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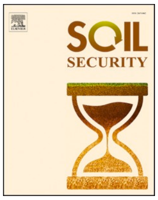

# Enhancing long-term no-till wheat systems with cover crops and flash grazing

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ABSTRACT

Monoculture practices under conventional tillage (CT) are detrimental to sustainable soil ecosystem functions and services under intensive agriculture practices, ultimately diminishing net benefits. Conservation practices, such as no-till (NT) and cover crops (CC) can nurture sustainable soil ecosystem functions and services. The impact of introducing CC, grazing, intercropping, and reverting to tillage in a long-term NT continuous wheat system on soil properties was evaluated in three years of implementation. Treatments were CT and combinations of NT, CC, grazing, and intercropping wheat with radishes and turnips. Tillage significantly decreased large macroaggregates (33–39%), mean weight diameter (21–26%), and POX-C (21–29%) within large macroaggregates and increased small macroaggregates (40–65%) compared to all CC treatments (including grazed and intercropped) within a 3-year period. Reverting to tillage after 12 years of NT significantly increased bulk density by 19%, reduced total porosity by 21% and soil water content by 28% compared to all CC treatments. In addition, Cover crops (including grazed and intercropped) enhanced NT as evident in significant improvements in POX-C (19–32%), large macroaggregates (37–51%), mean weight diameter (22–31%), bulk density (8–13%), total porosity (10–18%), and measured soil water content (11–14%). Flash grazing CC did not result in any adverse effects compared to all other treatments for measured parameters. Ultimately, reverting to tillage in a long-term NT system significantly degraded soil physicochemical properties. In contrast, implementing CC to long-term continuous wheat systems resulted in rapid soil improvements within the 3-year study period which were reflected in enhanced stored soil moisture storage of up to 39% higher under CC compared to CT. Flash grazing CC can be successfully implemented in NT systems without adversely affecting soil physicochemical properties. Intercrops did not show pronounced effects possibly due to winterkill.

## 1. Introduction

Anthropogenic effects manifested by intensive agricultural monoculture production systems negate sustainable soil ecosystem service provisions and productivity. In drier regions, intensive agricultural practices are characterized by wheat production solely for feeding cows as wheat provides an excellent forage (Grev et al., 2017; Newlin, 2019). Dual-purpose wheat systems are therefore a common practice, that is producing wheat for both grazing and grain (Carver et al., 2001). However, trampling from cattle traditional grazing can increase soil compaction, decrease infiltration, and increase the potential for soil erosion (Van Haveren, 1983; Daniel and Phillips, 2000; Daniel et al., 2002; Wheeler et al., 2002; Obour et al., 2020). Soil compaction reduces yields by negatively impacting root growth, water cycling, nutrient uptake, and gas exchange (Lipiec et al., 2003; Schafer-Landefeld et al., 2004; Stoessel et al., 2018).

Conventional tillage is a convenient and traditional practice under monoculture production to control weeds and diseases (Gunsolus, 1990; Murphy et al., 1996; Heer, 2006; Brandsaeter et al., 2017) and generally keep up with the intensity associated with monoculture systems. Dust storms are still a common sight, especially during land preparation periods, as most farmers turn to tillage. Conventional tillage hastens soil organic matter decomposition through alteration and disruption of soil aggregates (Six et al., 2000; Moebius-Clune et al., 2011; Gupta and Germida, 2015; Tian et al., 2015). Tillage reduces soil organic carbon (SOC) physical protection and stimulates microbial activity and soil C loss (Sa et al., 2001; Navarro-Garcia et al., 2012). In contrast, NT reduces

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**Abbreviations**

| | |
|---|---|
| $D_b$ | bulk density |
| CC | cover crop |
| CT | conventional tillage |
| LM | large macroaggregates |
| MWD | mean weight diameter |
| NT | no-tillage |
| NTC | no-tillage with cover crop |
| NTCG | no-till with grazed cover crop |
| NTCGI | no-tillage with intercrop and grazed cover crop |
| NTCI | no-tillage with cover crops and intercrops |
| NTI | no-tillage with intercrops |
| POX-C | permanganate oxidizable carbon |
| SOC | soil organic carbon |
| TP | total porosity |
| USA | United States of America |

soil disturbance, thereby improving microaggregation, SOC and nitrogen storage, and soil physical, chemical and biological properties relative to tilled systems (Paustian et al., 2000; Six et al., 2000; Helgason et al., 2010; Garcia-Franco et al., 2015).

