Soil pH and nutrients

The Crop Rotation × Tillage × Depth interaction had a significant effect on soil pH (Table 2.2). In the 0-to-5-cm depth in the WW rotation, soil pH under RT was 12% greater than NT, but ST was not different from either NT or RT (Table 2.5). For the WSF rotation, the RT treatment had 5% greater pH compared to the NT and ST treatments, but for WF, soil pH was not different among tillage treatments. In all tillage treatments, Rotation significantly affected pH, with WSF > WF > WW. In the 5-to-15-cm depth, tillage did not affect pH in any rotation, and rotation differences within a tillage were observed only in NT and RT. Within NT, the WSF rotation had 6% higher pH than WW, and WF was not significantly different from the WSF or WW rotations. Within the RT treatment, a similar trend is observed with a 6% increase in the WSF and WF rotations compared to WW. In the 15-to-30-cm depth, soil pH was not affected by tillage treatments or crop rotation (Table 2.5).

In addition to the Crop Rotation × Tillage × Depth interaction, there was also a significant Tillage × Depth interaction and Crop Rotation × Depth interaction for pH. For the Tillage × Depth interaction, the RT treatment at the 0-to-5-cm depth had 5% and 7% greater pH than ST and NT (Figure 2.1b). In the 5-to-15-cm depth, the ST treatment was 3% greater than NT but was not significantly different from RT. Finally, the results from the 15-to-30-cm depth indicated NT and RT were 2% and 4% greater than ST but were not significantly different from each other. The Crop Rotation × Depth interaction had an effect on soil pH with a decline in pH near the surface in soils under WW compared to WF or WSF. In the WW rotation, soil pH at 15-to-30-cm depth was 30% greater compared to the 0-to-5-cm depth (Figure 2.2 a). Interestingly, the WF and WSF rotations had similar trends of increasing soil pH with depth. The 15-to-30-cm depth had a 21% greater pH in comparison to the 0-to-5-cm depth in the WF rotation, and the 15-to-30-cm depth had a 16% greater pH than the 0-to-5-cm depth in the WSF rotation. For the main effect of Rotation, the WW rotation had 5% lower pH compared to the WSF rotation and 3% lower pH in comparison to the WF rotation. The main effect of Tillage indicated the RT treatment was 3% greater than ST and NT, but ST and NT were not significantly different from each other. Finally, the main effect of Depth was significant, and the soil surface was 14% lower pH than the 5-to-15-cm depth and 22% lower pH than the 15-to-30-cm depth.

The three-way interaction of Crop Rotation × Tillage × Depth influenced M3-P concentration (Table 2.2). When comparing tillage treatments within a rotation at the 0-to-5-cm soil depth, the WW rotation under NT had 14% greater M3-P concentration compared to the WW rotation under ST, and reduced tillage was not significantly different from NT or ST (Table 2.5). For the tillage treatments within the WSF rotation, the soil M3-P concentration within 0-to-5-cm depth under NT was 28% greater than RT, but ST and NT were not significantly different. In the 0-to-5-cm depth within the WF rotation, the NT treatment had 28% more M3-P concentrations than RT, but ST was not significantly different from NT or RT. Within a tillage treatment at the 0-to-5-cm depth, the only difference observed was the difference of WW under RT compared to WSF and WF, and the WW rotation under RT had 31% and 35% greater M3-P concentration than WF and WSF. For the 5-to-15-cm depth, the RT treatment within the WW rotation was 26% and 44% greater than the NT and ST treatments. The other difference observed in the 5-to-15-cm depth was the differences of among rotations within the ST treatment. The WF rotation had 30% and 34% greater M3-P concentration compared to the WSF and WW rotations. The rest of the rotations within the tillage treatments observed no differences. For the 15-to-30-cm depth, the only difference was the tillage treatments within the WW rotation. The ST treatment had 46% and 75% greater M3-P concentration compared to the RT and NT treatments (Table 2.5).

The soil M3-P concentration was also significantly affected by Tillage × Depth as well as Crop Rotation × Depth interactions (Table 2.2). For the Tillage × Depth interaction, soil M3-P concentration in the 0-to-5-cm depth under NT was 20% more than that measured in RT soils (Figure 2.1c). In the 5-to-15-cm depth, the RT treatment had 13% and 20% more M3-P concentration compared to the NT and ST treatments, respectively. At the 15-to-30-cm depth, there were no differences across tillage treatments. For the Crop Rotation × Depth interaction, the soil M3-P concentration at 0-to-5-cm depth in the WW rotation was 20% more compared to the 0-to-5-cm depth for the WSF rotation for the Crop Rotation × Depth interaction (Figure 2.2b). Similarly, at the 5-to-15-cm depth, M3-P concentration with WW was 31% greater compared to the WSF rotation. For the 15-to-30-cm depth, the WF rotation had a 51% greater concentration of M3-P compared to the WW rotation. In addition to the significant interactions listed above, there were also significant main effects of Crop Rotation and Depth. The soil M3-P concentration was 8% and 12% higher in the WW and WF rotations compared to the WSF rotation. For the main effect of Depth, M3-P concentrations in the 0-to-5-cm depth were 77% and 92% greater than the 5-to-15-cm and 15-to-30-cm depth.

The three-way interaction of Crop Rotation × Tillage × Depth did not influence soil K concentration (Table 2.2). However, soil K concentration was significantly affected by Tillage ×

Depth interaction with RT at the 0-to-5-cm depth having 7% greater concentration than ST and 9% greater than NT (Figure 2.1d). In the 5-to-15-cm depth, the RT treatment was 5% greater in K concentration compared to ST and NT, but ST and NT were not significantly different from each other. Finally, in the 15-to-30-cm depth, there were no significant differences in K concentration among tillage treatments. In addition to a significant Tillage × Depth interaction, there were also significantly main effects of Tillage, Crop Rotation, and Depth. For the Tillage main effect, the RT treatment was 4% and 5% greater than ST and NT, but ST and NT were not significantly different from each other. The WW rotation had the greatest K concentration, which was 3% greater than the WSF rotation, and the WW rotation was not significantly different from the WF or WSF rotations. Along the soil surface, soil K concentration was 6% greater compared to the 5-to-15-cm and 15-to-30-cm depths, which were not significantly different from each other.

Soil Fe concentration was affected by the Crop Rotation × Tillage × Depth interaction (Table 2.2). In the 0-to-5-cm depth, the NT treatment within the WW rotation was 34% greater compared to RT, but ST was not significantly different from the other tillage treatments (Table 2.5). For the tillage treatments within rotations with fallow at the 0-to-5-cm depth, there were no differences in Fe concentration. For the WW rotation under NT, the soil K concentration was 31% and 42% greater than the WF and WSF rotations. The trend continues for the ST treatment, which the WW rotation was 25% and 37% greater than WF and WSF. Finally, for RT, the WW rotation was 12% and 27% greater than WF and WSF. In the 5-to-15-cm depth, no differences in Fe concentration were observed comparing tillage treatments within a rotation. However, differences were observed for the rotations within a tillage treatment. For both NT and RT, the soil Fe concentration in the 5-to-15-cm depth with WW was significantly greater than the rotations with fallow. Under NT, the WW rotation was 26% greater than WSF, and the WF rotation was not significantly different from WW or WSF. Under RT, the trend is similar with a 31% increase of soil K concentration in WW compared to WSF, and the WF rotation was not significantly different from the other rotations. Finally, for the 15-to-30-cm depth, no differences were seen in NT or RT treatments. However, under ST, the WW rotation was 37% greater than WSF, and the WF rotation was not significantly different from WW or WSF.

The soil Fe concentration was also significantly affected by the Tillage × Depth interaction as well as the Crop Rotation × Depth interaction (Table 2.2). For the Tillage × Depth interaction, the NT at the 0-to-5-cm depth was 8% and 24% greater than the ST and RT treatments at the 0-to-5-cm depth (Figure 2.1e). At the 5-to-15-cm and 15-to-30-cm depths, there were no significant differences across tillage treatments. For the Crop Rotation × Depth interaction, the WW at the 0-to-5-cm depth was 24% and 37% greater than the WF and WSF rotations at the 0-to-5-cm depth (Figure 2.2c). The 5-to-15-cm depth observed a similar trend, and the WW at the 5-to-15-cm depth was 8% greater than the WSF rotation. However, the WF rotation at the 5-to-15-cm depth was not significantly different from WW or WSF. In addition to the significant interactions, there were also significant Tillage, Crop Rotation, and Depth main effects. For the Tillage main effect, the ST and NT treatments were 12% and 17% greater than RT. The WW rotation was 17% and 28% greater than the WF and WSF rotations. Finally, for depth, the soil surface was 49% and 70% greater than the 5-to-15-cm and 15-to-30-cm depths.

The three-way interaction of Crop Rotation × Tillage × Depth was significant for Mn concentration (Table 2.2). When comparing tillage treatments within the crop rotations, no differences in Mn concentration were observed at the 0-to-5-cm depth (Table 2.5). However, within tillage treatments, the WW rotation was greater than the treatments with a fallow period.

In NT, the WW rotation was 29% and 38% greater than the WF and WSF rotation, but the WF and WSF rotations were not significantly different from each other. For ST, the WW rotation was 30% and 41% greater than the WF and WSF rotation, and the WF rotation was 16% greater than the WSF rotation. Finally, for RT, the WW rotation was 22% and 37% greater than the WF and WSF rotations, and the WF rotation was 19% greater than WSF. For the 5-to-15-cm depth, there were not differences of tillage treatments within a rotation, but the rotations under the NT and RT treatments observed differences. In NT, the WW rotation was 30% and 34% greater than WF and WSF, but the WF and WSF rotations were not significantly different from each other. For RT, a similar trend is observed with WW being 32% and 39% greater than WF and WSF, but the WF and WSF rotations were not significantly different from each other. For the 15-to-30-cm depth, the differences observed were within the ST treatment. The WW rotation under ST was 25% and 27% greater than WF and WSF, but the WF and WSF rotations were not significantly different. The other difference observed was the tillage treatments within the WW rotation. For the WW rotation, the ST treatment was 34% and 40% greater than the RT and NT treatments. There were no other differences observed at the 15-to-30-cm depth.

Manganese concentration was also affected by Tillage × Depth and Crop Rotation × Depth interactions (Table 2.2). For the Tillage × Depth interaction, soil Mn concentration under NT and ST was 14% greater than the RT treatment at the 0-to-5-cm depth (Figure 2.1 f). At 5-to-15-cm depth, the ST treatment had 11% less Mn compared to the NT treatment. In the 15-to-30-cm depth, soil Mn under ST was 21% more than the RT treatment. For the Crop Rotation × Depth interaction, the Mn at the 0-to-5cm in WW rotation was 52% greater compared to the 5-to-15-cm depth and 75% greater than the 15-to-30-cm depth (Figure 2.2d). For the WF rotation, the Mn concentration measured within 5-to-15-cm and 15-to-30-cm depths were 47% and 63%

less compared to the 0-to-5-cm depth. The Mn concentration in the WSF rotation was 42% greater in the 0-to-5-cm depth than in the 5-to-15-cm depth and 59% higher than the 15-to-30-cm depth. In addition to the significant interactions, there were also significant main effects of Tillage, Crop Rotation, and Depth. For the Tillage treatments, the NT and ST treatments had 11% and 9% greater Mn concentration compared to the RT treatment, but the NT and ST treatments were not significantly different from each other. The WW rotation had 22% and 30% greater concentrations of Mn than the WF and WSF rotations, and the WF rotation was 8% greater than the WSF rotation. The soil surface had 48% and 68% higher Mn concentrations compared to the 5-to-15-cm and 15-to-30-cm depths, and the 5-to-15-cm depth was 37% greater than the 15-to-30-cm depth.

Soil nitrate (NO_{3-}-N) and soil copper (Cu) were not influenced by the effect of Tillage or any of its interactions (Table 2.2). However, both NO_{3-}-N and Cu were influenced by Depth. For NO_{3-}-N, the soil surface was 78% and 87% greater than the 5-to-15-cm and 15-to-30-cm depths. The same trend can be observed for Cu. The soil surface was 30% and 45% greater than the 5-to-15-cm depth, and the 5-to-15-cm depth was 45% greater than the 15-to-30-cm depth.

Bulk density

Bulk density results were not influenced by the 3-way interaction of Crop Rotation × Tillage × Depth, but the Crop Rotation × Tillage interaction and the Depth main effect significantly affected bulk density (Table 2.2). Among rotations and tillage treatments, WW under RT had the highest bulk density, which was 9% greater than NT, but ST was not significantly different from RT or NT (Table 2.3). For the WSF rotation, there were no differences among tillage treatments. In the WF rotation, there were no significant differences across tillage treatments, although visually it appears NT has higher bulk density than ST or RT.

For significant main effect of Depth, soil bulk density was least near the soil surface was 19% less than the 5-to-15-cm depth and 17% less than the 15-to-30-cm depth (Table 2.4).

Water and Wind Erodibility

The Crop Rotation × Tillage interaction influenced the MWD of water stable aggregates. In the WW rotation, the MWD under the RT and ST treatments were 51% and 35% less than the NT treatment (Figure 2.3). In the WSF rotation, the RT and NT treatments had 16% and 20% less MWD than the ST. However, in the WF rotation, tillage treatments had no significant effect on the MWD. In addition to the significant Crop × Tillage interaction, there were also significant Tillage and Crop Rotation main effects. The MWD under RT was 31% less than NT, and the MWD of ST was not significantly different from NT (Table 2.4). Across rotations, the WW rotation was 28% and 41% greater than the WSF and WF rotations, and the WSF rotation was 18% greater than the WF rotation.

The Crop Rotation × Tillage interaction was not significant for WEF, but there was a significant main effect of Crop Rotation. The WEF, which is the <0.42mm sieve and 0.42-to-0.84-mm sieve, was 17% greater in WF in contrast to WW or WSF, but the WW and WSF rotations were not significantly different from each other (Table 2.4).

Correlation Matrix

Correlation analysis results showed a highly positive relationship between SOC and NH_{4+}-N, NO_{3-}-N, P, K, Zn, Fe, Mn, Cu, and MWD (Table 2.6). The SOC concentration had a strong, negative relationship with pH, bulk density (BD), soil water content (WC), penetration resistance (PR), and wind erodible fraction (WEF). Interestingly, pH had a strong, negative relationship with all variables except for BD, WC, PR, and WEF. For nutrient interactions, NH_{4+}-N was highly correlated to NO_{3-}-N and Zn, and NO_{3-}-N was highly correlated to P, Zn, Fe, and Mn. Similarly, NO_{3^-}-N and P had a similar correlation with Zn, Fe, Mn, Cu. Soil K and Cu did not have a very strong relationship with any parameter measured. However, Zn, Fe, and Mn had a strong relationship.

Crop Yields

Grain sorghum yields were reported from 2017-2022, and grain yield differed over the 6-years with the largest yields obtained in 2020 and the smallest in 2019 (Figure 2.4). Across years, the grain sorghum yield from 2020 was 48%, 17%, 54%, 48%, and 35% greater than the yields from 2017, 2018, 2019, 2021, and 2022. Within tillage treatments, sorghum grain yields were 14% and 15% greater with ST and NT compared to RT.

Winter wheat yields were reported for 2017- 2020 and 2022 because the 2021 wheat crop was lost due to hail damage. Winter wheat yields were affected by Crop Rotation × Tillage × Year interaction. The WF rotation in 2020 under RT yielded 16% and 20% more than NT and ST (Table 2.7). The WW rotation under NT often saw the smallest yields, especially in 2017 and 2018, where there was up to a 21% decrease with NT compared to RT. The yield differences in the WSF rotation often depended on year, but the yields were often highest with RT or ST compared to NT. Within a rotation, wheat yields in the WW rotation were 27% and 36% smaller compared to the WSF and WF rotations. Across years, the wheat yields in 2020 were 18%, 37%, 38%, and 57% greater than the yields in 2022, 2019, 2017, and 2018 (Figure 2.5). Across tillage treatments, NT wheat yield was 17% less than RT, and ST was only 8% smaller than RT.

Weed Density

The weed density results for the fallow phase were not influenced by Tillage, Crop Rotation, or their interaction. For the wheat phase, there was a significant effect of Rotation. The weed density in the WF and WSF rotations were 57% and 61% greater than WW (Figure 2.6a).

Finally, for the sorghum phase, there was no influence of tillage. Across every rotation, Palmer amaranth (*Amaranthus palmeri*) was heavily present within the plots. In the WW rotation, common weeds were grasses, such as downy brome (*Bromus tectorum* L.) and little barley (*Hordeum pusillum*), and in the WSF rotation, kochia (*Bassia scoparia*), carpetweed (*Mollugo verticillata*), and spotted spurge (*Euphorbia maculata*) were common weeds. Across tillage treatments, NT had high populations of tumble windmill grass (*Chloris verticillata*), spotted spurge, and little barley. However, the ST and RT tillage treatments had a variety of weed populations present, such as Palmer amaranth, kochia, carpetweed, and spurge.

For the Shannon's Diversity Index, there was no influence of Tillage, Rotation, or their interaction for the fallow or wheat phases. However, for the sorghum phase, there was a significant influence of Tillage. The NT treatment had 58% greater SDI than the RT treatment, and ST was not significantly different from the other tillage treatments (Figure 2.6b).

Discussion

The SOC findings in the current study support the earlier findings of Obour et al. (2021) who sampled the experimental field three months after tillage treatments were implemented. In both studies, the WW rotation had a greater SOC concentration compared to WF and WSF. This can be attributed to the long fallow period in WF and WSF, and the WW rotation has a short fallow period between wheat crops. The rotations with fallow also do not have a living root system sequestering carbon as much as the WW rotation does. In addition to the rotational differences with SOC, sampling depth effects were also similar to the findings of Obour et al. (2021) because SOC was highly concentrated at the 0-to-5-cm depth, but the other depths were not influenced by crop rotations or tillage. The soil environment can explain the higher SOC concentrations in the 0-to-5-cm depth. Most soil microorganisms and organic matter are present closest to the soil surface. Lastly, with the tillage treatments, the SOC concentration with ST and NT were not different, but RT was statistically less in SOC, which matches the findings of Obour et al. (2021). The RT treatment has more intense and frequent tillage than the NT treatment, but the ST treatment is not statistically different from NT because the plots have returned to NT management since completion of the tillage operation in 2017. Therefore, the SOC concentrations have been able to increase over time. In addition to the findings of Obour et al. (2021), Baan et al. (2009) did not see a significant effect of tillage treatments on SOC after one cycle of tillage, with either one, two, or three tillage operations. Some research has investigated total carbon (TC) and active carbon (AC) and its presence in long-term plots under NT and conventional tillage (CT). Aziz et al. (2013) found the TC concentration was 30% greater in NT compared to CT. However, other research showed there can be differing results with SOC. Kirkegaard et al. (2020) found that SOC decreased in the 0-to-5-cm depth and increased in the 5-to-10-cm and 10-to-15-cm depth with tillage.

Potential near soil surface compaction is a challenge in long-term NT systems. In the present study, soil BD was unaffected by crop rotation or tillage treatments, but BD differences were observed between sampling depths (Table 2.4). Obour et al. (2021) saw differences in BD among the tillage and the crop rotation treatments in the 0-to-15-cm depth the months after tillage. The differences observed in Obour et al. (2021) could be short-term influences of tillage, but since no differences were observed in the 2022 sampling, the current results would suggest that tillage effects on BD can become transient over time because no difference across any tillage treatments were observed 6-yrs after tillage. Notwithstanding, there have been extremely dry conditions in the past few years (2021 through 2022), which can cause the soil to become harder and more compacted. Liu et al. (2016) found that regardless of tillage implement used or timing of tillage operations, ST was not found to significantly affect any soil physical or chemical properties, including BD. On an Aksarben silty clay loam and Wymore silty clay loam, Blanco-Canqui et al. (2017) found no significant differences in BD or soil porosity at any soil depth when comparing chisel plow, tandem disk, moldboard plow, and NT.