Parameters, such as soil aggregate stability, bulk density, porosity, compaction, and water infiltration, have a direct impact on soil productivity and susceptibility to wind (aeolian) and water erosion (Blanco-Canqui et al., 2015). The importance of cover crops and associated benefits for wind and water erosion control are well documented (Kasper et al., 2001; Colazo and Buschiazzo, 2010; Blanco-Canqui et al., 2013, 2015). Cover crops also improve soil water aggregate stability, bulk density, and penetration resistance (Villamil et al., 2006; Blanco-Canqui et al., 2011; Calonego et al., 2017; Çerçioğlu et al., 2019). Despite the potential economic risks associated with cover crops production, adding grazing may mitigate the cost of cover crop production (Franzluebbers and Stuedemann, 2008; Blanco-Canqui et al., 2015; Schomberg et al., 2014). Cover crops harmonized with grazing offers an opportunity for mitigating inhibitory cover crops cost of production (Plastina et al., 2018). Sij et al. (2011) noted that although NT has been reasonably successful on large farms in grain systems in north Texas, NT has not been adopted in dual-purpose wheat due to perceived problems with compaction, forage production, seedling establishment, weed control, and grain yield. Flash or mob grazing involves grazing a small piece of land by a large concentration of animals for a short period of time ranging from a few hours to a full day (Smart et al., 2008; Rocky, 2011). This approach maximizes gains per unit area whilst allowing longer rest periods to mitigate potential harmful effects to soil quality (Rocky, 2011).

Intercropping is the growing of two or more crops in the same field at the same time to enhance crops interaction (Vandermeer, 1990; Willey, 1990). Intercropping improves sustainable production especially under continuous cropping systems (Willey, 1990; Gebru, 2015; Raseduzzaman and Jensen, 2017) by increasing biodiversity of agroecosystems (Altieri, 1991; Afrin et al., 2017; Taschen et al., 2017). Turnips have deep tap roots that rip into subsoil, facilitating water, air, and earthworms' movement (Kennedy, 2012). Higher resource use efficiency is realized in intercropping component crops that have a huge difference in growth duration and a critical need for nutrients that occurs at different times (Willey, 1990; Fukai and Trenbath, 1993).

Soil physical properties are the key drivers in defining soil quality. Soil quality is the ability of a soil to perform and sustainably fulfill its ecosystem services and functions (Tilman et al., 2006; Cleland, 2011). This study sought to evaluate the impact of cover crops, flash grazing, intercropping and tillage on soil physicochemical properties that define soil quality for sustainable soil ecosystem management practices in the semi-arid US Great Plains. The objective of this study was to quantify and distinguish selected soil properties under continuous wheat production as affected by cover crops, grazing, intercropping, NT, and tillage. We hypothesized that the use of cover crops and grazing thereof, intercropping, and NT in monocultures would improve soil physical and chemical properties.

## 2. Materials and methods

The rainfed research study plots were established at the Texas A&M AgriLife Research Smith Walker Research Unit (34° 03′28.7 "N 99° 14′35.8 "W) near Vernon, Texas. NT continuous wheat production has been at this site since 2001 with occasional grazing as conditions allowed. The soil type is Rotan clay loam (Fine, mixed, superactive, thermic Pachic Paleustolls). In this semi-arid region, average annual precipitation is 711 mm, with mean annual Fig. 1 temperature of 17.1 °C (US climate data, 2017).

Research plots each measuring 2000 $m^2$ area were set up in a randomized complete block experimental design with seven treatments replicated four times in a continuous wheat (*Triticum aestivum*) cropping system. Summer cover crops were grown during the fallow period, while intercropped species [turnips (*Brassica rapa* subsp. Rapa) and [radishes (*Raphanus sativus*) subsp. Daikon] were seeded with wheat in the winter. Seven treatments were assessed in this research: 1) CT wheat without a cover crop (CT); 2) NT wheat without a cover crop (NT); 3) NT wheat intercropped with turnip/radish without a summer cover crop (NTI); 4) NT wheat with a grazed summer cover crop (NTCG); 5) NT wheat with a terminated summer cover crop (NTC); 6) NT wheat intercropped with turnip/radish with a grazed summer cover crop (NTCGI); 7) NT wheat intercropped with turnip/radish with a terminated summer cover crop (NTCI).

In 2013, the conventional till plots (CT treatment) were converted from NT to CT for the first time in twelve years, since the entire study field has been under NT wheat production beginning in 2001. This was accomplished by using a plow disk and chisel sweep to a depth of 15 cm every summer. The warm season multi-species cover crop mix was used as per recommendations from the USDA-ARS Soil Health Assessment Program in Temple, TX (NRCS, 2011). The Mix with individual rates in parenthesis [@ kg $ha^{-1}$] was generally composed of; Iron & Clay Cowpea (*Vigna unguiculata*) [@ 5.6], Guar (*Cyamopsis tetragonoloba*) [@ 6.7], Mungbeans (*Vigna radiate*) [@ 6.7], Pearl Millet (*Pennisetum glaucum*) [@ 2.2], Giant Foxtail Millet (*Setaria italic*) [@ 1.1], Forage Sorghum [*Sorghum bicolor* (L.) Moench.] [@ 3.4], and Buckwheat (*Fagopyrum esculentum*) [@ 2.2]. Full details of the cover crop mixture and management are provided in Mubvumba et al., 2021. In short, a warm-season cover crop mixture was planted using a NT drill at a row spacing of 19 cm every summer at seeding rates of 33.6 kg $ha^{-1}$ in 2013 and 28 kg $ha^{-1}$ for 2014 and 2015. Cover crops were chemically terminated after grazing in August/September each year with glyphosate and additional application of paraquat in 2015. Intercropping was achieved by mixing radishes, turnips and wheat seed before seeding. Winter wheat mixed with turnips and radishes was seeded at the following rates each year: winter wheat at 65 kg $ha^{-1}$, turnips at 0.56 kg $ha^{-1}$, and radishes at 1.68 kg $ha^{-1}$. All were planted using a NT drill at a row spacing of 19 cm in 2013 and 25 cm in 2014 and 2015.

### 2.1. Grazing and biomass production

Detailed grazing management strategies are provided in Mubvumba et al. (2021). In short, two adjacent plots were combined and grazed simultaneously. Each 4000 $m^2$ plot was rotationally grazed by cattle from one paddock to another. Each grazing paddock was grazed for a 6-to-24-hour period at stocking densities ranging from 23,813 kg $ha^{-1}$ to 28,350 kg $ha^{-1}$. Stocking density was calculated as total live weight of cows per unit area that was grazed (Rocky, 2011). Biomass produced was estimated by randomly placing two 1-$m^2$ grids in the CC plots prior

**Fig. 1.** Google Map of experimental design of study site at Smith Walker Research Unit near Vernon, TX. Numbers indicate treatment. Highlighted plot edges of same color represent plots grouped together as a single grazing paddock. 1, CT; 2, NT; 3, NTCG; 4, NTC; 5, NTCG; 6, NTCI and 7, NTI. CT, conventional till; NT, no-till; C, cover crop; G, graze and I, intercrop.

to termination. Biomass removed through grazing and trampling was projected by differences between pre- and post-grazing herbage dry weights. The biomass was dried at 65 °C for 48 h.

### 2.2. Soil physical and chemical properties

The following soil physical and chemical properties were assessed: bulk density, total porosity, soil aggregate stability, mean weight diameter (MWD), and permanganate oxidizable carbon (POX-C). Soil total N and organic C were analyzed using a Macro Elementar analyzer (Vario Max CN, Elementar Analysensysteme GmbH, Langenselbold, Germany) as described by McGeehan and Naylor (1988) after drying and grinding. Soil properties were measured following three years of cover cropping and wheat growing cycles in spring 2016. Bulk density was measured as described by Miller and Donahue (1990). Soil cores measuring 5-cm diameter were taken in each plot to a depth of 60 cm in depth increments of 0–15, 15–30, and 30–60 cm using a hydraulic soil probe. Total porosity was computed using particle density and bulk density as described by Hao et al. (2008).

Soil aggregate stability characterization samples were taken in two depth increments of 0–5 and 5–15 cm. A hydraulic Giddings machine (Giddings Machine Company, Windsor, Colorado) and 5-cm diameter soil probe was used. Dry-aggregate stability was determined as documented by Nimmo and Perkins (2002), and MWD used as the soil aggregation index. Soil sample portions from 0 to 5 and 5–15 depths weighing 100 g each were crushed gently using a wooden roller, and rotary sieved into four aggregate classes (Chepil and Bisal, 1943; Kemper and Chepil, 1965). After dry sieving, four aggregate classes were categorized as large macroaggregates (4 - 2 mm), small macroaggregates (2 – 0.250 mm), micro aggregates (0.250 – 0.053 mm) and silt + clay (<0.053 mm). Mean weight diameter was computed as a weighted average of the soil size fraction percentages (Haynes and Swift, 1990).

$$MWD = \sum_{i=1}^{n} XiWi$$

Where MWD is mean weight diameter (mm) of aggregates, Xi is mean diameter of the classes (mm), and Wi is the proportion of each aggregate class relative to the whole sample weight. The higher the proportion of large aggregates retained in the sieve, the higher the soil MWD.