In long-term NT fields, nutrient stratification within soil profile is a big issue for farmers, with generally greater concentration of nutrients and SOC near the soil surface as reported in the present study (Figure 2.1a-f; Table 2.5). Conyers et al. (2019) found SOC, N, and P were concentrated in the top 5-cm of the soil profile. Soil pH dictates nutrient availability, but pH can reach below ideal values in the surface soil more rapidly with NT compared with other forms of tillage (Blanco-Canqui and Wortmann, 2020). A study conducted in western Kansas by Obour et al. (2017) found a high concentration of P at the soil surface as well as soil acidification near the surface under NT. When applying fertilizer nutrients in a NT system, there is no incorporation of the nutrient applied into the soil, so the soil surface has a higher concentration of nutrients. Since the soil surface is higher in nutrient concentration, there are less nutrients available for plant uptake from the subsurface soil profile through the roots particularly in low precipitation years. In a meta-analysis by Dang et. al (2015), it was reported that tillage could reduce the P loss in runoff by redistributing soil P accumulated in the upper soil surface. The findings of Blanco-Canqui and Wortmann (2020) also reported that minimal to no incorporation of nutrients following a nutrient application could cause acidification of the topsoil.

Aggregate erodibility is a major concern when incorporating tillage into long-term NT fields. Although NT often had higher MWD of aggregates, the NT treatment was not significantly different from ST as compared to RT (Figure 2.4). The MWD findings of Obour et al. (2021) showed NT and ST were not significantly different, but the RT treatment had significantly less MWD compared to NT and ST. Similarly, the WW rotation had greater MWD than crop rotations that had fallow. The current findings are similar to those of Obour et al. (2021), but the current findings show ST treatment was not significantly different from NT or RT (Table 2.4). Overall, the MWD decreased from the initial sampling compared to this sampling in 2022. This could be attributed to the dry weather conditions in 2021 and 2022.

A study conducted on a Vertisol soil in a Mediterranean climate compared seven different tillage intensities: conventional tillage with stubbles, conventional tillage with stubbles burned, heavy disc harrow reduced tillage, rototiller reduced tillage, heavy disc harrow zero soil tillage, NT, and ST. The results indicated aggregate stability was highest in NT, ST, and heavy disc harrow zero soil tillage in comparison to the other tillage intensities (Celik et al. 2019). Lal (2015) mentioned increased and accelerated erosion can drain the SOC pool and nutrient reserves within the soil. In addition to accelerated erosion causing less SOC and nutrient accumulation, increased tillage frequency and intensity causes an increase in the rate of macro-aggregate degradation due to the soil being exposed to freeze-thaw and wet-dry cycles (Six et al., 2004; Shan et al. 2010). Rotation is a significant factor when thinking of soil erodibility and can play a large influence in soil loss (Table 2.4). In this study, there were no differences in the WEF across tillage treatments, but across rotations, the WF rotation had the highest WEF. Cropping intensity with a living root present in the soil helps prevent soil loss and encourages soil aggregation, which would decrease soil erosion. In addition to having a living root present, the long fallow period in WF can cause the soil to be more easily eroded because of limited soil cover over the prolonged fallow period.

Farmer profitability is a key concern, and ST can benefit grain yields of winter wheat and grain sorghum. Continuous wheat yields were less than the WF and WSF rotations, and NT was less than both RT and ST treatments. In addition to the wheat yields, RT grain sorghum yields were less than the ST and NT plots as well. Obour et al. (2021) had similar findings with winter wheat yields, with WW being lower than WF and WSF. As well as the winter wheat yield results being similar, the RT plots yielded less than the grain sorghum yields with the ST and NT plots. Over the study period, weed pressure in WW plots were high due to other grass weed species, such as downy brome and jointed goatgrass (Aegilops *cylindrica*), that compete with the winter wheat. In a WSF rotation, there's a shift of weed species (Palmer amaranth, kochia, carpetweed, and spotted spurge) due to different growing seasons for winter wheat and grain sorghum. Incorporating tillage also minimized weed populations and reduced windmillgrass infestation, which helps increase yield in the RT and ST treatment. The reduction in grain sorghum yields with RT can be explained by increased tillage intensity causing increased water evaporation. With minimal water available, the grain sorghum crops will not have sufficient water for optimal growth, and the past few years have been suboptimal for precipitation across western Kansas.

Conclusions

Overall, these results indicate that the long-term effects of a one-time ST pass are not harmful to soil properties built up in long-term NT fields. The long-term NT and ST plots had greater SOC concentrations than RT, which leads to the conclusion that the loss of SOC with ST is minimal compared to RT. Tillage had no significant effect on soil bulk density, so there is not a risk of increased soil compaction with the use of tillage. Reduced tillage had the highest soil surface pH followed by ST then NT, which provides evidence that tillage could mitigate soil acidification. Soil K, P, Fe, and Mn concentrations were influenced by tillage, but NO_3-N, NH_4-N, Cu, and Zn concentrations were not influenced by tillage treatments. The results of this study showed increased tillage can increase nutrient availability of some nutrients but not influence others, so there can be minimal or positive effects depending on the nutrient being considered. Strategic tillage had no effect on WEF or MWD, so there is not an increased risk of erosion with the use of ST. Reduced tillage and ST helped increase winter wheat yields compared to NT, possibly due to less weed density in the tillage plots. Grain sorghum yields under NT and ST yielded more than RT. Weed density was greatest under rotations with fallow compared to WW in the wheat phase but was not influenced by rotation in the fallow or sorghum phases. Additionally, Shannon's Diversity Index was influenced by Tillage in the sorghum phase of the crop rotation, and as tillage intensity increased, weed diversity decreased. Based on results from this study, we conclude that ST in long-term NT fields reduced weed density, had no negative effects on soil properties, minimizes nutrient stratification, and increased crop yields.

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Figures

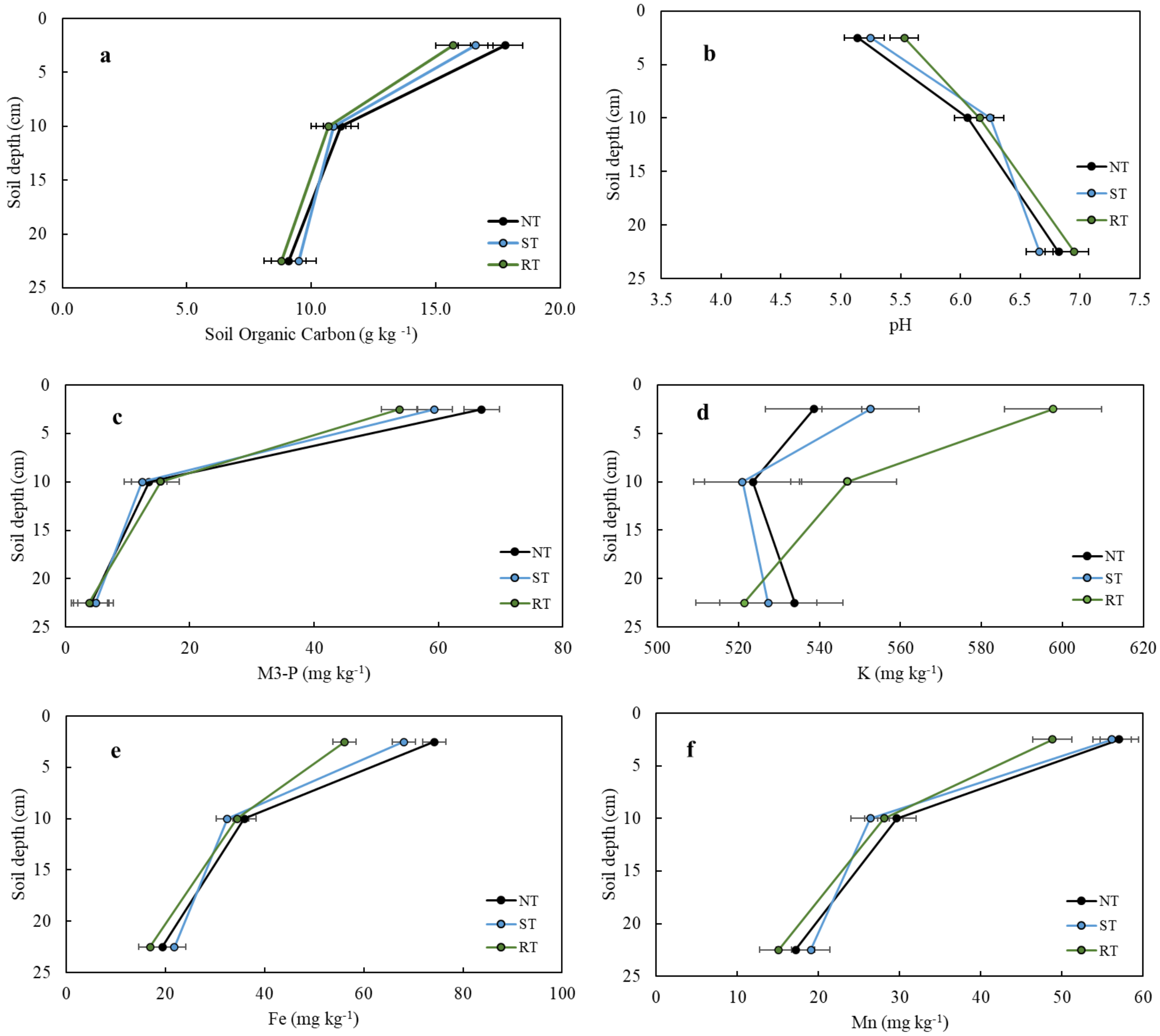

Figure 2.1. Tillage and sampling depth effects on soil organic carbon (SOC) concentrations (a), pH (b), Mehlich-3 phosphorus (M3-P) (c), potassium (K) (d), iron (Fe) (e), and manganese (Mn) (f) measured in the 0-to 5-cm, 5-to-15-cm, and 15-to-30-cm depths in 2022 near Hays, KS. Means are averaged across three crop rotations and three replications (n =9). Error bars represent one standard error of the means. NT = No-tillage; ST = Strategic tillage; RT = Reduced tillage.

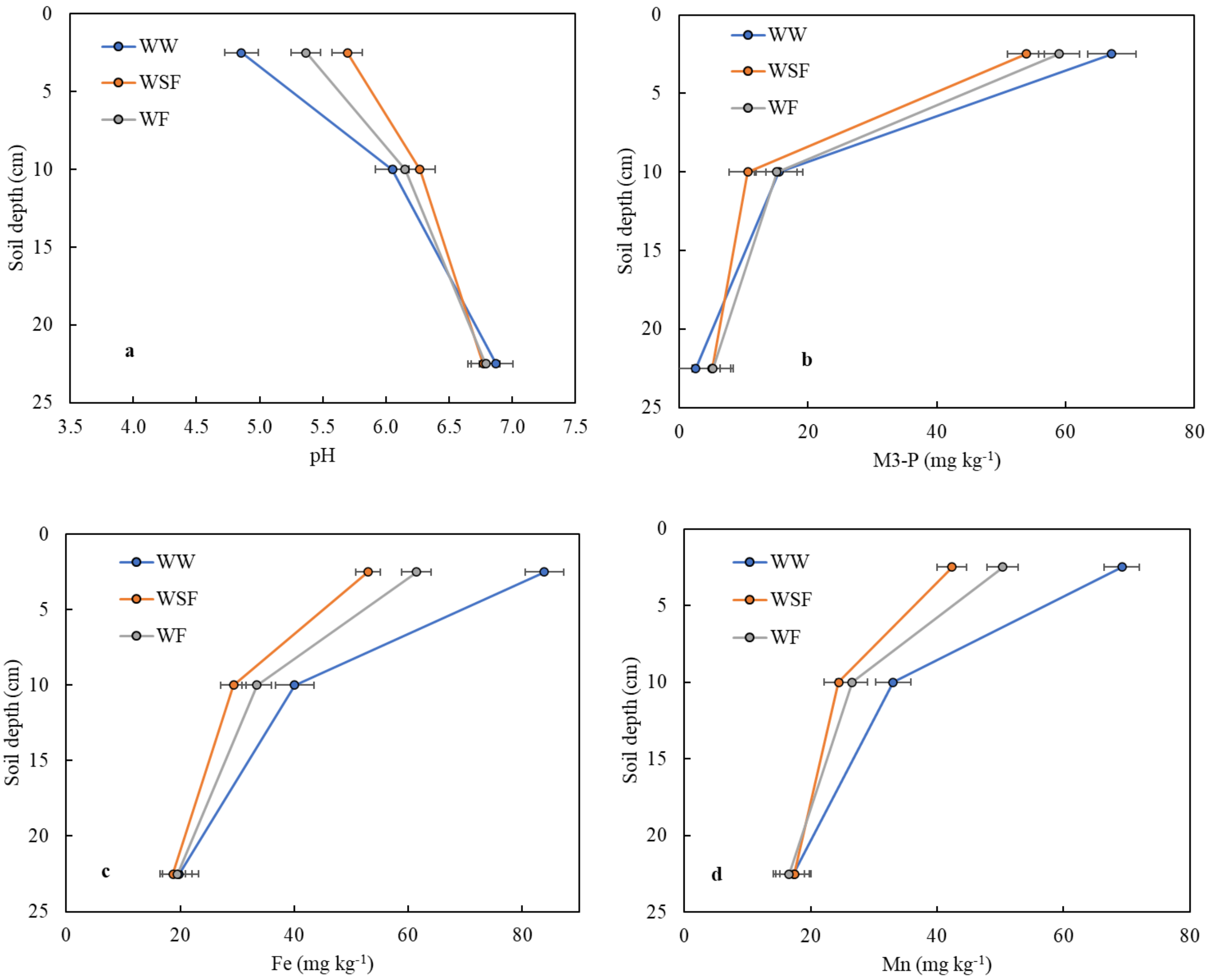

Figure 2.2. Crop rotation and soil sampling depth effects on soil pH (a), soil phosphorus (b), soil iron (c), and soil manganese (d) concentrations near Hays, KS. Means are averaged across three tillage treatments and three replications (n =9). Error bars represent one standard error of the means. WW = Wheat-wheat; WSF = Wheat-sorghum-fallow; WF = Wheat-fallow.

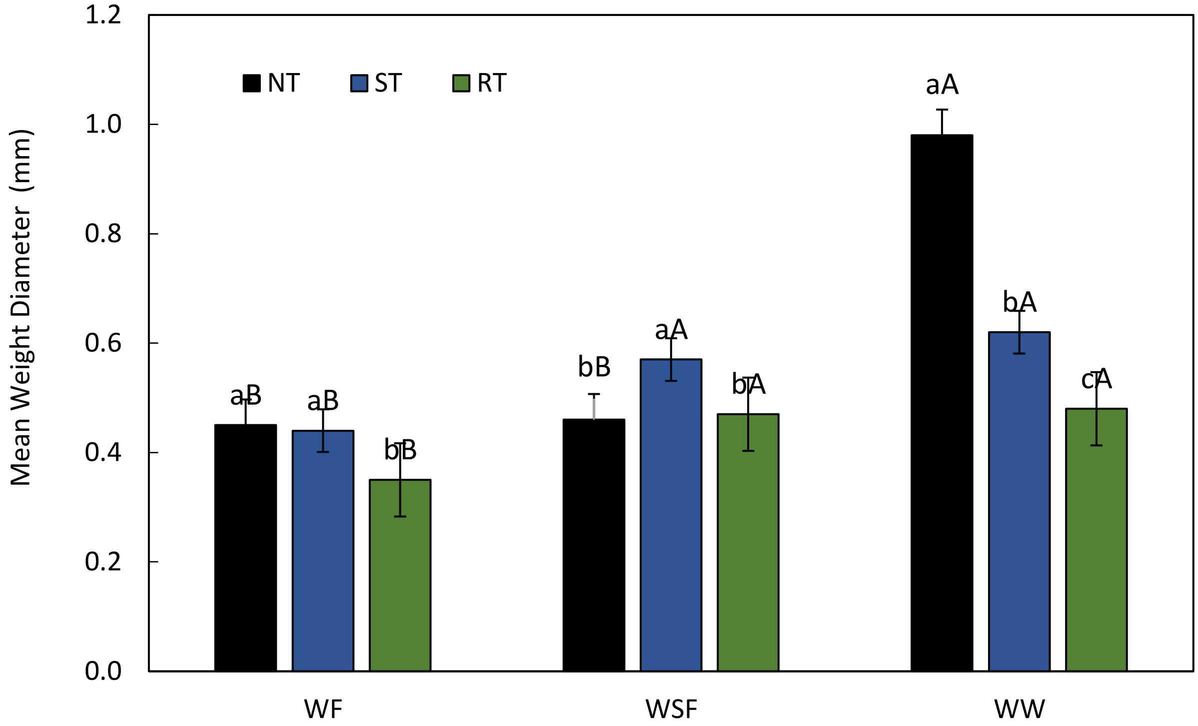

Figure 2.3. Crop rotation and tillage affected the mean weight diameter of water stable aggregates in 2022 near Hays, KS. Means are averaged across three tillage treatments and three replications (n =9). Error bars represent one standard error of the means. Means followed by the same letter (s) are not significantly different using the least squares means (LSMEANS) multiple comparison procedure (*P* < 0.05). Lower case letters separate means within each rotation, and upper-case letters separate means within each tillage treatment. NT = No-tillage; ST = Strategic tillage; RT = Reduced tillage. WF = Wheat-fallow; WSF = Wheat-sorghum-fallow; WW = Wheat-wheat.

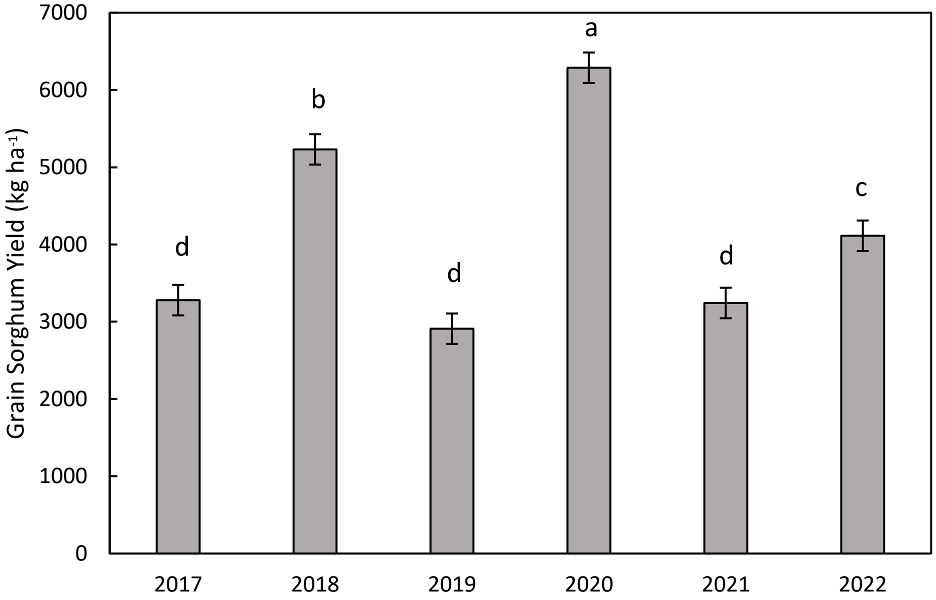

Figure 2.4. Grain sorghum yields in wheat-sorghum-fallow crop rotation from 2017 through 2022. Means are averaged across three replications and three tillage treatments (n =9). Error bars represent one standard error of the means. Bars with the same letter are not significantly different using the least squares means (LSMEANS) multiple comparison procedure (*P* < 0.05).