Permanganate oxidizable carbon was determined in the four aggregate classes. Subsamples of each aggregate category were finely ground, and a 2.5 g sample was allowed to react for 10 min with potassium permanganate (0.02 M $KMnO_4$) solution made from 2 mL of 0.2 M $KMnO_4$ and 18 ml of deionized water (Weil et al., 2003). An aliquot was then diluted with deionized water for reading on a spectrophotometer for POX-C calculation.

### 2.3. Soil moisture

Soil water content was measured to 150 cm depth using a neutron moisture meter (Model 503DR, CPN International Inc, Martinez, CA, Serial No. H350607921) as described by Mubvumba et al., 2021. Briefly 5-cm diameter and 180 cm long aluminum access tubes were installed into the ground using a Giddings hydraulic coring machine (Giddings Machine Company, Windsor, CO). Readings for stored soil water were taken at 20 cm depth increments from 0 to 140 cm. Calibration equations determined on site were used to convert readings to volumetric water contents.

### 2.4. Statistical analysis

The collected data were analyzed using Proc GLIMMIX using SAS Version 9.4 (SAS Institute Inc., Cary, NC). The GLIMMIX procedure combines characteristics of generalized linear models and mixed models (SAS Institute, 2017). Treatment was considered a fixed effect and block (nested within year), random when analyzed by year. Mean separations were determined using Fisher's protected least significant difference (LSD) at $p<0.05$ when the ANOVA was significant at $P<0.05$. Simple linear Pearson's correlation regression analysis of measured soil parameters was done using PROC REG procedure SAS 9.4 at 95% confidence interval and prediction limits.

## 3. Results and discussion

### 3.1. Grazing and biomass removal

Cover crop production was on average 2141 kg $ha^{-1}$ (2013), 3503 kg $ha^{-1}$ (2014) and 2861 kg $ha^{-1}$ (2015). Flash grazing the cover crops left 37–42% biomass (2014) and 45–53% biomass (2015) in the plots. The USDA-NRCS recommends leaving 50% of cover crop biomass post-grazing (Local soil Health workshops). The Pre-Graze (Pre-G) and Post-Graze (Post-G) biomass in (kg $ha^{-1}$) were; No-till (NT) cover crop (C) Grazed (G) Intercropped (I) treatment, NTCGI: Pre-G (3590) and Post-G (1190) for year 2014 and Pre-G (2961) and Post-G (1557) for year 2015. The treatment NTCG was Pre-G (3133 and 3120) and Post-G (1305 and 1391) for years 2014 and 2015 respectively (Mubvumba et al., 2021).

### 3.2. Bulk density and porosity

The average $D_b$ for all treatments for the 0–15 cm, 15–30 cm, and 30–60 cm depths were 1.44, 1.64, and 1.83 Mg $m^{-3}$, respectively. Treatment significantly affected $D_b$ in the top 15 cm of soil, with values ranging from 1.31 to 1.65 Mg $m^{-3}$ ($p<0.05$; Table 1). No treatment differences in $D_b$ were noted for the 15–30 cm and 30–60 cm depths. Conventional till wheat without a cover crop (CT) increased $D_b$ by 9%, while grazed NT wheat intercropped with radishes and turnips with a terminated summer cover crop (NTCGI) reduced $D_b$ 13% in the 0–15 cm depth compared to the long-term NT ($p<0.05$; Table 1). Radishes and turnips have been reported to alleviate soil compaction (Seidel et al., 2012; Gruver et al., 2016). Radishes and turnips did not perform well during the first two years and only fairly during the third year; hence, we are hesitant to attribute reduced $D_b$ to intercropping alone as no significant difference between NT and NTI were observed. Radishes emergence was observed each year, but extreme winterkill occurred.

Cover crops treatments grazed and ungrazed, (NTCG, NTC, NTCGI and NTCI) resulted in a 13% lower $D_b$ compared to no cover crop treatments in the top 15 cm (CT, NT and NTI) ($p<0.05$; Table 1). Cover crops have been reported to enhance benefits associated with NT practice (Blanco-Canqui et al., 2015). Conventional till resulted in greater $D_b$ than all treatments, including NT without a cover crop and/or intercrop ranging from 8% to 21% ($p<0.05$; Table 1). The study site had been under NT since 2001 and reverting to tillage for three successive years after 12 years of NT increased soil compaction. Rotational grazing did not increase $D_b$ in the short term which concurred with other findings (Obour et al., 2021; Franzluebbers and Stuedemann, 2008; Arevalo et al., 1998). This was contrary to assertions that grazing hinders NT adoption in North Texas due to soil compaction concerns under dual forage/grain systems (Sij et al., 2011; Obour et al., 2020; Tobin et al., 2020). Both Obour et al., 2020 and Tobin et al., 2020 attributed the noted increased bulk densities to grazing under wet field conditions and high grazing intensities (Willatt and Pullar, 1984; Poffenbarger, H., 2010). Working in wet fields increases the chances of soil compaction (Al-Kaisi, 2001; Poffenbarger, 2010). However, other studies have shown an increase in bulk density albeit due to continuous grazing (Daniel et al., 2002; Qin et al., 2015). In the Texas Rolling Plains, DeLaune et al. (2013) reported rotational grazing in dual-purpose, NT wheat systems had no significant effect on bulk density. The cover crop NT combination improved the soil bearing capacity through reduced

**Table 1**
Treatment effects on soil bulk density and Total Porosity by depth.

| Bulk Density ($D_b$) and Total Porosity (TP) | | | | | | |
|---|---|---|---|---|---|---|
| Treatment | 0–15 cm depth | | 15–30 cm depth | | 30–60 cm depth | |
| | $D_b$ (Mg $m^{-3}$) | TP (%) | $D_b$ (Mg $m^{-3}$) | TP (%) | $D_b$ (Mg $m^{-3}$) | TP (%) |
| CT[§] | 1.65a[†] | 37.7d[†] | 1.68a | 36.3a | 1.89a | 29.8a |
| NT | 1.51b | 43.0c | 1.69a | 36.6a | 1.86a | 30.2a |
| NTI | 1.48b | 44.0c | 1.64a | 39.7a | 1.85a | 32.4a |
| NTCG | 1.39c | 47.5b | 1.64a | 38.0a | 1.83a | 30.6a |
| NTC | 1.39c | 47.7b | 1.64a | 38.2a | 1.79a | 31.0a |
| NTCGI | 1.31d | 50.6a | 1.60a | 38.3a | 1.79a | 31.5a |
| NTCI | 1.32dc | 50.0ab | 1.62a | 38.9a | 1.81a | 32.3a |

[†] Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

[§] CT, conventional-till; NT, no-till; C, cover crop; G, graze; I, intercropping.

bulk density, mitigating potential animal trampling soil compacting effects. Flash grazing that was used in this study ensured more control over when to graze, avoiding less than ideal situations and soil conditions as needed. In our study, tillage had a more deleterious effect compared to rest of the treatments in the short term.

Characterizing the impact of conservation practices on wheat monoculture systems, we found that NT significantly reduced soil compaction, increasing total porosity relative to CT ($p<0.05$; Table 1), and the addition of cover crops (including grazed and intercropped) further enhanced the benefits through soil macro-aggregation in the 0–15 cm depth ($p<0.05$;). Total porosity was on average greatest for cover crop treatments (including grazed and intercropped) compared to NT without cover crops and CT for the surface depth by 18%. Total porosity was significantly lower for CT compared to all other treatments ranging 12–25%. Grazing had no detectable adverse effects on total porosity. No significant differences in total porosity were observed in the lower depths among treatments. The total porosity increases that were observed were reflected in enhanced stored soil moisture detected three years following NT, CC, and grazing treatment effects (Table 4; Fig. 2) (Mubvumba et al., 2021).