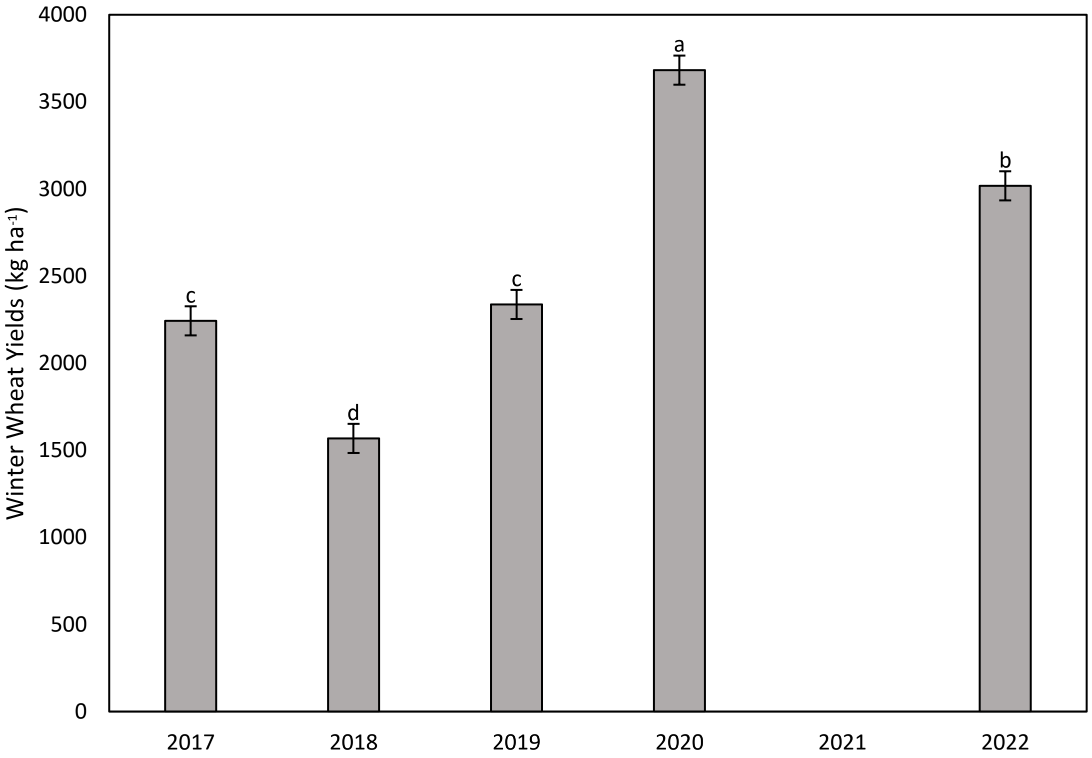

Figure 2.5. Average winter wheat yields across tillage treatments for 2017-20220 + 2022 growing seasons near Hays, KS. There was no 2021 wheat harvest due to a hailstorm eliminating the crop. Means are averaged across three replications, three crop rotations, and three tillage treatments (n =27). Error bars represent one standard error of the means. Bars with the same letter are not significantly different using the least squares means (LSMEANS) multiple comparison procedure (*P* < 0.05).

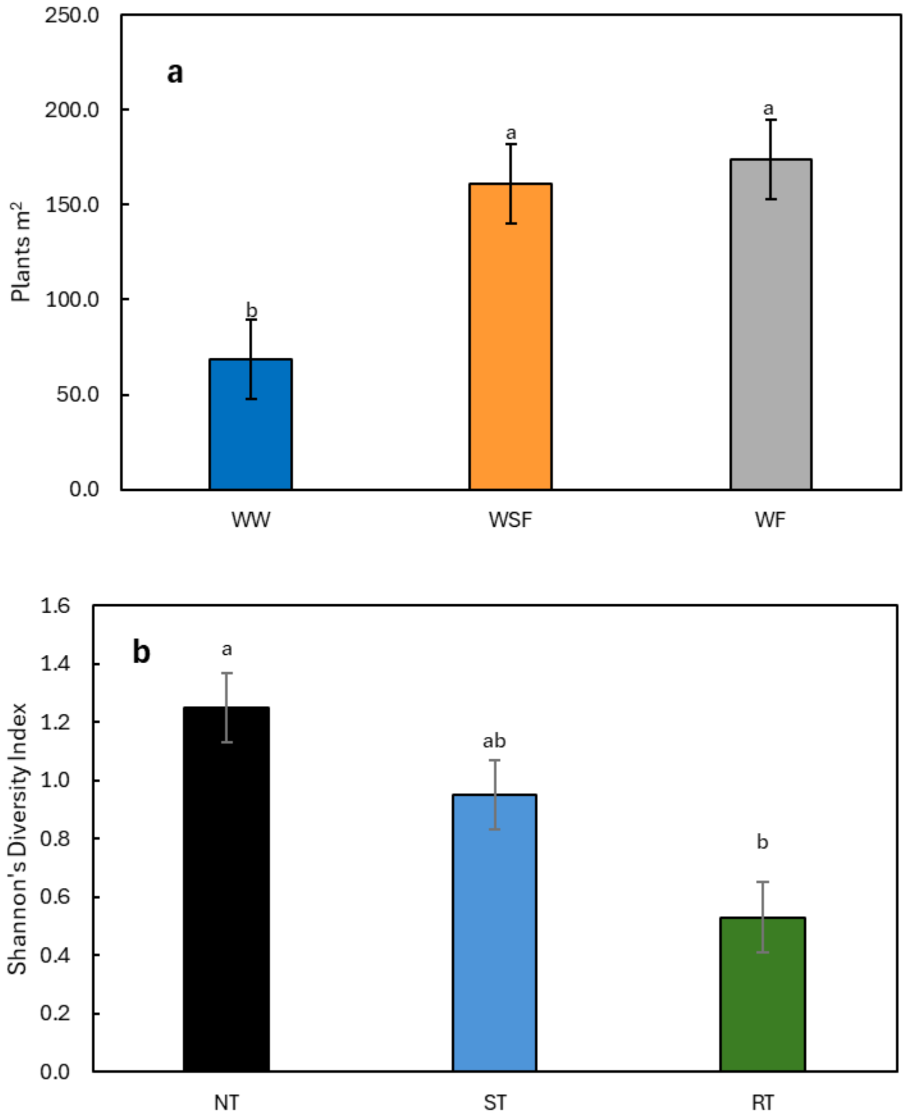

Figure 2.6. Effect of crop rotation on weed density (a) and influence of crop rotation on weed diversity (b) from weed counts measured in summer 2023 near Hays, KS. Means are averaged across three replications and three crop rotations or tillage treatments (n =9). Error bars represent one standard error of the means. Bars with the same letter are not significantly different using the least squares means (LSMEANS) multiple comparison procedure ($P < 0.05$). WF = Wheat-fallow; WSF = Wheat-sorghum-fallow; WW = Wheat-wheat. NT = No-tillage; ST = Strategic tillage; RT = Reduced tillage.

Tables

Table 2.1. Monthly precipitation from 2010 to 2023 near Hays, KS.

	Year														
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	30-yr avg.†
Month	mm														
Jan.	3	2	0	7	0	17	9	29	1	13	25	12	5	23	6
Feb.	4	0	20	3	0	4	5	2	1	8	40	0	0	7	8
Mar.	43	6	29	5	0	1	11	33	8	18	11	113	31	6	21
Apr.	62	16	16	17	23	21	176	135	17	23	12	27	11	18	49
May	46	47	26	53	15	153	69	100	92	197	81	194	86	98	87
Jun.	104	50	17	55	200	16	80	40	94	40	61	20	36	81	64
Jul.	41	3	1	146	43	102	79	39	199	24	178	61	45	57	95
Aug.	83	92	69	12	41	10	118	82	142	318	62	84	35	95	78
Sept.	55	23	22	64	117	10	33	47	87	40	24	64	54	17	39
Oct.	5	30	22	22	44	43	16	51	78	38	2	29	4	19	34
Nov.	7	27	0	24	1	38	29	2	12	10	24	5	6	11	15
Dec.	0	29	16	0	16	29	10	0	43	59	8	0	17	45	12
Annual	453	325	238	408	500	444	635	559	775	789	527	609	329	477	509

†30-year averages are for the period of 1990-2020.

Table 2.2. Analysis of variance results for 2022 pre-tillage soil samples taken near Hays, KS. The p-values are shown for soil organic carbon (SOC), pH, ammonium (NH_4^+), nitrate (NO_3^-), phosphorus (M3-P), potassium (K), zinc (Zn), iron (Fe), manganese (Mn), copper (Cu), bulk density (BD), mean weight diameter (MWD), penetration resistance (PR), and wind erodible fraction (WEF).

	Parameter													
Fixed Affects	SOC	pH	NH_4^+	NO_3^-	M3-P	K	Zn	Fe	Mn	Cu	BD	MWD	PR	WEF
Crop Rotation	0.0107	<0.0001	0.1755	0.7027	0.0196	0.5244	0.0107	<0.0001	<0.0001	0.9345	0.5555	<0.0001	0.6912	0.0002
Tillage	0.0492	0.0217	0.5480	0.2403	0.0756	0.0370	0.5717	0.0176	0.0426	0.7868	0.4970	0.0263	0.2780	0.3990
Crop Rotation × Tillage	0.1329	0.6359	0.4226	0.6302	0.2111	0.1190	0.5999	0.6238	0.8890	0.4620	0.0070	0.0003	0.1919	0.1715
Depth	<0.0001	<0.0001	0.0855	<0.0001	<0.0001	0.0136	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	-	-	-
Crop Rotation × Depth	0.4905	<0.0001	0.6620	0.8988	0.0418	0.3231	0.4255	<0.0001	<0.0001	0.2296	0.7520	-	-	-
Tillage × Depth	0.0177	<0.0001	0.8146	0.3564	0.0058	0.0003	0.7876	<0.0001	0.0002	0.5911	0.7920	-	-	-
Crop Rotation × Tillage × Depth	0.1064	0.0001	0.9067	0.7788	0.0162	0.0965	0.9440	0.0003	<0.0001	0.1074	0.7721	-	-	-

Table 2.3. Effect of crop rotation and tillage on bulk density averaged across depths from samples obtained in summer 2022 near Hays, KS. Means are averaged across three replications (n =3). Means within a rotation followed by the same letter are not significantly different using the least squares means (LSMEANS) multiple comparison procedure (*P* > 0.05). WW = Wheat-wheat; WSF = Wheat-sorghum-fallow; WF = Wheat-fallow. NT = No-tillage; ST = Strategic tillage; RT = Reduced tillage.

	Tillage		
Crop Rotation	NT	ST	RT
	—————————— g cm^{-3}——————————		
WW	1.28 c	1.34 abc	1.40 a
WSF	1.34 abc	1.35 ab	1.32 bc
WF	1.35 abc	1.30 bc	1.31 bc

Table 2.4. Crop rotation and tillage effects on bulk density (BD), wind erodible fraction (WEF), and mean weight diameter (MWD) of water stable aggregates near Hays, KS. Means are averaged across three replications and three tillage treatments or crop rotations (n =9). Means followed by the same letter (s) are not significantly different using the least squares means (LSMEANS) multiple comparison procedure (*P* > 0.05). WW = Wheat-wheat; WSF = Wheat-sorghum-fallow; WF = Wheat-fallow. NT = No-tillage; ST = Strategic tillage; RT = Reduced tillage.

Factor	BD	WEF	MWD
	g cm^{-3}	%	mm
Crop Rotation			
WW	1.34	28.70 b	0.69 a
WSF	1.34	28.30 b	0.51 b
WF	1.32	34.50 a	0.41 c
Tillage			
NT	1.32	29.3	0.62 a
ST	1.33	31.4	0.55 ab
RT	1.35	30.9	0.43 b
Depth			
0-5cm	1.16 c	-	-
5-15cm	1.44 a	-	-
15-30cm	1.39 b	-	-

Table 2.5. Three-way interaction (Crop Rotation × Tillage × Depth) effects on soil pH, iron (Fe), manganese (Mn), and phosphorus (M3-P). Means per depth are averaged across three tillage treatments and 3 crop rotations (n =9). Means followed by the same letter (s) are not significantly different using the least squares means (LSMEANS) multiple comparison procedure (*P* > 0.05). Within a depth for each parameter, lower case letters separate tillage treatment means within each rotation, and upper-case letters separate rotation treatment means within each tillage. WW = Wheat-wheat; WSF = Wheat-sorghum-fallow; WF = Wheat-fallow. NT = No-tillage; ST = Strategic tillage; RT = Reduced tillage.

Depth	pH			Fe			Mn			M3-P		
Crop Rotation	NT	ST	RT	NT	ST	RT	NT	ST	RT	NT	ST	RT
				mg kg^{-1}								
0-5 cm												
WW	4.6 bC	4.8 abC	5.2 aC	97.3 aA	85.0 abA	64.7 bA	73.3 aA	73.6 aA	60.8 aA	71.3 aA	61.0 bA	69.0 abA
WSF	5.6 bA	5.6 bA	5.9aA	56.2 aB	53.4 aB	47.0 aB	45.6 aB	43.2 aC	38.2 aC	62.7 aA	60.3 aA	44.9 bB
WF	5.3 aB	5.3 aB	5.5 aB	67.0 aB	64.0 aB	57.0 aAB	52.2 aB	51.7aB	47.4 aB	65.8 aA	55.0 abA	47.3 bB
5-15 cm												
WW	5.9 aB	6.5 aA	5.9aB	41.3 aA	28.3 aA	41.7 aA	37.4 aA	25.0 aA	36.8 aA	14.0 bA	10.7 cB	19.0 aA
WSF	6.3 aA	6.2 aA	6.3 aA	30.4 aB	32.4 aA	28.9 aB	24.9 aB	26.1 aA	22.3 aB	10.8 aA	11.3 aB	12.0 aA
WF	6.1 aAB	6.1 aA	6.3aA	34.0 aAB	35.3 aA	30.7 aAB	26.1 aB	28.0 aA	25.1 aB	16.2 aA	16.2 aA	13.8 bA
15-30 cm												
WW	6.9 aA	6.5 aA	7.1 aA	18.7 aA	28.7 aA	15.7 aA	15.1 aA	23.0 aA	13.9 bA	2.0 bA	8.0 aA	4.3 bA
WSF	6.7 aA	6.8 aA	6.8 aA	19.8 aA	18.2 aB	18.6 aA	19.0 aA	16.9 aB	16.4 aA	5.3 aA	3.7 aA	4.8 aA
WF	6.8 aA	6.7 aA	6.9 aA	20.3 aA	19.7 aAB	16.8 aA	17.4 aA	17.3 aB	15.0 aA	5.8 aA	5.0 aA	4.8 aA

Table 2.6. Correlation matrix across soil depths for soil organic carbon (SOC), pH, ammonium-N (NH_4-N), nitrate (NO_3-N), Mehlich-3 phosphorus (M3-P), potassium (K), zinc (Zn), iron (Fe), manganese (Mn), copper (Cu), mean weight diameter (MWD), bulk density (BD), gravimetric water content (GWC), penetration resistance (PR), and wind erodible fraction (WEF) from 2022 soil sampling near Hays, KS. The top number in each cell is Pearson's Correlation Coefficient, and the bottom number in each cell is the p-value associated with that coefficient.

Soil Properties (All Depths)	pH	NH_{4+} (mg $kg^{-1)}$	NO_{3-} (mg $kg^{-1)}$	M3-P (mg $kg^{-1)}$	K (mg $kg^{-1)}$	Zn (mg $kg^{-1)}$	Fe (mg $kg^{-1)}$	Mn (mg $kg^{-1)}$	Cu (mg $kg^{-1)}$	MWD (mm)	BD (g g^{-3})	GWC (g g^{-1})	PR (MPa)	WEF (%)
SOC (g kg^{-1})	-0.88 <0.0001	0.37 <0.0001	0.63 <0.0001	0.89 <0.0001	0.20 0.0123	0.71 <0.0001	0.85 <0.0001	0.87 <0.0001	0.64 <0.0001	0.40 0.0028	-0.52 <0.0001	-0.63 <0.0001	-0.23 0.0950	-0.40 0.0023
pH		-0.21 0.0074	-0.54 <0.0001	-0.86 <0.0001	-0.15 0.0630	-0.61 <0.0001	-0.93 <0.0001	-0.94 <0.0001	-0.70 <0.0001	-0.37 0.0066	0.50 <0.0001	0.57 <0.0001	0.33 0.0136	0.29 0.0295
NH_{4+} (mg $kg^{-1)}$			0.84 <0.0001	0.37 <0.0001	-0.06 0.4386	0.66 <0.0001	0.24 0.0026	0.28 0.0004	0.14 0.0857	0.17 0.2301	-0.24 0.0026	-0.22 0.0044	-0.11 0.4363	-0.16 0.2423
NO_{3-} (mg $kg^{-1)}$				0.66 <0.0001	0.11 0.1648	0.72 <0.0001	0.53 <0.0001	0.62 <0.0001	0.36 <0.0001	0.24 0.0810	-0.39 <0.0001	-0.36 <0.0001	-0.34 0.0115	-0.21 0.1224
M3-P (mg $kg^{-1)}$					0.30 0.0001	0.78 <0.0001	0.88 <0.0001	0.89 <0.0001	0.67 <0.0001	0.20 0.1491	-0.57 <0.0001	-0.66 <0.0001	-0.46 0.0004	-0.45 0.0005
K (mg $kg^{-1)}$						0.20 0.0095	0.21 0.0088	0.20 0.0132	0.26 0.0009	-0.29 0.0325	-0.11 0.1518	-0.26 0.0011	-0.02 0.8986	-0.17 0.2094
Zn (mg $kg^{-1)}$							0.62 <0.0001	0.63 <0.0001	0.49 <0.0001	0.17 0.2080	-0.41 <0.0001	-0.53 <0.0001	-0.21 0.1193	-0.26 0.0573
Fe (mg $kg^{-1)}$								0.93 <0.0001	0.73 <0.0001	0.37 0.0058	-0.54 <0.0001	-0.63 <0.0001	-0.07 0.6293	-0.29 0.0346
Mn (mg $kg^{-1)}$									0.68 <0.0001	0.38 0.0046	-0.55 <0.0001	-0.64 <0.0001	-0.27 0.0466	-0.25 0.0669
Cu (mg $kg^{-1)}$										0.01 0.9410	-0.33 <0.0001	-0.46 <0.0001	0.09 0.5382	-0.32 0.0169
MWD (mm)											0.00 0.9904	-0.05 0.7251	0.01 0.9206	-0.38 0.0047
BD (g g^{-3})												0.46 <0.0001	0.26 0.0551	-0.75 <0.0001
GWC (g g^{-1})													-0.43 0.0012	-0.02 0.9012
PR (MPa)														-0.14 0.3235

Table 2.7. Three-way interaction (Crop Rotation × Tillage × Year) for winter wheat yields for 2017-2020 + 2022. Means per year are averaged across three crop rotations and 3 tillage treatments (n = 9). Within each year, means followed by the same letter (s) are not significantly different using the least squares means (LSMEANS) multiple comparison procedure (*P* > 0.05). Lower case letters are tillage treatment mean separation within a rotation, and upper-case letters are mean separation within tillage. WW = Wheat-wheat; WSF = Wheat-sorghum-fallow; WF = Wheat-fallow. NT = No-tillage; ST = Strategic tillage; RT = Reduced tillage.

Year	Tillage		
Crop Rotation	NT	ST	RT
	———————————— kg ha^{-1} ————————————		
2017			
WW	816 bC	1484 aC	1480 aC
WSF	2190 aB	2475 aB	2009 aB
WF	3195 abA	3468 aA	3065 bA
2018			
WW	937 bB	1014 abB	1186 aB
WSF	1428 bA	1697 abA	1856 aA
WF	1653 aA	2291 aA	2052 aA
2019			
WW	2073 bA	2822 aA	2574 abA
WSF	1652 aA	1733 aB	1824 aB
WF	2640 aA	2825 aA	2887 aA
2020			
WW	1602 bB	2831 aB	3325 aB
WSF	4182 aA	3854 aA	4349 aAB
WF	4141 aA	3924 aA	4927 aA
2021			
WW	-	-	-
WSF	-	-	-
WF	-	-	-
2022			
WW	1595 bB	2327 abB	3294 aAB
WSF	3659 abA	3275 aA	4045 bA
WF	3250 aA	2629 aAB	3092 aB

Chapter 3 - Occasional tillage effects on soil properties, crop yields, and weed populations in dryland systems

Abstract

In the semi-arid central Great Plains of the United States, long-term no-tillage (NT) systems struggle with herbicide resistant weeds, nutrient stratification, and soil acidification. Occasional tillage (OT) in an otherwise NT system could be a strategy to mitigate these challenges, but there is little information on the long-term effects of OT on crop yields and soil properties in this region. This study was initiated in 2013 near Garden City and Tribune, and in 2014 near Hays, Kansas to evaluate the effectiveness of OT to control weeds and its impact on crop yields and soil properties. The initial treatments were NT, single tillage pass in May or June before wheat (*Triticum aestivum*) (STBW), and a single tillage pass after wheat harvest (STAW). However, treatments were updated in 2016 at Garden City and Tribune and 2017 at Hays to include two tillage passes before wheat (2TBW) and two tillage passes after wheat (2TAW). The experimental design was a randomized complete block, and treatments sampled were NT, STBW, 2TBW, STAW, and 2TAW. There were four replications in Garden City and Tribune, and three replications in Hays. At all locations, tillage was implemented using a sweep plow to minimize residue disturbance. Across years with the current set of treatments (2019-2023), tillage increased winter wheat yields in 2019 and 2021 at Garden City compared to NT, but in the other years, there were no differences among tillage treatments. At Hays and Tribune, OT treatments did not affect winter wheat yields compared to NT. There were no significant differences in grain sorghum *(Sorghum bicolor* Moench) yields among tillage treatments at Garden City and Tribune. However, there was a 25% decrease in grain sorghum yield with

2TBW compared to STBW and NT in 2019 and 2020 at Hays. Weed density was not influenced by tillage, but there was an influence of location. Overall, Hays had greater weed density than Garden City and Tribune for 2022 post-tillage samples. Shannon's Diversity Index (SDI) was highest under NT at Hays, but there were no significant differences at Garden City for 2022 post-tillage samples. Occasional tillage had no negative effect on the measured soil properties (SOC, bulk density, and aggregate stability) compared to NT. These properties differed only by sampling depth and location. However, cumulative water infiltration increased with the incorporation of OT at two of the locations. Tillage had a positive, negative, or negligible effect on gravimetric water content measured pre- or post-tillage depending on the year and location. These results indicate that OT had minimal negative effects on crop productivity or soil properties in the short-term (8-9 yrs after initiation) in a NT dryland WSF cropping system.