### 3.3. Dry aggregate stability

Aggregate-size distribution was significantly different in the top 5 cm as affected by treatment ($p<0.05$; Table 2). Large macroaggregates (4 – 2 mm) in CT and NT were significantly lower compared to cover crop treatments (including grazed and intercropped) ($p<0.05$; Table 2). Grazing did not lower LM contrary to other findings (Wen et al., 2016). Cover crop treatments increased topsoil LM aggregation by 48–64% compared to CT and 36–51% compared to NT no cover crop treatments; conversely the no cover crop treatments CT and NT raised small macroaggregates by 40–65% and 25–47% respectively. Large macroaggregates are essential in that they have a strong bearing on soil aggregate stability (Tisdall and Oades, 1980; Elliott, 1986), with a greater proportion of C in large macroaggregates traced back to recent vegetation compared to microaggregates (Skjemstad et al.,1990; Puget et al., 1995; Angers and Carter, 1996), suggesting a role for cover crops in aggregate formation in this study. Small macroaggregates (2 mm–0.250 mm) were highest under CT and lowest under NTCGI ($p<0.05$). CT was about 33% higher in small macroaggregates compared to the NTCGI treatment. The NTCG, NTC, and NTCI also had fewer small macroaggregates compared to CT ($p<0.05$; Table 2). Large macroaggregates (4 – 2 mm) strongly negatively correlated with bulk density ($r^2 = 0.93$; $p<0.05$, Table 5). Increased macroaggregate sizes decreased bulk density, increasing total porosity ($p<0.05$; Tables 1 and 2), consistent with other studies (Blanco-Canqui et al., 2011; Calonego et al., 2017).

No significant treatment effects were found for micro aggregates (0.250 mm–0.053 mm) or silt plus clay (Table 2). In the 0–5 cm depth, CT and NT exhibited the least mean MWD of 1.67 and 1.73 mm respectively, and NTCGI had the highest MWD of 2.26 mm ($p<0.05$). Flash grazing cover crops did not lower MWD like other findings under NT (Obour et al., 2021; Franzluebbers and Stuedemann, 2008). Other research has shown significant reduction in MWD in the top 20 cm depth under long-term free grassland grazing (Wen et al., 2016). Treatments

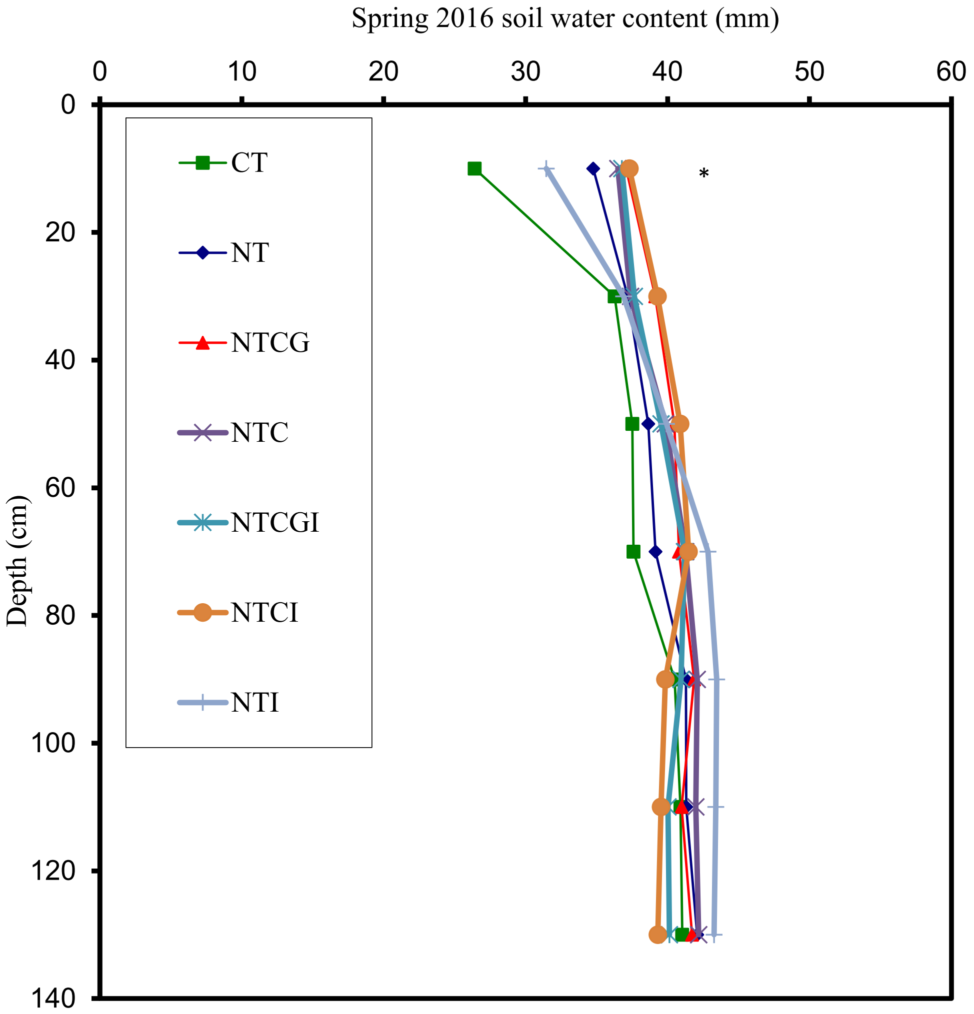

**Fig. 2.** 2016 Spring soil water content. CT, conventional-till; NT, no-till; C, cover crop; G, graze; I, intercropping. * Significant at $p<0.05$.

**Table 2**

Aggregate size distribution and mean weight diameter.

| Treatments | Aggregate sizes & mean weight diameter (MWD) for 0–5 and 5–15 cm depth | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Large-macro | | Small-macro | | Micro-aggregate | | Silt + clay | | MWD | |
| | 4 - 2 mm | | 2 - 0.25 mm | | 0.25–0.053 mm | | <0.053 mm | | mm | |
| Depth(cm) | 0–5 | 5–15 | 0–5 | 5–15 | 0–5 | 5–15 | 0–5 | 5–15 | 0–5 | 5–15 |
| CT[§] | 39.94c[†] | 48.20a[†] | 40.34a | 34.08a | 12.40a | 12.7a | 4.88a | 5.03a | 1.67c | 1.85a |
| NT | 43.46c | 62.64a | 36.01ab | 25.98a | 11.92a | 8.20a | 5.18a | 3.18a | 1.73c | 2.18a |
| NTI | 49.52bc | 48.20a | 32.48bc | 34.08a | 10.52a | 12.7a | 4.79a | 5.03a | 1.86bc | 1.85a |
| NTCG | 59.40ab | 59.21a | 28.10dc | 28.31a | 8.97a | 8.68a | 4.33a | 3.80a | 2.11ab | 2.11a |
| NTC | 63.70a | 63.12a | 25.58d | 25.03a | 8.92a | 8.54a | 3.96a | 3.31a | 2.21a | 2.19a |
| NTCGI | 65.55a | 62.58a | 24.51d | 22.00a | 8.14a | 12.4a | 3.53a | 3.03a | 2.26a | 2.14a |
| NTCI | 58.96ab | 65.11a | 28.86dc | 23.64a | 9.90a | 8.18a | 4.24a | 3.07a | 2.11ab | 2.23a |

[†] Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

[§] CT, conventional-till; NT, no-till; C, cover crop; G, graze; I, intercropping.

without cover crops recorded the least MWD compared to treatments with cover crops ($p<0.05$). Mean weight diameter is a tool for evaluating soil physical conditions. A higher MWD is an indication of higher aggregate stability and an improvement in soil physical condition. Research has shown that NT and cover crops can increase soil aggregation (Kabir and Koide, 2000; Sainju et al., 2003; Blanco-Canqui et al., 2011) and stability of soil aggregates (Roberson et al., 1991). One mechanism for this is polysaccharide exudation by cover crop roots, which can help bind soil particles together into aggregates (Liu et al., 2005). Dapaah and Vyn (1998) showed how aggregate stability was higher following cover crops than where no cover crops were used. Stavi et al. (2012), in a study in the Midwestern USA, showed how mixed cover crops increased MWD, and had a strong positive correlation with SOC. Although we did not observe any significant differences in SOC, the measured POX-C of LM positively correlated with MWD ($r^2 = 0.86$; $p<0.05$; Table 5). Mean Weight Diameter negatively correlated with $D_b$ $r^2 = 0.93$ ($p<0.05$; Table 5). Aggregate size distribution and MWD for the 5–15 cm soil depth showed no significant differences due to treatment for large and small macroaggregates, micro aggregates and silt plus clay, though trends were similar as for 0–5 cm (Table 2). The NT conservation practice stimulate natural conditions that nurture soil stratification reinforcing upper soil profile development characterized by a homogeneous layer, rich in organic matter and a well-developed soil structure due to macro aggregation. Greater uniformity observed in the subsurface depth might be due to the site having been under NT for 12 years prior to this study.