Introduction

Dryland no-tillage (NT) crop production is challenged by herbicide-resistant weed populations, soil compaction, and varmint holes causing rough surfaces for field operations, as well as stratification of pH, nutrients, and soil organic carbon (SOC) in the soil profile (Obour et al., 2021). Occasional tillage (OT) has been suggested as a strategy to mitigate some of these challenges associated with long-term continuous NT farming systems (Peixoto et al., 2020; Obour et al., 2021). However, there are concerns that implementing a pass of tillage will increase weed emergence. Cordeau et al. (2020) found that 77.1% of weed seeds were concentrated in the 0-10 cm soil depth (0–10 cm: 12 ± 2.7 species; 10–30 cm: 9.2 ± 3.1 species), and reduced tillage (RT) or OT resulted in greater weed emergence than in NT. Kettler et al. (2000) reported that incorporating OT into an otherwise NT system reduced downy brome (*Bromus tectorum* L.) populations by 97% and 41% in the first and third cropping cycle following the tillage pass.

However, long-term NT farmers are having to implement tillage operations in their fields due to herbicide resistant weeds. A study reported there was a 9.2% decrease in the use of NT across the United States because producers switched back to conventional tillage (CT) (Van Deynze et al., 2018).

In addition to increasing prevalence of herbicide resistant weeds in NT, nutrient stratification can occur near the soil surface. A study in western Nebraska compared the use of OT with a moldboard plow to correct nutrient stratification in NT (Kettler et al. 2000). Their findings showed that soil inorganic N in an otherwise NT system decreased 37%, and soil pH increased 9% at the 0-to-7.5-cm depth five years after moldboard plowing. The authors also reported soil organic carbon (SOC) increased 15% in the 7.5-cm-to-15-cm depth but was not different in the 0-to-30-cm depth between the NT and the moldboard plowed. Thapa et al. (2023) found that CT and strip tillage had 44-79% and 43% more soil inorganic N compared to NT and stubble mulch tillage 7 months and 19 months following tillage in the 0-to-15-cm depth. In a review conducted by Dang et al. (2015), strategic tillage (ST) or OT reduced stratification of SOC, phosphorus, and potassium concentrations in the soil surface and redistributed these nutrients in the subsoils. Overall, according to other literature, soil nutrients are heavily concentrated in the upper layer of the soil profile under NT, but in other tillage systems, such as CT, RT, or OT, there can be an increase in nutrient availability lower in the soil profile.

Another key concern of implementing tillage in an otherwise NT system is the loss of SOC and release of carbon dioxide (CO_2) to the atmosphere. Coulibaly et al. (2022) investigated the short-term effects of NT, RT, and CT on SOC stocks, potential C mineralization, and microbial biomass carbon (MBC). Their results indicated that shortly after tillage, potential C mineralization increased in RT and CT compared to NT, but the increase lasted for only 7 days.

After 7 days, the authors observed that all the tillage treatments decreased in potential C mineralization. Calderon et al. (2001) reported similar results, indicating that the potential CO_2 increase lasted for only four days following tillage. In a study conducted in New Mexico from 2020-2021, Paye et al. (2023) compared CT, ST, NT, and OT and found that under CT, soil aggregate-associated carbon was 28-31% less in macro-aggregates and 47-53% less in small aggregates compared to NT 26 months after the tillage operations. The authors focused on mineral-associated carbon (MAOM-C) and soil particulate carbon (POM-C) and found that ST, OT, and NT were similar in MAOM-C and POM-C and were all greater than CT in the 0-to-15-cm and 15-to-30-cm depths. Other studies have shown surface (<10 cm) SOC concentration can be reduced by OT; however, tillage can increase SOC concentration in the subsoil (Kettler et al., 2000; Wortmann et al., 2010; Celik et al., 2019).

Tillage in NT systems can cause negative effects on soil physical properties, such as soil compaction and aggregate instability. Quincke et al. (2007) investigated bulk density and did not see any differences when comparing NT to various chisel and moldboard plow setups, depths, and timings in eastern Nebraska. However, in western Nebraska, Kettler et al. (2000) found NT plots that received tillage had a 5% greater bulk density compared to plots without tillage in the 0-to-7.5-cm depth. Another concern with implementing OT is the risk of reducing aggregate stability and increasing runoff, but Nunes et al. (2015) found that soil aggregates in the 7-to17-cm depth were reduced the first 6 months following tillage but returned to pre-tillage levels 12 months after tillage.

Although the impacts of tillage on soil properties can vary in literature, some authors strongly recommend against any tillage in NT fields because of significant concerns about soil degradation from even a single tillage operation. For example, Grandy et al. (2006) expressed concerns of rapid losses of carbon and nitrogen following the resumption of tillage in a long-term NT system and concluded that years spent building soil health and regeneration could potentially be lost to a single tillage event. In their study, the total carbon protected within 2-to-8-mm aggregates was originally 28% and reduced by 16% with OT, while CO_2 emissions increased from 28 to 65% over a 3-year period. However, a key consideration in the study by Grandy et al. (2006) is the environment and the tillage implement. The research took place in southwest Michigan on soils with a clay content that raged from 15 % to 20% and silt content of 40%. Additionally, the tillage implement was a moldboard plow. A study in eastern Ohio also found smaller aggregate stability and greater bulk density and penetration resistance with OT compared to NT (Stavi et al., 2011). Additionally, the authors reported the experimental plots were disk plowed every 3-4 years.

Even though there have been varying results of incorporating OT into long-term NT systems regarding its impact on soil properties, most research has indicated that OT has varying or very little effect on crop yields (Blanco-Canqui et al., 2019; Baumhardt et al., 2017; Schlegel et al., 2020). A review by Blanco-Canqui et al. (2020) found that crop yield increased in 15%, decreased in 5%, and was unaffected by OT in 80% of cases based on data from 12 studies and 31 soils. In a study conducted in Brazil, grain yield of soybean (*Glycine max*), corn (*Zea mays*), and wheat increased by 14%, 6%, and 18% with tillage compared to NT (Peixoto et al., 2019). In western Nebraska, Kettler et al. (2000) found wheat yields increased 30% and 9% in the first and third crop cycles following a single tillage implementation in NT. In an economic analysis completed by Vandeveer et al. (2023), overall net returns with CT and RT were smaller in comparison to NT, but net returns with OT were not significantly different compared to NT. In addition, the authors reported crop yields with OT averaged over the 5 years study were not different from NT.

To our knowledge, there is minimal information on the long-term effects of OT on various aspects of soil health and crop yield in the central Great Plains. The objective of this study was to evaluate the effect of OT on soil properties and crop yield. Specifically, this study investigated the i) direct effects of tillage practices on soil properties and crop yield, and ii) how tillage practices affect weed abundance and diversity. Our hypotheses were that increased tillage intensity will negatively affect soil physical properties and crop yields. Furthermore, we hypothesized that there will be a decrease in weed abundance and diversity of weed species with increasing tillage intensity.

Materials and Methods

Experimental Layout

This experiment was conducted at the Kansas State University Research and Extension Centers at Hays (38°52′46″N 99°19′20″W), Garden City (37°99′07″ N, 100°82′47″ W), and Tribune, KS (38°28′05″ N, 101°46′37″ W). The soil at the Hays location was a Crete silty clay loam (Fine, smectitic, mesic Pachic Udertic Argiustolls), at Garden City it was a Ulysses silt loam soil (fine-silty, mixed, superactive, mesic Aridic Haplustolls), and at Tribune it was a Richfield silt loam (a fine smectitic, mesic Aridic Argiustoll). The long-term (1990-2020) average annual precipitation for Hays was 509 mm, Garden City was 497 mm, and Tribune was 468 mm (Tables 3.1, 3.2, 3.3). The open-pan evaporation (April-June) for Hays is 1741 mm, Garden City is 1810 mm, and Tribune is 1643 mm. The Garden City and Tribune research plots were initiated in 2013, and Hays plots were started in 2014. The crop rotation was a three-year winter wheat (*Triticum aestivum* L.)- grain sorghum *(Sorghum bicolor* Moench)-fallow (WSF) cropping system. Tillage treatments were updated to those evaluated in the current study in 2016 at Garden City and Tribune and in 2017 at Hays.

The experimental design was a randomized complete block design with a split plot arrangement with crop phase (wheat, sorghum, and fallow) as the whole plot and tillage treatments as subplots. All crop rotation phases were present each year. The five tillage treatments assigned to subplots were a continuous no-tillage system (NT), a single tillage pass during fallow ahead of wheat planting (STBW), two tillage passes in fallow prior to wheat planting (2TBW), a single tillage after wheat (STAW) and two tillage passes after wheat (2TAW). The STBW tillage operation was in June, and the 2TBW tillage operations were done in June and July. The STAW tillage operation was done in July following wheat harvest, and the 2TAW tillage operations were done in June in fallow and July after wheat harvest. The tillage implement was a sweep plow (Premier Tillage or Flex-King) with three 1.5 m sweeps. Individual subplot sizes at Garden City were 5 m by 23 m, 6 m by 36 m at Tribune, and 12 m by 30 m at Hays. There were four replications at Garden City and Tribune and three replications at Hays.

Soil sampling and analysis

Soil sampling occurred at two sites (Hays and Garden City) in June of 2022 ahead of tillage, and at two sites (Tribune and Hays) in August of that year for post-tillage soil sampling. No pre-tillage sampling occurred at the Tribune site in 2022 because the plots were tilled before samples were collected, and post-tillage Garden City soil samples were collected in September of 2022 due to delayed tillage because of dry weather. During the summer of 2023, the sampling for Garden City and Tribune occurred in early August following the tillage operations. However, Hays was not sampled until early September due to delays caused by dry weather

For the assessment of bulk density, two soil cores (5-cm diameter) were randomly taken from each plot and separated into 0-to-5 and 5-to-15-cm depth. Samples were dried at 105 °C for 48 hr. Bulk density was determined as the mass of oven-dry soil divided by volume of the core. Soil penetration resistance was assessed using an Eijelkamp-type hand penetrometer and was measured from the 0-to-15-cm depth (Herrick and Jones, 2002). To assess soil chemical properties, ten soil cores (2.5-cm diameter) randomly taken within each plot were composited for determining pH, nitrogen (NO_{3-}-N), phosphorus (M3-P), and soil organic carbon (SOC) concentrations at the 0-to-5 and 5-to-15-cm depths. These soil samples were air-dried and ground to pass through a 2-mm sieve. Soil nitrate-N (NO_3-N) concentrations were determined once the samples were extracted with 2 M KCl. Plant available phosphorus (M3-P) was determined colormetrically after extracting the soil samples using the Mehlich-3 extraction method (Mehlich, 1984). The NO_3-N and M3-P were determined using a Seal AQ2 soil nutrient analyzer. The soil pH was determined potentiometrically by an electrode (Thomas, 1996).

In addition to bulk density and nutrient samples, additional soil samples were collected from the 0-to-5-cm soil depth using a flat shovel for determining wet aggregate stability and dry aggregate stability. Following collection, soil samples were split into two, with one half of each sample passed through 8.0-mm mesh sieves and allowed to air-dry. Two sub-samples from each plot were used to estimate wet aggregate stability by the wet-sieving method (Nimmo and Perkins, 2002). This was done by placing a 50 g sample on top of a stack of nested sieves of 2- and 0.25-mm sized openings in a water column. Samples were allowed to wet for 5 minutes, and then, sieve stacks were oscillated a vertical distance of 3.7-cm at 30 oscillations minute-1 for 5 minutes. Aggregate fractions were transferred into glass beakers, dried at 105°C, and weighed to determine the proportion of aggregates within each size fraction. Each dry sample was then corrected for sand by mixing the oven-dried aggregates with 30 ml of 5g L-1 sodium hexametaphosphate solution to disperse soil particles. Samples were allowed to soak for a minimum of one hour and were then swirled on an orbital shaker for an additional hour. Each sample was then poured back through individual sieves with the same sized openings. The recovered sand was oven-dried and weighed to correct for coarse particles. Sand-corrected values were then used to compute the mean weight diameter (MWD) and aggregate size distribution.

To determine dry aggregate stability, the remaining half of each sample was air-dried and used to determine stability with a system of nested rotary sieves with 19-, 6.3-, 2-, 0.84-, and 0.42-mm diameter openings (Chepil, 1962). Samples were shaken for 5 minutes using a portable sieve shaker (W.S. Tyler Model RX-812, Mentor, OH). The soil particles remaining on each sieve were weighed, and the data was used to compute dry aggregate size distribution (DASD), mean weight diameter of dry aggregates (MWDDA), and wind-erodible fraction (WEF).

Following the tillage operations in the summer of 2023, infiltration rate estimates were obtained using the Cornell sprinkle infiltrometer (Ogden et al., 1997). Briefly, a Cornell sprinkle infiltrometer consists of a water reservoir with a perforated bottom, which delivers a simulated rainfall onto a 241-mm diameter area delimited by a metal ring. When surface ponding occurs, the ring allows water runoff from the device. When a steady state in the water outflow is achieved, the field saturated infiltration rate is estimated as the difference between the applied rainfall and the runoff rate (Ogden et al., 1997). In the current study, the infiltrometer was calibrated to deliver simulated rainfall of 25 cm hr^{-1}. The measurements were taken for one hour, and the time to runoff was recorded. Additionally, runoff volume was measured every three minutes with a 1000-ml measuring cylinder and recorded.

Crop Management

At all sites, winter wheat was planted in late September to early October and harvested the following July. After an eleven-month fallow period, grain sorghum was planted in late May or early June and harvested in late October or early November. Herbicides were applied to control weeds as needed during the fallow period in all treatments. The locations varied in wheat varieties and sorghum hybrids and in fertility management (Tables 3.4 and 3.5). Each location had their own fertilizer management based on organic matter and soil test results.

At Hays, winter wheat and grain sorghum yields were determined by harvesting an area 1.5 m wide by 30 m long from the center of each plot using a Kincaid 8XP single plot combine harvester (Kincaid, Haven, KS). Grain moisture content was determined using a DICKEY-john grain moisture tester (DICKEY-john Inc., Auburn, IL), and yield of both wheat and grain sorghum were adjusted to 13.5% moisture content. For Garden City grain harvest, a Wintersteiger Delta single plot combine (Salt Lake City, UT) was used, and a 2.5 m wide and 23 m length of the plot was cut using a Shelbourne stripper header for wheat. The grain sorghum was harvested with a John Deere 253 2-row crop header and were cut at 0.76 m wide for the whole plot length of 23 m. At Tribune, the center portion, which was 2.0 m wide by 18 m for wheat and 1.5 m wide by 18 m long for sorghum, was machine harvested with a Kincaid 8-XP single plot combine harvester (Kincaid, Haven, KS). For grain harvest at Tribune, a Shelbourne stripper header was used for wheat, and a two-row header was used for grain sorghum.

Using the crop yield and precipitation data, water use and water use efficiency were calculated using the following equations:

WU (mm) = [Plant available water in profile at planting (mm) – Plant available water in profile at harvest (mm)] + in season precipitation (mm)

WUE (kg ha^{-1} mm^{-1}) = Y/WU where Y is the yield of the crop and WU is the calculated water use.

Weed seed bank analysis

Soil samples were taken before tillage in June 2022, following tillage in July 2022, and before pre-emergence herbicide application in March 2023 for weed seed bank (WSB) analysis. About 10-15 soil cores were randomly taken in each plot to a depth of 15 cm with a 3.0-cm diameter probe. The samples were stored in plastic bags in cold storage at 4° C to prevent germination of warm-season weeds. To assess the WSB, 200 grams of potting soil were added to a 31 cm by 31 cm plastic tray. Then, 1,000 grams of the soil sample were spread uniformly over the potting soil with duplicates for each plot. If the weight of the sample from a plot was less than 2,000 grams, the sample was split in half to have two trays representing each plot. The samples were grown in a greenhouse setting for 12 weeks. After the first six weeks, the weeds were counted, identified, and removed from the tray. Following identification, the soil was disturbed and thoroughly mixed in case any seeds were present in the bottom portion of the tray. The experiment continued for another 6 weeks following the mixing of soil. Samples were watered as needed. The data collected after exhaustive germination of the WSB was used to compute weed seed density and Shannon's Diversity Index (SDI). Shannon's Diversity Index (SDI) was calculated using the equation:

$$SDI = -\Sigma pi * \ln (pi)$$

where Σ is the sum of the weeds emerged, pi is the proportion of the community made up of species *i*, and ln is the natural log (Ortiz-Burgos, 2016).

Statistical analysis

The data were tested for normal distribution and equal variance using the Shapiro-Wilk Test and Levene's Test to fulfill the assumptions for ANOVA. Data analyses were performed using PROC GLIMMIX in SAS ver. 9.3 (SAS Institute, 2012, Cary, NC). Soil physical and chemical properties were modeled against the fixed-effect variables of tillage, depth, location, and their interactions for 2022 and 2023 soils data. Crop yield was modeled against fixed-effect variables of tillage, location, and year. Winter wheat and grain sorghum yields for Hays were analyzed separated for 2019 and 2020 because there were three treatments in those years at all locations, and 2021, 2022, and 2023 because there were five treatments in those years at all locations. Replication and year were considered random for soil properties because treatments were re-randomized in each replication and sampling occurred in only one phase (during fallow) of the rotation each year, with a differently randomized set of plots sampled each year. For crop yields, only replication was considered random. Effects were considered significant at $P \leq 0.05$. Weed density and SDI data were modeled against the fixed effects of tillage, location, and their interaction separately for each location.

Results

Long-term weather patterns

The precipitation across the three locations varied, with both dry and wet years during the study period. For Hays, the average annual precipitation from 2010 to 2015 was 81% of the 30-year average (Table 3.1). However, the average annual precipitation from 2020 to 2023 was 95% of the 30-year average. The precipitation received in 2018 and 2019 at Hays was 152% and 155% greater than the 30-year average. In most years, spring precipitation (March-May) allowed winter wheat to continue growing and recharged the subsurface soil moisture. For Garden City, the average annual precipitation from 2010 to 2015 was 75% of the 30-year average (Table 3.2). The average annual precipitation from 2020 to 2023 was 77% of the 30-year average. The precipitation received in 2018 and 2023 was 125% and 114% greater than the 30-year average. The spring precipitation (March-May) was highly variable, with 2010 and 2015 receiving up to 84% more precipitation than 2011, 2012, 2013, and 2014. In Tribune, the average annual precipitation from 2010 to 2015 74% of the 30-year average (Table 3.3). However, the average annual precipitation from 2020 to 2023 was 92% of the 30-year average. The precipitation received in 2017 and 2021 was 111% and 114% greater than the 30-year average.

Soil organic carbon

For the 2022 pre-tillage sampling, the three-way interaction of Tillage × Depth × Location had no effect on SOC (Table 3.6). Similarly, the two-way Tillage × Location and Tillage × Depth interactions were not significant. However, the Depth × Location interaction and the main effects of Depth and Location influenced SOC concentration. The SOC concentration measured at 0-to-5-cm depth was 13% greater than the 5-to-15-cm depth at Hays and 33% greater at Garden City (Figure 3.1a). The average SOC concentration at the 0-to-5-cm depth was 12.5 g kg^{-1} compared to 9.8 g kg^{-1} measured within 5-to-15-cm depth. Across locations, Garden City had 33% less SOC (8.9 g kg^{-1}) compared to Hays (13.3 g kg^{-1}). The post-tillage SOC samples also had a significant Depth × Location interaction as well as main effects of Depth and Location (Table 3.7). At all locations, the soil surface had greater SOC concentration compared to the 5-to-15-cm depth (Figure 3.2a). For the main effect of Depth, the SOC concentration within the 5-to-15-cm depth was 24% less than in the 0-to-5-cm depth. Across locations, Hays had the greatest SOC (15.56 g kg^{-1}), followed by Tribune (11.94 g kg^{-1}), and then Garden City (9.90 g kg^{-1}).

Soil pH and nutrient concentrations

Soil pH was not influenced by the main effect of Tillage or any interaction with Tillage. For 2022 pre-tillage samples, soil pH differed only by the main effects of Depth and Location (Table 3.6). The soil pH at the 5-to-15-cm depth was 6.71 compared to 6.38 at the 0-to-5-cm depth. The 2022 pre-tillage results indicated that the soil pH at Garden City (6.93) was significantly higher than the 6.16 pH at Hays. For post-tillage samples, the Depth × Location interaction as well as main effects of Depth and Location had effect on soil pH (Table 3.7). For the Depth × Location interaction, all the locations had greater pH in the 5-to-15-cm depth compared to the 0-to-5-cm depth with the difference between the depths ranging from 8-12% (Figure 3.2b). For the main effect of Depth, the 5-to-15-cm depth was 10% greater than the surface layer. Across locations, Garden City (6.70) and Tribune (6.91) had higher pH than Hays (5.75) but were not significantly different from each other.

For M3-P, there was no influence of tillage on pre- or post-tillage samples. The 2022 pre-tillage M3-P soil concentration was affected by the Depth × Location interaction and the main effect of Location (Table 3.6). The 5-to-15-cm depth had 58% greater M3-P concentration than the 0-to-5-cm depth at Garden City, but there were no differences in M3-P concentration between sampling depths at Hays (Figure 3.1b). Hays (15.53 mg kg^{-1}) was 88% less M3-P concentration than Garden City (131.37 mg kg^{-1}). The post-tillage samples also had a significant Depth × Location interaction as well as main effects of Depth and Location (Table 3.7). For the Depth × Location interaction, Hays had almost 50% greater M3-P concentration in the 0-to-5-cm depth compared to the 5-to-15-cm depth (Figure 3.2c). However, the opposite trend was observed at Garden City where the 5-to-15-cm depth had more than 50% greater M3-P concentration compared to the surface layer. At Tribune, there were no differences between depths. Comparing depths across locations, M3-P at the soil surface (53.78 mg kg^{-1}) was nearly 50% less than the lower soil profile (97.16 mg kg^{-1}). For the main effect of Location, M3-P at Garden City (148.93 mg kg^{-1}) was significantly higher than Tribune (55.14 mg kg^{-1}) and Hays (22.34 mg kg^{-1}).

The 2022 pre-tillage NO_{3^-}-N concentration was unaffected by the main effects of Tillage, Depth, or Location or their interactions (Table 3.6). However, the post-tillage NO_{3^-}-N samples were affected by the main effect of Tillage (Table 3.7). The 2TBW treatment had 25-30% greater NO_{3^-}-N concentration than the STBW and NT treatments (Table 3.8).

Bulk density, penetration resistance, and water content

Soil bulk density was not influenced by Tillage as a main effect or any of its interactions at any sampling time (Tables 3.6 and 3.7). Only the main effects of Depth and Location significantly affected soil bulk density measured in 2022 pre-tillage samples. Soil bulk density was 21% less in the 0-to-5-cm depth (1.17 g cm^{-3}) compared to the 5-to-15-cm depth (1.48 g cm^{-3}). Garden City had 6% higher bulk density (1.36 g cm^{-3}) than Hays (1.28 g cm^{-3}). Similar to the 2022 pre-tillage samples, the post-tillage samples had a significant Depth effect. The bulk density of the top layer (1.13 g cm^{-3}) was roughly 25% less than at the 5-to-15-cm depth (1.49 g cm^{-3}).

For the 2022 pre-tillage samples, there was no influence of Tillage on gravimetric water content (Table 3.6). However, the Depth × Location interaction and the Depth, and Location, main effects significantly affected gravimetric water content in those samples. The soil water content within the 5-to-15-cm depth was 50% greater than in the 0-to-5-cm depth at both locations (Figure 3.1c). Averaged across both locations, the water content at the 0-to-5-cm depth (0.09 g g^{-1}) was 50% less than the 5-to-15-cm depth (0.20 g g^{-1}). Averaged across depths, Hays had 37% greater water content (0.19 g g^{-1}) than Garden City (0.10 g g^{-1}). For GWC of post-tillage samples, there were significant Tillage × Location and Depth × Location interactions as well as main effects of Depth and Location (Table 3.7). For the Tillage × Location interaction, Hays had an 18% increase in GWC with the 2TBW tillage treatment compared to NT, and the STBW tillage treatment was not significantly different from NT or 2TBW (Figure 3.3a). Overall, GWC increased with increasing tillage intensity at Hays. At Garden City, there were no differences among tillage treatments. Finally, at Tribune, the opposite trend to Hays was observed because NT had roughly 10% greater GWC than the tillage treatments (Figure 3.3a). For the Depth × Location interaction, all the locations had greater GWC in the 5-to-15-cm depth compared to the surface layer (Figure 3.3b), with the differences ranging from 20-50% across the locations. For the main effect of Depth averaged across locations, the 5-to-15-cm depth (0.20 g g^{-1}) was greater than the soil surface (0.12 g g^{-1}). The main effect of Location averaged across depths indicated that Tribune (0.20 g g^{-1}) had the highest GWC, followed by Hays (0.15 g g^{-1}), and finally, Garden City (0.13 g g^{-1}).

The 2022 pre-tillage PR was not influenced by Tillage and only had a significant Location effect (Table 3.9). The PR value measured at Hays was 24% greater compared to Garden City. The post-tillage samples had a significant Tillage effect (Table 3.10). The PR with NT was more than 10% greater than the STBW and 2TBW treatments (Table 3.8)

For cumulative water infiltration, at Hays and Garden City, the 2TBW and STBW treatments had greater water infiltration compared to NT. The NT treatments at Hays had less infiltration compared to STBW and 2TBW (Figure 3.4a). At Garden City, the cumulative infiltration was similar to that at Hays after 30 minutes, but the differences were small (Figure 3.4b) However, at Tribune, all tillage treatments had similar cumulative water infiltration (Figure

3.4c). There were less consistent results for cumulative water infiltration at Tribune, with the NT treatment being less consistent compared to STBW and 2TBW treatments. Overall, the Hays and Garden City water infiltration data showed a tendency of increasing water infiltration with OT. However, a consideration for this data is the amount of precipitation received before sampling. Garden City and Tribune had received more rainfall than Hays prior to sampling, which would decrease infiltration. At Garden City and Tribune, the months of May, June, and July had greater precipitation than Hays, and the difference in precipitation received per month at Garden City and Triune compared to Hays was as high as 50% (Tables 3.1, 3.2, 3.3).

Aggregate stability and wind erodibility

The pre-tillage wet aggregate size distributions (WASD), which were <0.25-mm, 0.25-to-2-mm, and 2-to-8-mm, and mean weight diameter (MWD) were not affected by the main effect of Tillage or its interaction with Location in pre-tillage samples (Table 3.9). However, there was a significant Location effect for the 2-to-8-mm class and MWD. In 2022 pre-tillage samples, the MWD at Hays (0.49 mm) and Garden City (0.59 mm) were not significantly different from each other. Across the size classes, the locations were similar in the proportions of aggregates per size, except for the 2-to-8-mm size. For the post-tillage samples, the <0.25mm and 0.25-to-2-mm WASD had a significant Tillage × Location interaction (Table 3.10). In the <0.25-mm size class, Hays and Tribune both had a greater proportion of aggregates under 2TBW than the other tillage treatments, but the opposite was observed at Garden City (Table 3.11). For the 0.25-to-2-mm size class, Hays had a greater proportion of aggregates under NT and STBW compared to 2TBW, but Garden City had greater proportion of aggregates under 2TBW than STBW and NT. For the 2-to-8-mm size class and MWD, there were no significant tillage treatment or location differences. The differences in the smallest and intermediate size classes can cause an increase in susceptibility to erosion because they are the smallest size classes.

The 2022 pre-tillage dry aggregate size distributions (DASD), which were <0.42-mm, 0.42-to-0.84-mm, 0.84-to-2-mm, 2-to-6.3-mm, 6.3-to-19-mm, had interesting results (Table 3.9). Only the 2-to-6.3-mm size class was significantly affected by the Tillage × Location interaction. At Garden City, the NT treatment had over 50% of aggregates in the 2-to-6.3-mm DASD than STBW and 2TBW treatments (Figure 3.1d). At Hays, there were no significant differences among the tillage treatments. For the pre-tillage WEF, Hays was greater than Garden City, and this correlates to Hays having a higher proportion of aggregates in the smallest size classes (Table 3.11). Garden City had greater portions of aggregates in the 2-to-6.3-mm and 6.3-to-19-mm aggregate sizes than Hays.

For post-tillage samples, all the DASD except for <0.42-mm and the WEF were affected by Tillage (Table 3.10). In the 0.42-to-0.84-mm, 0.84-to-2-mm, and 2-to-6.3-mm DASD, NT had greater proportions of aggregates than the STBW and 2TBW treatments (Table 3.8). However, in the 6.3-to-19-mm DASD, the 2TBW treatment had a greater proportion of aggregates than STBW and NT. Overall, increased tillage intensity caused a decrease in the proportion of aggregates in the small size classes. However, increased tillage intensity caused an increase in the proportion of aggregates in the largest size classes. The 2-to-6.3-mm DASD was also influenced by Location (Table 3.10). Garden City (21.61%) had a higher proportion of aggregates in this size class than Tribune (17.20%), and Hays (20.22%) was not significantly different from the other locations.

Crop Yields

For winter wheat yields at Hays, there was no influence of Tillage, but there was a significant effect of Year in both sets of years (Table 3.12). The 2019 (2766 kg ha^{-1}) yield was less than 2020 (3460 kg ha^{-1}), and the 2022 (2450 kg ha^{-1}) yield was greater than 2023 (952 kg ha^{-1}) (Figure 3.5a). There was no wheat yield at Hays in 2021 due to a hailstorm eliminating the crop. At Garden City, there was a significant Tillage × Year interaction (Table 3.12). In 2019 and 2021, wheat yields were greater with the STBW, 2TAW, and 2TBW tillage treatments compared to NT, but this trend wasn't observed in 2020, 2022, or 2023 (Figure 3.5b). In 2023, the 2TBW and STAW treatments decreased wheat yields compared to NT. The yields in 2020 were the exception at this location because there were no significant differences across treatments. At Tribune, there was not a significant Tillage × Year interaction, but there was a significant Year effect (Table 3.12). The yields in 2019 (6079 kg ha^{-1}) and 2021 (4580 kg ha^{-1}) were greater than 2020 (2800 kg ha^{-1}) and 2023 (1557 kg ha^{-1}) (Figure 3.5c). There was no 2022 wheat yield due to a hailstorm eliminating the crop.

There was a significant effect of Tillage for the 2019 and 2020 sorghum yields at Hays (Table 3.13). The NT was greater than the 2TBW, but the STBW treatment was not significantly different from the other treatments (Figure 3.6a). In 2021 to 2023, Tillage had no effect on sorghum yields but there was a significant Year effect, and 2021 (5711 kg ha^{-1}) had 30-40% greater yield than the 2022 (3276 kg ha^{-1}) and 2023 (3921 kg ha^{-1}) growing seasons (Figure 3.6b). For Garden City and Tribune, there was only a significant effect of Year (Table 3.13). The trend was similar at both locations with the yields at Garden City in 2019 (2669 kg ha^{-1}) and 2020 (3062 kg ha^{-1}) being greater than in the other years (Figures 3.6c), and at Tribune, the yields in 2019 (7571 kg ha^{-1}), 2020 (5315 kg ha^{-1}), and 2021 (6626 kg ha^{-1}) being greater than the other years (3.6d). In Garden City, there was no grain sorghum yield in 2021 due to herbicide injury, and in 2023 due to crop failure caused by sorghum midge.

Water use and water use efficiency

At Garden City, the water use (WU) for winter wheat had significant Tillage and Year effects (Table 3.14). For the Tillage effect averaged over 2019 through 2023, STBW, 2TBW, and 2TAW had greater WU than STAW, and NT was not significantly different from any other treatment (Figure 3.7a). For the Year effect, 2019 and 2021 were greater than 2020 and 2023 (Figure 3.7b). Garden City grain sorghum WU was not influenced by Tillage or Year. For Tribune, both wheat and sorghum WU only differed by Year. For wheat, 2019 and 2021 had the greatest WU (Figure 3.7c), and a similar trend can be observed with sorghum WU (Figure 3.7d).

The water use efficiency (WUE) at Garden City and Tribune were unaffected by tillage (Table 3.14). Both wheat and sorghum WUE were significantly affected by Year at Garden City. The Garden City WUE for wheat was highest in 2019 and 2021, and the other years were not significantly different from each other (Figure 3.8a). For sorghum, WUE was the highest at Garden City in 2020 (Figure 3.8b). At Tribune, there was also a significant effect of Year. The WUE was highest in 2019, 2020, and 2021, for wheat (Figure 3.8c) and for sorghum (Figure 3.8d).

Weed Seed Bank

Weed seed bank (WSB) across the three samplings timings was unaffected by tillage (Table 3.15). The Tillage × Location interaction had no significant effect on WSB in 2022 pre-tillage, but there was a significant Location effect. However, for the 2022 post-tillage sampling, there was a significant Location effect. For 2022 post-tillage, Hays had 86% and 96% greater

WSB than Garden City and Tribune (Figure 3.9a). There was no influence of Tillage or Location on 2023 pre-herbicide samplings.

For pre-tillage samples, the SDI value for Garden City (0.43) was 61% less than Hays (1.11) SDI. However, the 2022 post-tillage SDI had a significant Tillage × Location interaction as well as main effects of Tillage and Location. At Hays, the NT had 16% and 40% greater SDI than the STBW and 2TBW treatments (Figure 3.9b). The SDI was not different among tillage treatments in Garden City. Among Tillage treatments, the SDI for NT was 17% and 33% greater than STBW and 2TBW. In general, the SDI at Garden City (0.05) was 96% less than Hays (1.41). Tribune had no weeds emerge from 2022 post-tillage WSB samples. The 2023 pre-herbicide sampling was not affected by Tillage × Location interaction or Tillage main effect, but there was a significant Location main effect. Overall, the SDI at Garden City (1.05) and Hays (0.73) were 70% and 56% greater than the SDI value calculated for Tribune (0.32).

Discussion

The SOC findings in the current study support the findings of other researchers (Kettler et al., 2000; Obour et al., 2021; Thapa et al., 2023). Soil organic carbon was not affected by tillage, and instead, the SOC concentrations differed by depth and location (Figure 3.1a and 3.2a). The lack of tillage effect on SOC was possibly because of the tillage implement used and frequency of tillage operations in the present study. Single or two tillage operations with a sweep plow left more residue on the soil surface resulting in no negative impacts on SOC compared to NT. Other studies in the Midwest and Southwestern United States (e.g. Nebraska, Kansas, and Texas) have also found that OT with residue saving implements had no effect on SOC compared to NT (Kettler et al., 2000; Obour et al., 2021; Thapa et al., 2023). The rotations of the previously mentioned studies were wheat-fallow, wheat-sorghum-fallow, continuous wheat, and corn-sorghum. Generally, the soil surface has increased root and biological activity and tends to have greater SOC concentration compared to the 5-to-15-cm depth, which is similar to previous reports in the literature (Chen et al., 2003; Fang and Moncrieff, 2005). In New Mexico, Thapa et al. (2023) reported 12-27% decrease in SOC in the 0-to-15-cm depth and 11-16% decrease in SOC in the 15-to-30-cm depth with the use of conventional tillage (CT) compared to NT, stubble mulch tillage, and strip tillage. However, the authors noted there was no difference in SOC between NT and stubble much tillage. Similarly, Quincke et al. (2007) concluded no differences in SOC concentrations among one-time tillage with moldboard plow, chisel plow, disking compared with NT, which agrees with results of the present study. The locations of this study differed geographically, but they also differ by precipitation (Tables 3.1, 3.2, and 3.3).

In long-term NT systems, nutrient stratification is a concern for farmers, and generally, the concentrations are highest near the soil surface, which is not what the present study concluded. Soil pH was not influenced by tillage in the current study. However, the pH results in this study showed the 5-to-15-cm depth to be greater than the 0-to-5-cm depth, so OT with a sweep plow does not aid in redistributing or mixing the soil because the implement does not invert the soil. A study conducted in New South Wales, Australia found pH, soil P, and soil nitrogen were stratified in the top 5 cm of the soil profile (Conyers et al., 2019). Additionally, in the current study, soil M3-P and NO_3-N were greatest in the 5-to-15-cm depth at Garden City, which disagrees with the findings of Conyers et al. (2019). However, a key consideration is the tillage implement used and fertility management, and for the current study, all three locations had differing fertility management practices (Table 3.5). In the present study, tillage did not affect soil M3-P concentration, but it varied depending on depth and location (Figures 3.1b and 3.2c). The locations had different soils, precipitation, fertility management practices, and crop yields, all of which likely interacted to influenced M3-P concentrations (Tables 3.1-3.5 and Figures 3.5a-3.6d). The results of the current study indicated the NO_3-N was influenced by tillage in the post-tillage samplings (Table 3.7). The 2TBW treatment was greater than the NT treatment, and the STBW treatment was not significantly different from the other treatments (Table 3.8). The tillage helps convert organic forms of nitrogen to inorganic forms through mineralization, which increases nitrogen in the soil. The findings of this study agree with those of Thapa et al. (2023) who observed differences in NO_3-N across tillage treatments for two sampling times and sampling depths. Thapa et al. (2023) reported 7 months after stubble mulch tillage implementation, the soil N in the 0-to-15-cm depth was 12% and 31% greater with CT than under stubble mulch tillage and strip tillage, and the authors reported similar results 14 months after implementation with 11-24% greater soil N with CT than other tillage treatments. The increased tillage intensity resulted in increasing N mineralization from soil organic matter, which could explain why the authors observed an increase with CT compared to stubble mulch tillage and strip tillage as well as why there was an increase in the current study.

Another issue in long-term NT systems in compaction. In the current study, tillage had no effect on bulk density, which differed only by depth across sampling times (Tables 3.6 and 3.7). It is important to note neither of the depths at any sampling time had bulk density values near 1.66 g cm^{-3}, which is known to cause root limiting growth (USDA-NRCS). A study in the Czech Republic compared reduced tillage (RT), OT, CT, and NT and reported that CT reduced bulk density by 15.3% (Abebrese et al., 2023). However, the authors observed no significant differences among the other tillage treatments. It is important to note some potential rotational and climatic differences with the study by Abebrese et al. (2023). The authors noted the rotation was oil seed rape (*Brassica napus* subsp. *napus*), winter wheat, and pea (*Pisum sativum*), and the average annual precipitation was 522 mm with maximum recorded values of 731 mm and the least was 344 mm. Bordovsky et al. (1999) compared RT and CT in an irrigated wheat-grain sorghum rotation, and in an initial sampling, the authors observed a lower bulk density with CT compared to RT and NT. However, five years later the bulk density had been increased in the CT treatment and was similar to the RT and NT. A review by Blanco-Canqui and Ruis (2018) found 15 studies that compared soil bulk density between NT and RT, and in eleven of the fifteen studies no difference was observed between RT and NT or between RT and CT. Similarly, the authors indicated that RT had no effect on penetration resistance in 64% of cases. However, it is important to note the studies reported by Blanco-Canqui and Ruis (2018) were from various countries across the world, such as Canada, United States, Brazil, Chile, Italy, Switzerland, Spain, India, and New Zealand. Additionally, the authors noted the various crop rotations, such as wheat-sorghum-fallow, corn (Zea *mays*)-soybean (Glycine *max*), corn-wheat, and sugarbeet (Beta *vulgaris* L.). This highlights the variations in soil responses to tillage treatment in a variety of environments and crop rotations. Penetration resistance differed among tillage treatments for post-tillage sampling, in which NT had greater penetration resistance than STBW and 2TBW. In this instance tillage alleviated soil compaction, which likely decreased penetration resistance.

Tillage affected water content differently depending on tillage, depth, and location (Figures 3.1c, 3.3a, 3.3b). The amount of precipitation received varied during the study period, which played a large role in soil water content (Tables 3.1-3.3). Schlegel et al. (2020) measured available soil water (ASW) at planting and harvest at Garden City and Tribune, KS. The authors observed no differences among tillage treatments, but the ASW varied by depth and location. In addition to measuring ASW, the authors also reported WUE, which varied only by year and location. The current study observed differences in water use (WU) and WUE across year and tillage at Garden City and only year at Tribune for WU and WUE (Figure 3.7a-3.8d). This could be explained by the variability in precipitation the past few growing seasons, which in turn affected crop yield.

Soil erosion is another large concern for producers when incorporating tillage into their long-term NT systems. The pre- and post-tillage samples for MWD indicated there was no negative influence of tillage (Tables 3.5 and 3.7). Instead, the MWD differed only by location. The location differences observed in the current study can be explained by the differing soil types across the locations. This can influence aggregates and their size distribution as well as biological activity. Additionally, the weather patterns across the locations were similar but not identical. The 30-year average of annual precipitation indicates Hays and Garden City had greater precipitation than Tribune (Tables 3.1 a-c). The findings of this study don't match those found by other researchers who reported that macroaggregates were reduced with the tillage, but there can be an increase, which take up to 6 months, in aggregate stability over time between tillage operations (Conyers et al., 2019; Daraghmeh et al., 2009; Wortmann et al., 2010). Paye et al. (2023) found that macroaggregates ranged from 51-54% across ST, OT, and NT in the 0-to-15-cm sampling depth, which was 44% greater than in CT. The lack of influence of the tillage treatments in the current study compared to the results reported by others could be due to the use of different tillage implements, such as offset discs or moldboard plow, and tillage intensity, which influenced the level of soil disturbance and its impacts of aggregate stability. In the current study, a sweep plow was used, which is a low disturbance implement with minimal incorporation of crop residue, which tends to have minimal effects on the soil as suggested in the present study.

Particularly in western Kansas, intense windstorms are another concern when implementing a tillage operation. Tillage had no effect on WEF, which differed only by location (Table 3.5 and Table 3.7). The dry, hot conditions through the summer months can also cause erosion to increase because the aggregates continue to shrink in size, which can make them easily erodible. Daraghmeh et al. (2009) reported that dry aggregate stability was lowest under RT compared to CT. However, as noted by other authors, aggregate stability can be increased over time after a tillage operation (Conyers et al., 2019). However, a consideration when comparing Conyers et al. (2019) to the current study would be the climate, tillage implement, and crop rotation, and Conyers et al. (2019) highlighted the on-farm research locations were southern New South Wales, Australia and the tillage was done with off-set discs in wheat-based systems. However, the authors noted the rotations were up to the producers. Blanco-Canqui and Ruis (2018) reported similar dry aggregate stability in 50% of cases comparing NT and RT from 14 studies, which were mostly located in the United States as well as Brazil, Argentina, and Malawi. The authors discussed crop rotations, which were mostly wheat based, but other rotations were corn-soybean, corn, or sunflower (*Helianthus* sp.)-corn-soybean-wheat. The authors also noted a couple key considerations to minimize erosion, such as avoiding tillage prior to intense rainstorms as well as attempting to till prior to planting instead of during fallow periods. In the current study, the tillage occurred in June and July prior to winter wheat planting in October.

Increasing overall net returns is a key concern for farmers, and the thought process of the incorporation of tillage is to increase crop yield. However, tillage had a minimal effect on winter wheat yields at Hays and Tribune, but the winter wheat yields at Garden City were affected by the interaction of Year and Tillage (Table 3.12). Overall, the grain yields across all locations depended on year (Figures 3.5a-c and 3.6a-c). The increases of winter wheat yield with more intense tillage at Garden City can be explained by the increased infiltration observed in the tillage treatments (Figure 3.4b). Holman et al. (2021) found increased soil water in winter triticale [×*Triticosecale Wittm. ex A. Camus* (*Secale* ×*Triticum*)] and forage sorghum with the use of RT compared to NT. At Hays, grain sorghum yields decreased with the more intense tillage treatments compared to NT in 2019 and 2020, which could be due to exposed soil and evaporation of soil water (Figure 3.6a).

Similarly, to the current study, others have also found minimal improvement of crop yields with tillage (Paye et al., 2023; Schlegel et al., 2020). However, there have also been studies that reported mixed influences of OT on yields. From 12 site-years of data, there were three negative effects and one beneficial effect with the use of tillage on grain yield (Conyers et al. 2019), in a wheat-based system in south New South Wales, Australia. In a review conducted by Blanco-Canqui and Wortmann (2020), crop yields increased in 15%, decreased in 5%, and did not change in 80% of cases, which allowed them to conclude there is an inconsistent effect of OT on crop yield. The authors reported this information from 12 studies on 31 soils from countries such as Canada, United States, Brazil, Spain, Turkey, and Australia. The findings reported by the authors above concluded there are varying effects of OT on grain yield, but overall, there is often minimal influence on yield, which aligns with the findings of the present study.

The weed density was not influenced by tillage, but there was an influence of location for 2022 post-tillage samples. Overall, Hays had greater weed density than Garden City and Tribune (Figure 3.9a). This could be due to varying weed populations across the locations and differing modes of action of herbicides that were used for pre- and post-emergence applications. The

Shannon’s Diversity Index for 2022 post-tillage samples indicated the NT treatment at Hays was greater than the tillage treatments (Figure 3.9b). With the incorporation of OT, weed populations are eliminated prior to winter wheat planting, which allows the crop to be well established. Good establishment minimizes the chance of competition for water, nutrients, and sunlight between the weeds and crops. There can also be better seed-to-soil contact with tillage because it helps break up leftover crop residue and weed biomass and create a good seedbed.

Conclusions

For most soil parameters, the results from this study showed that the effect of OT is not harmful to soil properties or crop yields. The results of soil organic carbon, pH, Mehlich-3 phosphorus, bulk density, mean weight diameter, and wind erodible fraction did not support our hypothesis because tillage did not have a negative influence on these parameters. Instead, these parameters differed only by depth, location, year, or their interactions.

The soil parameters influenced by tillage were soil nitrate, penetration resistance, gravimetric water content, and water infiltration, depending on the location. However, gravimetric water content was one of the few soil parameters that was negatively influenced by tillage. Gravimetric water content differed by tillage, location, and year, and there were varying effects of tillage on water content, with positive, negative, or minimal influence. However, these influences can depend on precipitation received at a given location and within a year. Therefore, the decision to incorporate OT could potentially harm water content depending on the year.

Overall, there was minimal negative influence of tillage on crop yields. Dependent on the year, tillage increased winter wheat yields in Garden City, but tillage had no effect on winter wheat yields in Hays and Tribune. The grain sorghum yields at Hays decreased with increased tillage intensity compared to NT in 2019 and 2020, but the other locations observed no differences. Both winter wheat and grain sorghum yields were affected by year, which can be explained by the varying amount of precipitation received per year. Weed density was not influenced by tillage, which differed only by location. The Shannon's Diversity Index was influenced by tillage, and the greatest weed diversity was under NT compared to the tillage treatments, which supported our hypothesis.

These results allow us to conclude that OT did not significantly harm soil properties or crop yields. For this study, further research could be done on the long-term economic analysis of NT compared to the tillage treatments. Additionally, the >5-year influences of tillage on soil physical and chemical properties. The weed seed bank is an area of research that also will need to have more research conducted because it is a key source of competition for growing crops.

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Figures

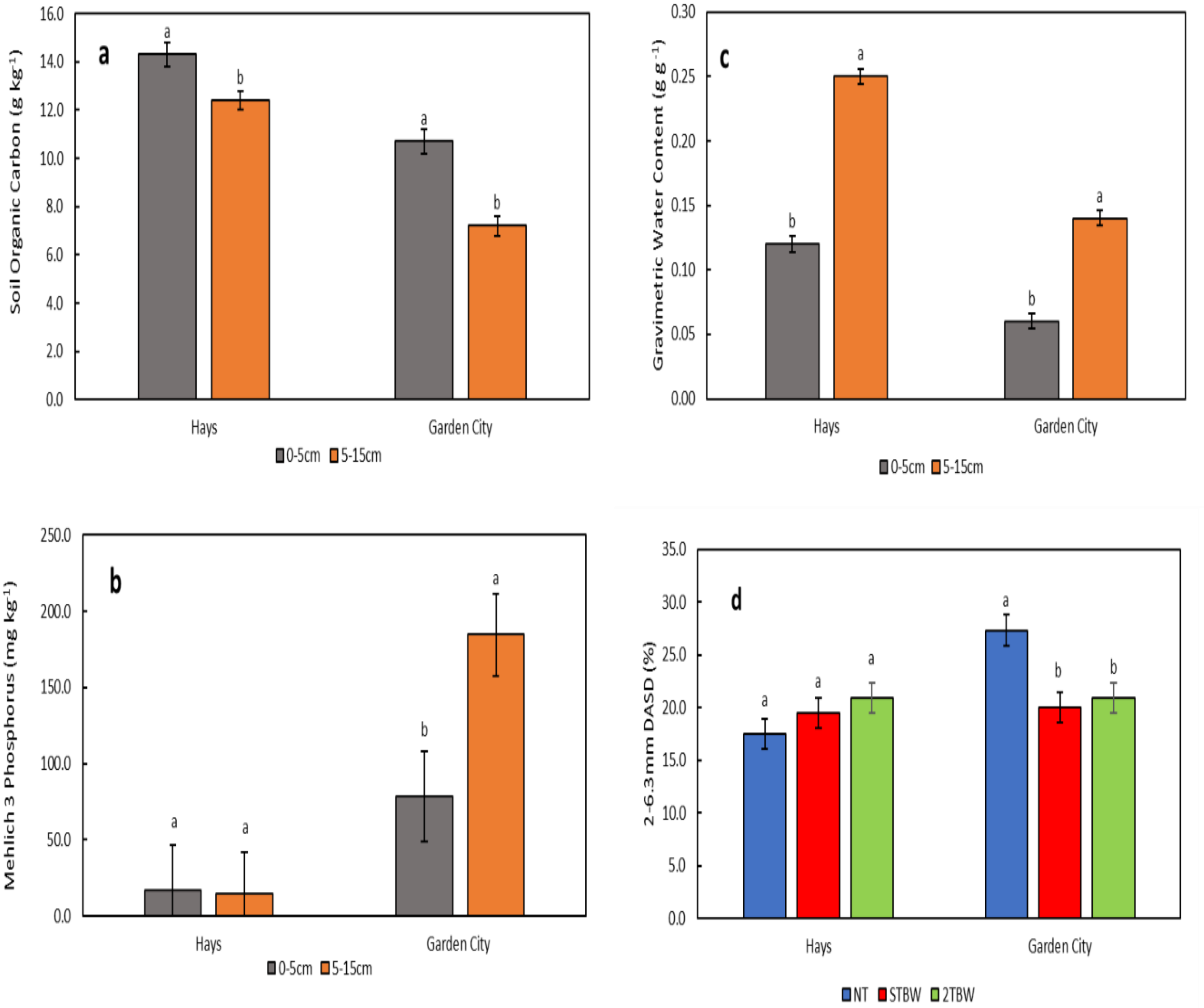

Figure 3.1. Sampling depth and location effects on soil organic carbon (a)**, Mehlich-3 phosphorus** (b)**, and gravimetric water content** (c) **from 2022 pre-tillage soil samples near Hays and Garden City, KS. Tillage treatment and location effects on 2-to-6.3-mm dry aggregate size distribution (DASD)** (d) **from 2022 pre-tillage samples near Hays and Garden City, KS. Bars within a subfigure with the same lower-case letter are not different (α=0.05).**

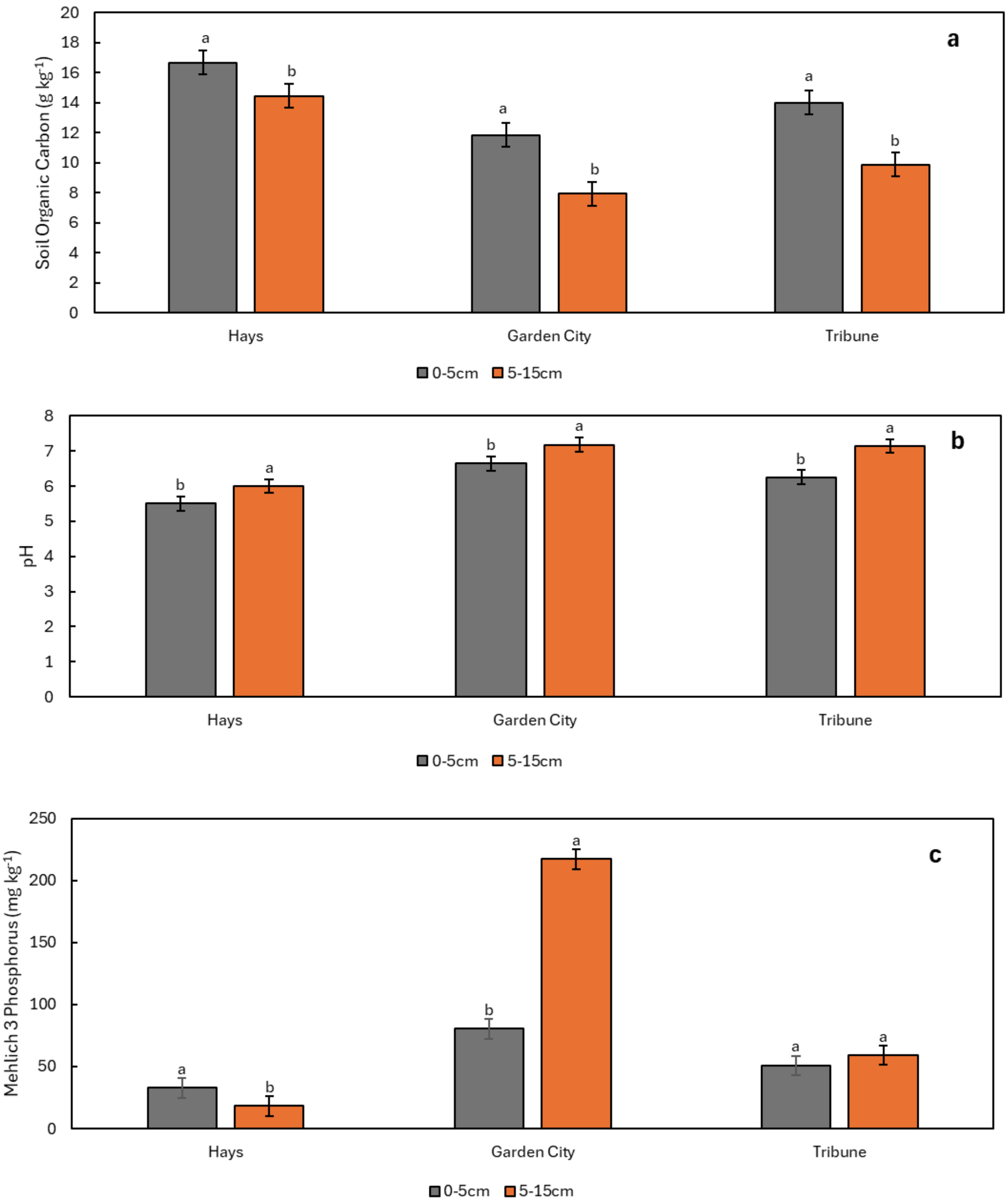

Figure 3.2. Sampling depth and location effects on soil organic carbon (a)**, pH** (b)**, and Mehlich-3 phosphorus** (c) **from 2022 and 2023 post-tillage samples near Hays, Garden City, and Tribune, KS. Bars within a subfigure with the same lower-case letter are not different (α=0.05).**

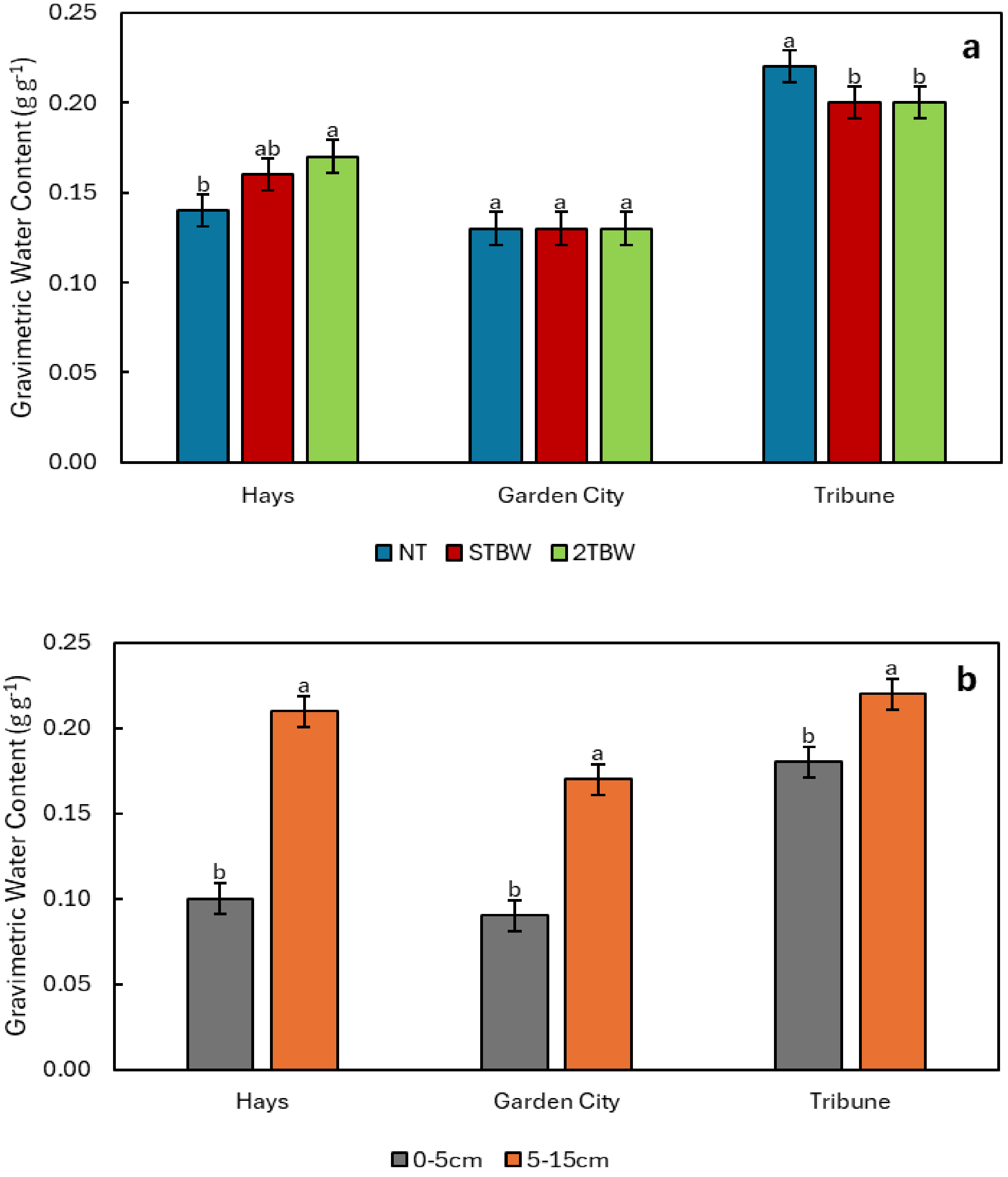

Figure 3.3. Tillage and location effects on gravimetric water content (a) **and depth and location effects on gravimetric water content** (b) **from 2022 and 2023 post-tillage samples near Hays, Garden City, and Tribune, KS. Bars within a subfigure with the same lower-case letter are not different (α=0.05).**

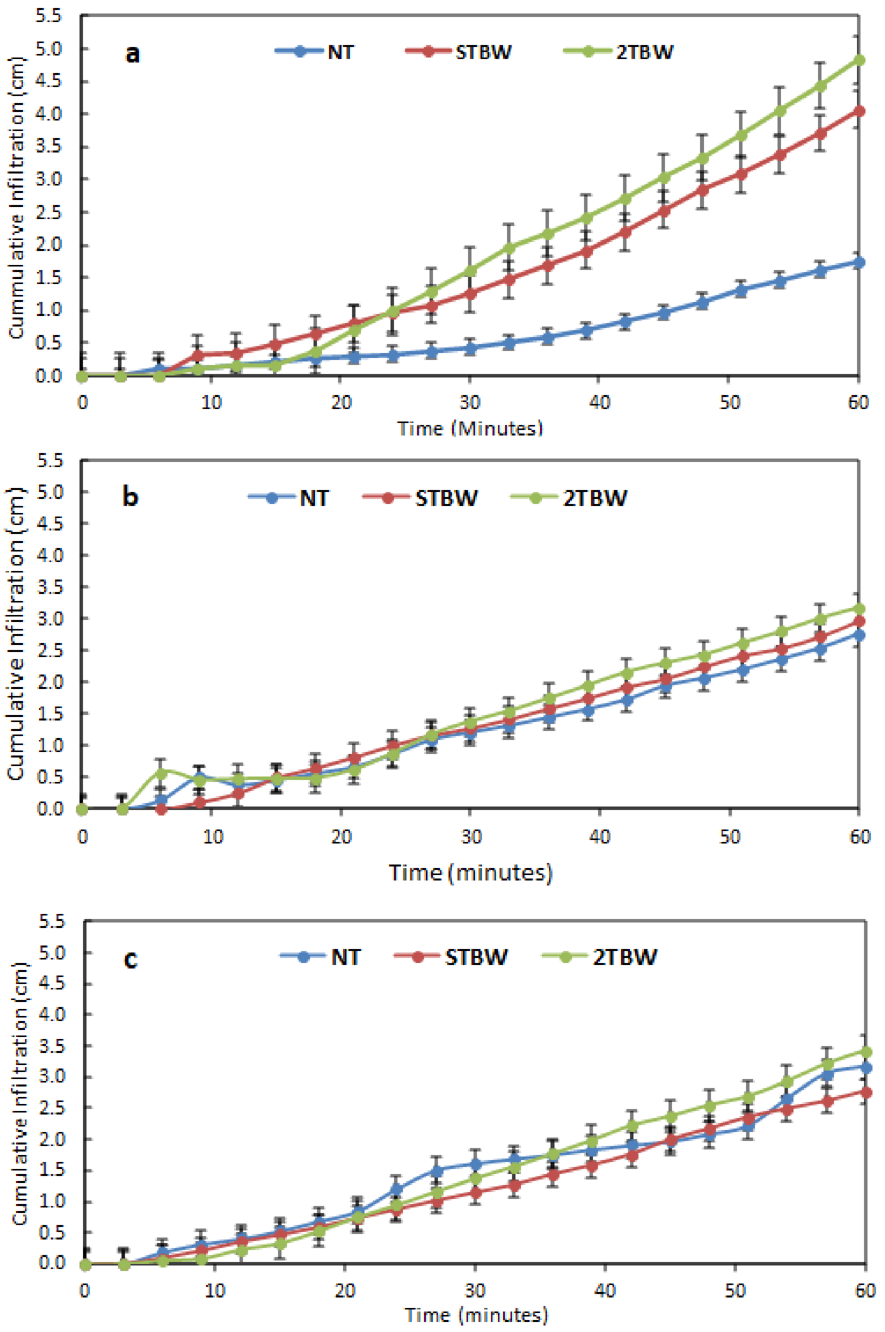

Figure 3.4. Influence of tillage on cumulative infiltration post-tillage in 2023 near Hays (a)**, Garden City** (b) **and Tribune, KS** (c)**.**

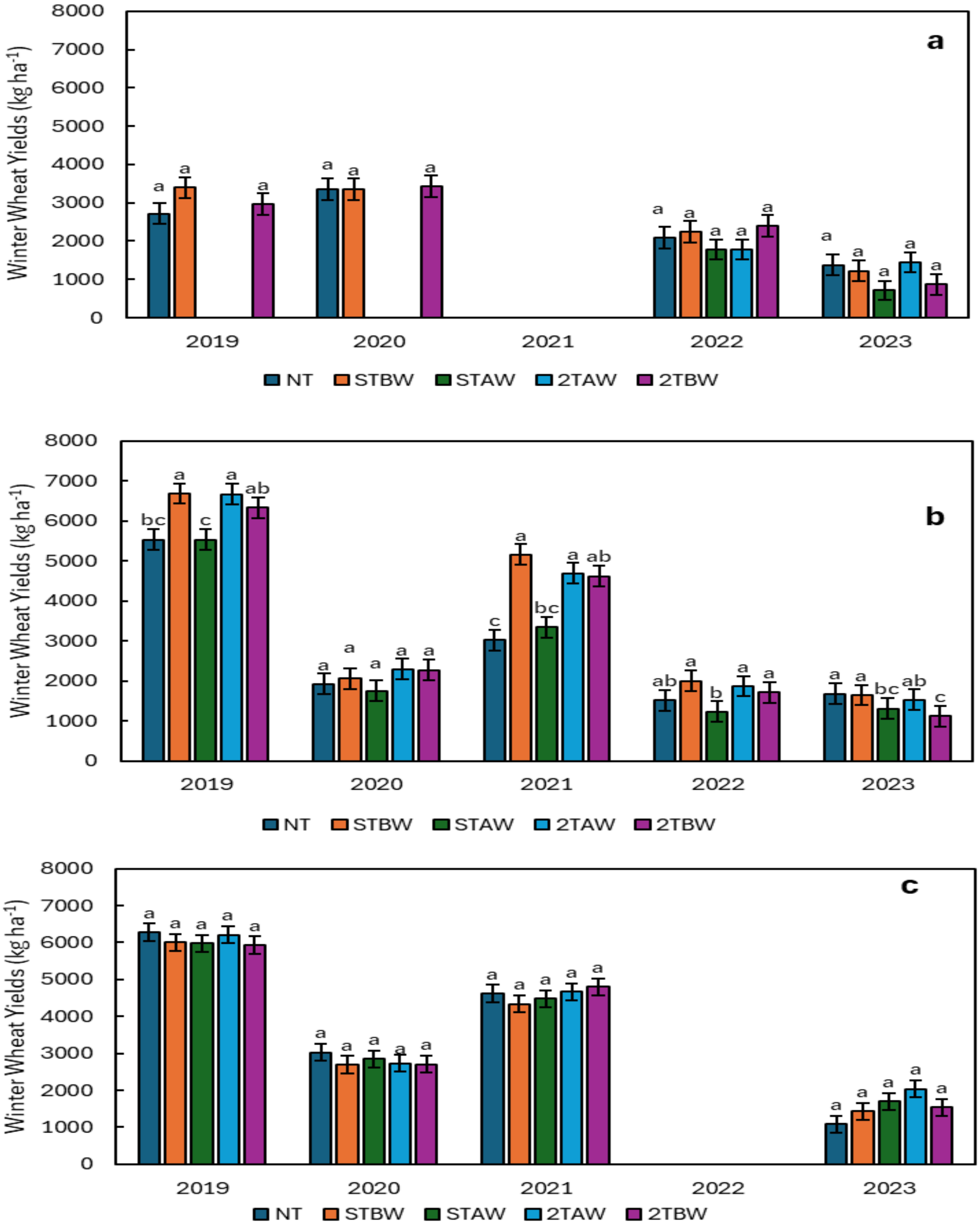

Figure 3.5. Influence of tillage treatment and year on winter wheat yields from 2019-2023 near Hays (a)**, Garden City** (b)**, and Tribune, KS** (c)**. Bars within a subfigure with the same lower-case letter are not different (α=0.05). Only three treatments are reported for Hays in 2019 and 2020 due to treatment implementation timing. No 2021 wheat yield at Hays or 2022 wheat yields at Tribune due to a hailstorm eliminating the crop.**

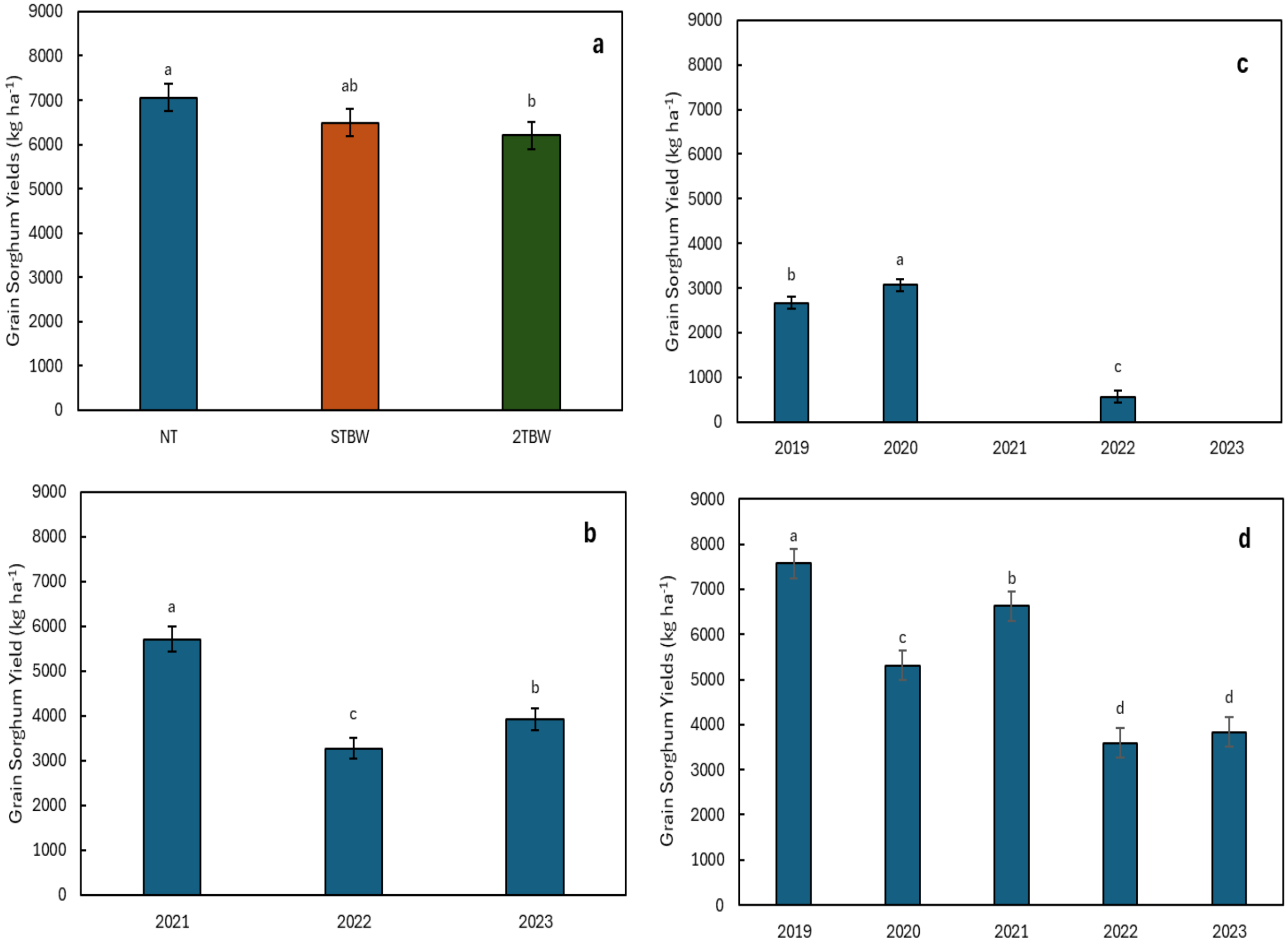

Figure 3.6. Influence of tillage treatment on grain sorghum yields from 2019 and 2020 near Hays (a)**. Influence of year on grain sorghum yields from 2021-2023 near Hays** (b)**, 2019-2023 near Garden City** (c)**, and 2019-2023 near Tribune, KS** (d)**. Bars within a subfigure with the same lower-case letter are not different (α=0.05). Only three treatments in Hays in 2019 and 2020 due to implementation timing. No 2021 grain sorghum yield due to herbicide injury and 2023 due to crop failure at Garden City.**

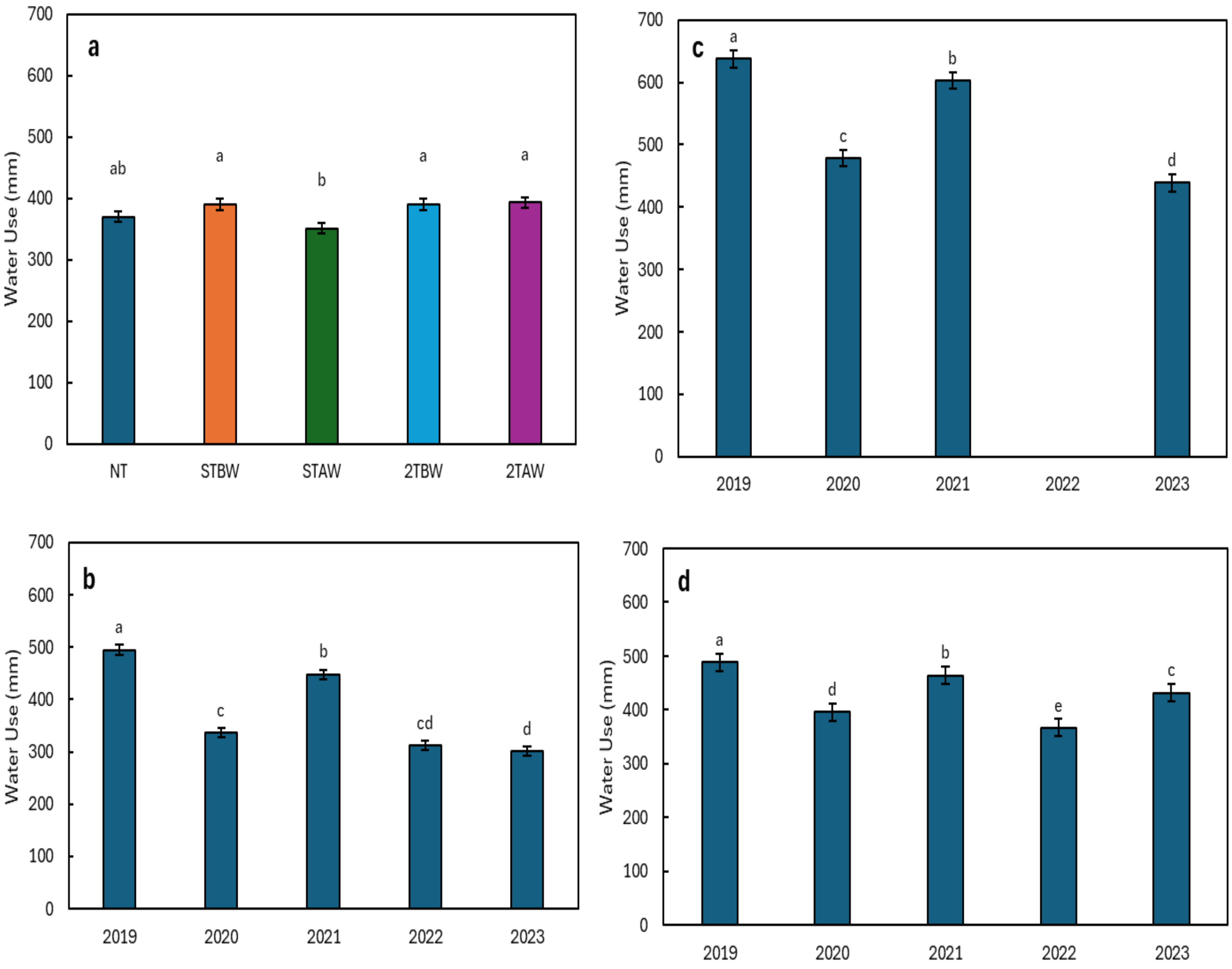

Figure 3.7. Influence of tillage treatments on winter wheat water use (a) **and influence of year on winter wheat water use** (b) **from soil water profile samples taken near Garden City, KS from 2019-2023. Influence of year on winter wheat water use** (c) **and grain sorghum** (d) **from soil water profile samples taken near Tribune, KS from 2019-2023. Bars within a subfigure with the same lower-case letter are not different (α=0.05). No 2022 winter wheat yield at Tribune due to a hailstorm.**

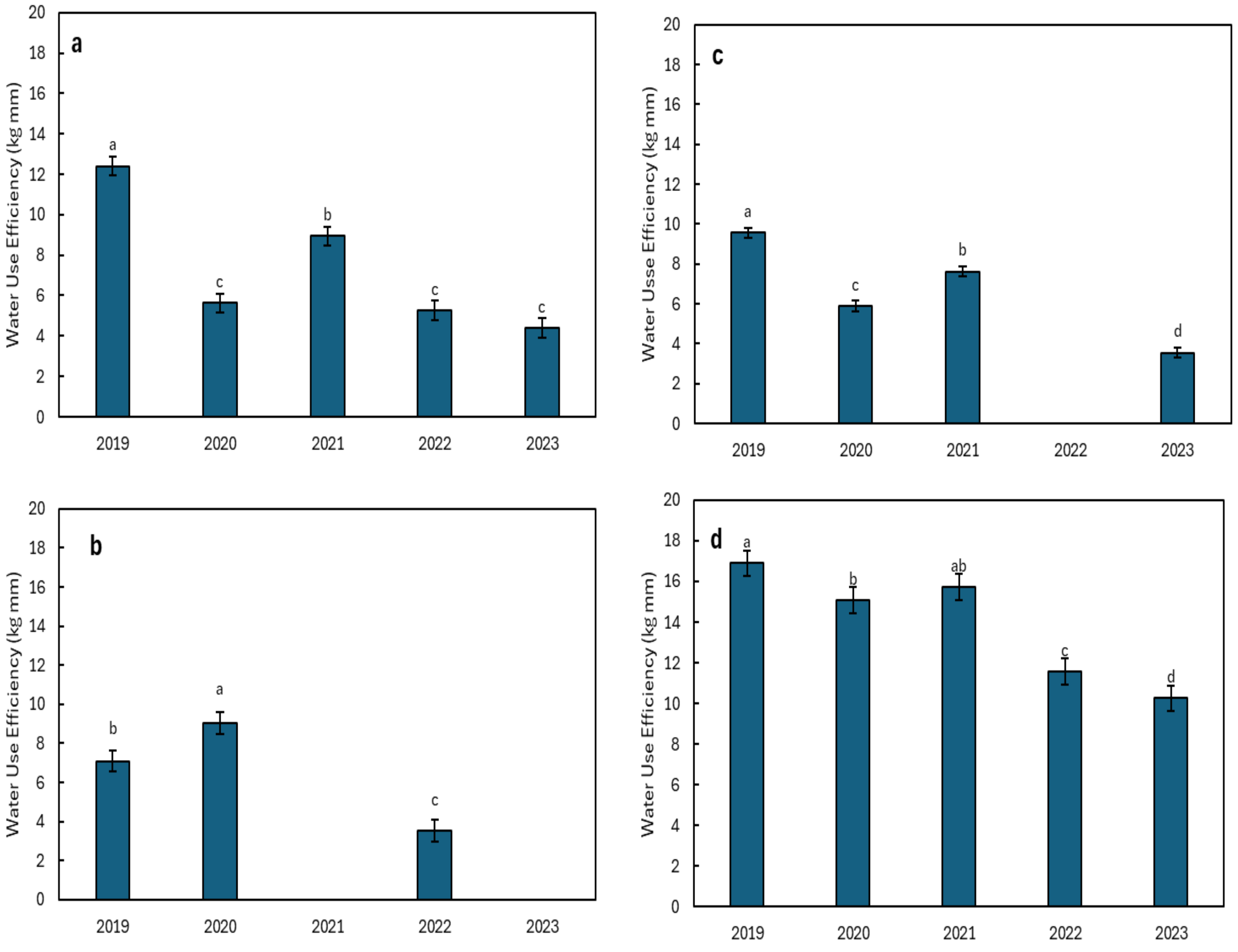

Figure 3.8. Influence of year on winter wheat water use efficiency (a) **and grain sorghum water use efficiency** (b) **from soil water profile samples taken near Garden City, KS from 2019-2023. Influence of year on winter wheat water use efficiency** (c) **and grain sorghum water use efficiency** (d) **from soil water profile samples taken near Tribune, KS from 2019 2023. Bars within a subfigure with the same lower-case letter are not different (α=0.05). No 2021 sorghum yield at Garden City due to herbicide injury and 2023 due to sorghum midge. No 2022 winter wheat yield at Tribune due to a hailstorm.**

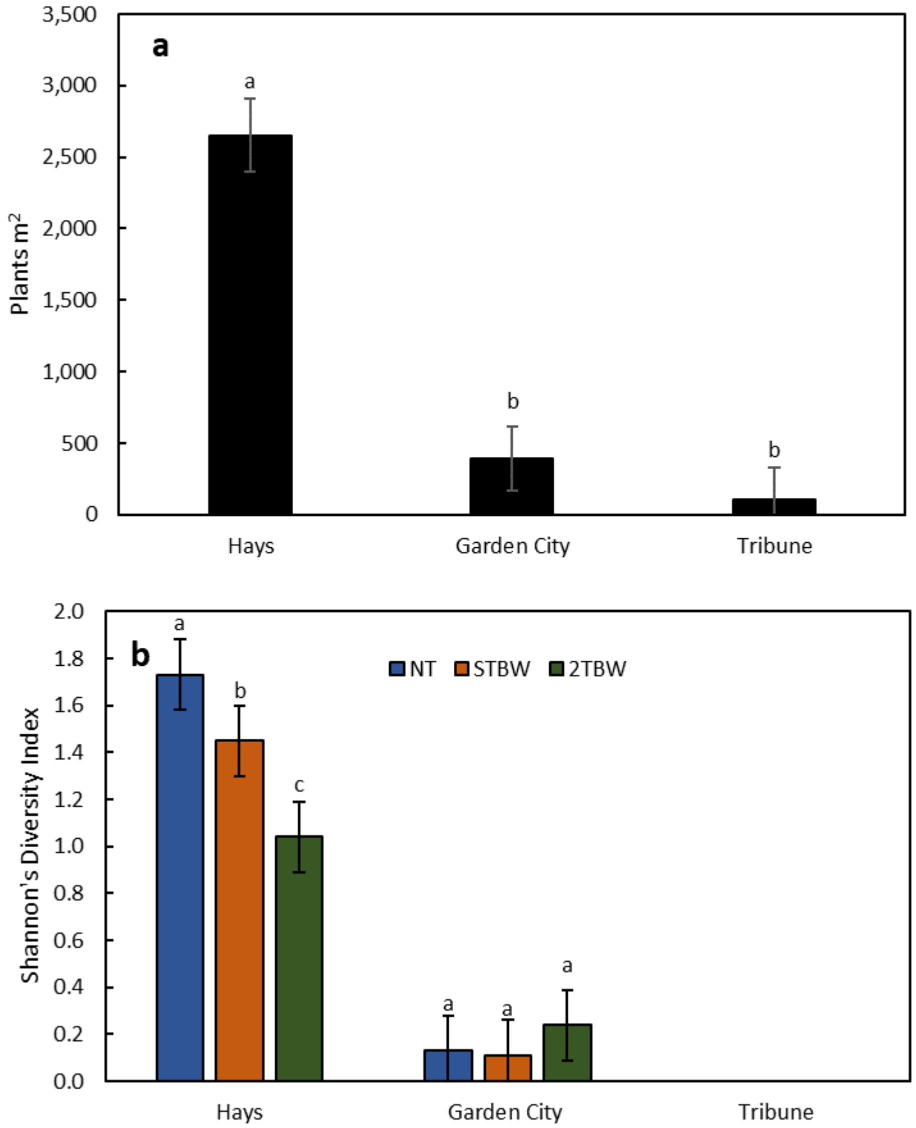

Figure 3.9. Influence of location on weed density from 2022 post-tillage samples near Hays, Garden City, and Tribune, KS (a). **Influence of tillage and location on Shannon's Diversity Index from 2022 post-tillage soil samples near Hays and Garden City, KS** (b). **Bars within a subfigure with the same lower-case letter are not different (α=0.05). No Shannon's Diversity Index for Tribune due to there being no diversity among emerged weeds.**

Tables

Table 3.1. Monthly precipitation from 2010 to 2023 near Hays, KS.

	Precipitation														
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	30-yr avg.†
Month	mm														
Jan.	3	2	0	7	0	17	9	29	1	13	25	12	5	23	6
Feb.	4	0	20	3	0	4	5	2	1	8	40	0	0	7	8
Mar.	43	6	29	5	0	1	11	33	8	18	11	113	31	6	21
Apr.	62	16	16	17	23	21	176	135	17	23	12	27	11	18	49
May	46	47	26	53	15	153	69	100	92	197	81	194	86	98	87
Jun.	104	50	17	55	200	16	80	40	94	40	61	20	36	81	64
Jul.	41	3	1	146	43	102	79	39	199	24	178	61	45	57	95
Aug.	83	92	69	12	41	10	118	82	142	318	62	84	35	95	78
Sept.	55	23	22	64	117	10	33	47	87	40	24	64	54	17	39
Oct.	5	30	22	22	44	43	16	51	78	38	2	29	4	19	34
Nov.	7	27	0	24	1	38	29	2	12	10	24	5	6	11	15
Dec.	0	29	16	0	16	29	10	0	43	59	8	0	17	45	12
Annual	453	325	238	408	500	444	635	559	775	789	527	609	329	477	509

†30-year averages are for the period of 1990-2020.

Table 3.2. Monthly precipitation from 2010 to 2023 near Garden City, KS.

	Precipitation														
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	30-yr avg.†
Month	mm														
Jan.	7	2	0	7	0	12	1	39	0	9	21	7	12	3	12
Feb.	9	0	21	4	0	8	7	0	0	19	20	2	0	15	15
Mar.	49	14	47	2	3	8	1	70	10	53	12	60	7	1	29
Apr.	48	44	40	7	13	9	120	111	21	2	3	13	10	57	42
May	91	24	6	24	14	160	27	27	57	149	18	151	55	111	71
Jun.	30	38	30	41	239	36	101	101	98	28	48	34	32	130	78
Jul.	61	10	48	77	76	123	147	147	217	49	132	18	54	97	80
Aug.	60	54	24	87	45	74	44	44	45	34	47	18	10	54	71
Sept.	6	7	27	38	62	1	4	4	47	4	40	75	15	47	34
Oct.	16	12	22	20	39	64	0	0	92	9	4	22	1	21	34
Nov.	1	13	0	18	1	22	2	2	6	6	14	4	3	5	12
Dec.	1	24	11	3	6	29	6	6	41	31	9	0	1	38	19
Annual	378	243	276	328	498	546	460	551	634	393	368	404	200	579	497

†30-year averages are for the period of 1990-2020.

Table 3.3. Monthly precipitation from 2010 to 2023 near Tribune, KS.

	Precipitation														
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	30-yr avg.†
Month	mm														
Jan.	0	4	1	0	1	4	0	25	1	5	9	13	11	19	9
Feb.	0	0	2	4	2	4	0	2	4	4	29	4	1	13	11
Mar.	0	0	13	7	1	4	2	34	6	43	42	87	14	4	23
Apr.	31	30	39	3	20	52	137	69	36	3	2	19	7	25	42
May	77	18	0	35	24	169	38	92	39	96	27	209	53	98	59
Jun.	39	104	0	37	84	26	48	58	87	62	47	26	33	152	69
Jul.	104	108	0	59	69	96	94	114	59	96	111	65	178	69	84
Aug.	62	71	16	136	73	54	98	42	72	56	59	25	43	23	78
Sept.	8	20	11	37	35	8	39	74	34	29	19	53	9	32	32
Oct.	30	55	17	19	47	65	1	8	85	14	3	28	3	11	35
Nov.	0	0	0	1	2	18	0	1	7	8	2	3	0	3	14
Dec.	0	14	4	0	13	1	9	0	20	17	8	0	0	32	12
Annual	351	424	103	338	371	501	466	519	450	433	358	532	352	481	468

†30-year averages are for the period of 1990-2020.

Table 3.4. Crop variety or hybrid and seeding rate per location and crop from 2019-2023.

		Crop Management		
Location	Year	Crop	Variety/Hybrid	Seeding Rate
Hays	2019-2023	Wheat	Joe	73 kg ha^{-1}
Hays	2019-2023	Sorghum	Pioneer 86P33	77 seeds ha^{-1}
Garden City	2019	Wheat	T158	78 kg ha^{-1}
Garden City	2020	Wheat	Tanaka	78 kg ha^{-1}
Garden City	2021	Wheat	Tam 114	78 kg ha^{-1}
Garden City	2022	Wheat	WB4792	78 kg ha^{-1}
Garden City	2023	Wheat	Tam 114	78 kg ha^{-1}
Garden City	2019	Sorghum	SP68M57	58,100 seeds ha^{-1}
Garden City	2020	Sorghum	DKS36-07	58,100 seeds ha^{-1}
Garden City	2021	Sorghum	DKS23-07	58,100 seeds ha^{-1}
Garden City	2022	Sorghum	DKS36-07	58,100 seeds ha^{-1}
Garden City	2023	Sorghum	Sorghum Partners SP31C06DT	58,100 seeds ha^{-1}
Tribune	2019 & 2020	Wheat	Oakley	67 kg ha^{-1}
Tribune	2021	Wheat	Dallas	73 kg ha^{-1}
Tribune	2022	Wheat	Dallas	78 kg ha^{-1}
Tribune	2023	Wheat	Dallas	101 kg ha^{-1}
Tribune	2019 & 2020	Sorghum	Pioner 87P06	111,197 seeds ha^{-1}
Tribune	2021	Sorghum	Pioneer 88P71	111,197 seeds ha^{-1}
Tribune	2022	Sorghum	Pioneer 88P71	123,500 seeds ha^{-1}
Tribune	2023	Sorghum	Sorghum Partners 31A15	123,500 seeds ha^{-1}

Table 3.5. Fertility management by location and crop from 2019-2023.

		Crop Management		
Location	Year	Crop	Fertilizer Rate	Application Time
Hays	2019-2023	Wheat	90 kg N ha $^{-1}$	Mid-fall
Hays	2019-2023	Sorghum	90 kg N ha^{-1} 28% UAN	Early summer
Hays	2019-2023	Wheat & Sorghum	23 kg P205 ha^{-1}	At planting
Garden City	2019-2022	Whole plot	45 kg N ha^{-1}	Early spring
Garden City	2023	Whole plot	50 kg N ha^{-1} 32% UAN	Early spring
Garden City	2020-2023	Wheat	56 kg ha^{-1} 11-52-0	At planting
Tribune	2019-2023	Wheat	45 kg ha^{-1} 12-40-0-7.5-1	Before planting
Tribune	2019-2023	Wheat	112 kg ha^{-1} 28% UAN	March
Tribune	2019-2022	Sorghum	112 kg ha^{-1} 28% UAN	May
Tribune	2023	Sorghum	112 kg ha^{-1} 28% UAN	Before planting

Table 3.6. Analysis of variance results for soil organic carbon (SOC), pH, bulk density (BD), gravimetric water content (GWC), Mehlich-3 phosphorus (M3-P) and nitrate (NO_{3^-}-N) of 2022 pre-tillage soil samples from experiments near Hays and Garden City, KS.

	Parameter					
Fixed Affects	SOC	pH	M3-P	NO_{3^-}-N	BD	GWC
Tillage	0.93	0.12	0.49	0.70	0.28	0.76
Depth	**<0.0001**	**0.0003**	0.09	0.69	**<0.0001**	**<0.0001**
Tillage × Depth	0.76	0.15	0.37	0.71	0.19	0.42
Location	**<0.0001**	**<0.0001**	**0.0001**	0.18	**0.03**	**<0.0001**
Tillage × Location	0.69	0.70	0.58	0.99	0.90	0.76
Depth × Location	**0.03**	0.51	**0.02**	0.30	0.29	**0.0003**
Tillage × Depth × Location	0.14	0.15	0.26	0.73	0.26	0.11

Table 3.7. Analysis of variance results for soil organic carbon (SOC), pH, Mehlich-3 phosphorus (M3-P), nitrate (NO_{3^-}-N), bulk density (BD), and gravimetric water content (GWC) for 2022 and 2023 post-tillage soil samples from experiments near Hays, Garden City, and Tribune, KS.

	Parameter					
Fixed Affects	SOC	pH	M3-P	NO_{3^-}-N	BD	GWC
Tillage	0.19	0.09	0.29	**0.0007**	0.77	0.49
Depth	**<0.0001**	**<0.0001**	**<0.0001**	0.96	**<0.0001**	**<0.0001**
Tillage × Depth	0.71	0.35	0.88	0.16	0.74	0.11
Location	**0.0001**	**0.0005**	**<0.0001**	0.10	0.69	**<0.0001**
Tillage × Location	0.69	0.23	0.75	0.80	0.82	**<0.0001**
Depth × Location	**0.0002**	**0.0091**	**<0.0001**	0.47	0.10	**<0.0001**
Tillage × Depth × Location	0.99	0.27	0.75	0.16	0.86	0.62

Table 3.8. **Effects of tillage on soil nitrate (NO3- -N), penetration resistance (PR), dry aggregate size distributions (DASD), and wind erodible fraction (WEF). Means with the same letter within a column are not significantly different (α =0.05) among treatments.**

	Soil Properties and Dry Aggregate Size Distributions							
	NO_3-N	PR	<0.42mm	0.42-0.84mm	0.84-2mm	2-6.3mm	6.3-19mm	WEF
	mg kg^{-1}	MPa^{-1}	%					
NT	15.16 b	1.26 a	16.12 a	14.94 a	15.17 a	20.98 a	35.42 b	27.65 a
STBW	16.56 b	1.13 b	17.68 a	12.24 ab	11.95 b	20.05 a	37.42 b	27.51 a
2TBW	22.60 a	1.11 b	16.85 a	10.44 b	10.42 c	18.00 b	43.27 a	25.45 a

Table 3.9. Analysis of variance results for wet aggregate size distribution (WASD), mean weight diameter (MWD), penetration resistance (PR), dry aggregate size distribution (DASD), and wind erodible fraction (WEF) for 2022 pre-tillage soil samples from experiments near Hays and Garden City, KS.

		Parameter									
		Wet aggregate size distribution				Dry aggregate size distribution					
Fixed Affects	PR	<0.25 mm	0.25-2 mm	2-8 mm	MWD	<0.42 mm	0.42-0.84 mm	0.84-2 mm	2-6.3 mm	6.3-19 mm	WEF
Tillage	0.90	0.32	0.61	0.31	0.13	0.64	0.68	0.47	0.19	0.61	0.55
Location	**0.006**	0.22	0.17	**0.03**	**0.05**	0.09	**0.0003**	**0.005**	**0.01**	**0.003**	**0.001**
Tillage × Location	0.74	0.75	0.81	0.99	0.93	0.45	0.82	0.51	**0.007**	0.37	0.47

Table 3.10. Analysis of variance results for wet aggregate size distribution (WASD), mean weight diameter (MWD), penetration resistance (PR), dry aggregate size distribution (DASD), and wind erodible fraction (WEF) for 2022 and 2023 post-tillage soil samples from experiments near Hays, Garden City, and Tribune, KS.

	Parameter										
		Wet Aggregate Size Distributions				Dry Aggregate Size Distributions					
Fixed Affects	PR	<0.25 mm	0.25-2 mm	2-8 mm	MWD	<0.42 mm	0.42-0.84 mm	0.84-2 mm	2-6.3 mm	6.3-19 mm	WEF
Tillage	**0.03**	**0.03**	**0.04**	0.48	0.10	0.42	**0.01**	**<0.0001**	**0.0008**	**0.003**	0.45
Location	0.35	**0.01**	**0.0081**	0.95	0.39	0.22	0.26	0.83	**0.05**	0.22	0.57
Tillage× Location	0.41	**0.0083**	**0.0029**	0.92	0.59	0.89	0.70	0.33	0.14	0.83	0.97

Table 3.11. Tillage treatment and location effects on wet aggregate size distributions (WASD) and mean weight diameter (MWD) of water stable aggregates for 2022 and 2023 post-tillage soil samples from experiments near Hays, Garden City, and Tribune, KS. Means with the same letter within a location within a parameter are not significantly different (α =0.05) among treatments.

	Soil Physical Properties and Wet Aggregate Size Distributions											
	<0.25mm			0.25-2mm			2-8mm			MWD		
	NT	STBW	2TBW	NT	STBW	2TBW	NT	STBW	2TBW	NT	STBW	2TBW
	%									mm		
Hays	48.86 b	61.65 ab	69.23 a	47.01 a	34.09 b	26.79 c	4.13 a	4.26 a	3.98 a	0.61 a	0.54 a	0.48 a
Garden City	71.79 a	73.17 a	66.63 b	23.85 b	23.68 b	29.57 a	4.37 a	3.15 a	3.79 a	0.49 a	0.42 a	0.49 a
Tribune	73.55 b	77.00 a	77.42 a	21.80 a	19.06 a	19.16 a	4.65 a	3.53 a	3.84 a	0.50 a	0.42 a	0.44 a

Table 3.12. Analysis of variance results for winter wheat yields from 2019 and 2020, and 2021-2023 near Hays and 2019-2023 near Garden City and Tribune, KS.

	Location			
Fixed Affects	Hays (2019 & 2020)	Hays (2021-2023)	Garden City (2019-2023)	Tribune (2019-2023)
Tillage	0.46	0.57	0.80	0.25
Year	**0.0059**	**<0.0001**	**<0.0001**	**<0.0001**
Tillage × Year	0.40	0.49	**0.01**	0.07

Table 3.13. Analysis of variance results for grain sorghum yields from 2019-2023 near Hays, Garden City, and Tribune, KS.

	Location			
Fixed Affects	Hays (2019 & 2020)	Hays (2021-2023)	Garden City (2019-2023)	Tribune (2019-2023)
Tillage	**0.05**	0.76	0.99	0.86
Year	0.99	**<0.0001**	**<0.0001**	**<0.0001**
Tillage × Year	0.98	0.12	0.99	0.64

Table 3.14. Analysis of variance results for water use and water use efficiency from winter wheat and grain sorghum yields from 2019-2023 near Garden City and Tribune, KS.

	Location			
Crop	Garden City		Tribune	
Fixed Affects	WU	WUE	WU	WUE
Wheat				
Tillage	**0.0067**	0.38	0.99	0.34
Year	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
Tillage × Year	0.20	0.32	0.75	0.23
Grain Sorghum				
Tillage	0.38	0.73	0.29	0.5
Year	0.59	**<0.0001**	**<0.0001**	**<0.0001**
Tillage × Year	0.51	0.48	0.82	0.80

Table 3.15. Analysis of variance results for weed density and weed diversity for 2022 pre-tillage, 2022 and 2023 post-tillage, and 2023 pre-herbicide samples near Hays, Garden City, and Tribune, KS.

Parameter	Sampling Time		
Fixed Affects	Pre-tillage	Post-tillage	Pre-herbicide
Shannon's Diversity Index			
Location	**0.0037**	**<0.0001**	**0.0002**
Tillage	0.85	**0.0041**	0.62
Tillage × Location	0.98	**0.0003**	0.12
Weed Density			
Location	0.21	**<0.0001**	0.07
Tillage	0.43	0.17	0.78
Tillage × Location	0.14	0.24	0.93