### 3.4. *Permanganate oxidizable carbon*

Permanganate oxidizable carbon (POX-C) concentrations in the 0–5 and 5–15 cm aggregate separates (Table 3) were generally analogous to aggregate size distribution and MWD across treatments, shown in Table 2. Permanganate oxidizable carbon in large macroaggregates from 0 to 5 cm was lowest for CT and highest for NTCG, and the latter was not statistically different from rest of cover crop treatments ($p<0.05$; Table 3). No treatment differences for POX-C were observed in aggregate fractions from 5 to 15 cm (Table 3). A strong positive correlation between large macroaggregates (4 – 2 mm) in the 0–5 cm depth and POX-C was observed, $r^2 = 0.86$ ($p<0.05$; Table 5). Tillage tends to disrupt soil macroaggregates, resulting in loss of particulate organic matter C and N protected by soil aggregates (Tiessen and Stewart, 1983; Cambardella and Elliot, 1992; Wander and Bidart, 2000; Moebius-Clune et al., 2011; Gupta and Germida, 2015; Tian et al., 2015). No-till may shield organic C and N from decomposition through the formation of more stable aggregates (Six et al., 2002; Garcia-Franco et al., 2015). Cover crops (including grazed and intercropped) and NT combination enhanced POX-C levels in the 0–5 cm depth by 19–32% relative to CT.

The soil POX-C pool, though a small proportion of total SOC (5–20%), plays a significant role in defining soil quality (Wander and Drinkwater, 2000; Haynes, 2005; White et al., 2020). Permanganate oxidizable carbon functions in C accrual and associated cycling and availability of nutrients (Weil and Magdoff, 2004; Grandy and Robertson, 2007) and soil aggregation and stability (Tisdal and Oades, 1982; Gunapala and Scow, 1998; Bronick and Lal, 2005; Six and Paustian, 2014; Shi et al., 2017). Recent findings are isolating Weil et al. (2003) permanganate oxidized "labile" C compounds as complex polyphenolic organic compounds (Christy et al., 2021; Kleber et al., 2021) bringing controversy over the use of the terms "active or labile carbon". Although there were no significant differences in SOC amongst all treatments (Table 4), however after 3 years of treatment effects, POX-C in LM separates in the 0–5 cm depth spiked by 19–32% to cover crops introduction and contrary for CT going down by 6% relative to the long-term NT practice. Cover crops are credited for increasing POX-C (White et al., 2020). POX-C is a fraction of soil organic matter with a relatively shorter turnover time compared to SOC and is more sensitive to changes in management and indicate carbon sequestration initiation in the soil.

**Table 3**

POX-C in soil aggregate fractions.

| Treatment | POX-C in aggregate fractions for 0–5 and 5–15 cm depths (mg C kg$^{-1}$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Large-macro | | Small-macro | | Micro-aggregate | | Silt + clay | |
| | 4 – 2 mm | | 2 – 0.25 mm | | 0.25 – 0.053 mm | | <0.053 mm | |
| Depth(cm) | 0–5 | 5–15 | 0–5 | 5–15 | 0–5 | 5–15 | 0–5 | 5–15 |
| CT[§] | 441c[†] | 424a[†] | 295a | 466a | 300a | 509a | 319a | 425a |
| NT | 467bc | 397a | 266a | 505a | 343a | 667a | 298a | 562a |
| NTI | 471bc | 432a | 293a | 474a | 321a | 611a | 290a | 607a |
| NTCG | 618a | 509a | 311a | 447a | 381a | 594a | 330a | 421a |
| NTC | 565ab | 431a | 296a | 524a | 324a | 542a | 310a | 415a |
| NTCGI | 557ab | 484a | 317a | 467a | 399a | 582a | 313a | 441a |
| NTCI | 590a | 497a | 313a | 482a | 383a | 598a | 316a | 429a |

[†] Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

[§] CT, conventional-till; NT, no-till; C, cover crop; G, graze; I, intercropping.

**Table 4**
Soil total nitrogen, organic C and water content.

| Treatment | Soil total nitrogen (STN), organic carbon (SOC) and soil water content (SWC) | | | | | |
|---|---|---|---|---|---|---|
| | STN (mg kg$^{-1}$) | | SOC (g kg$^{-1}$) | | SWC (mm) | |
| Depth(cm) | 0–5 | 5–15 | 0–5 | 5–15 | 0–20 | 20–40 |
| CT[§] | 604c | 513b | 8.08a | 5.83a | 26.5c | 36.5c |
| NT | 710c | 547ab | 8.27a | 5.83a | 32.5b | 37abc |
| NTI | 655c | 551ab | 8.10a | 5.81a | 31.5b | 36.8bc |
| NTCG | 802a | 583ab | 8.59a | 5.93a | 37.3a | 39.3ab |
| NTC | 754ab | 569b | 8.34a | 6.37a | 36.5a | 37.3abc |
| NTCGI | 806a | 607a | 8.62a | 6.23a | 36.5a | 37.8abc |
| NTCI | 769ab | 641a | 8.45a | 5.99a | 37.3a | 39.5a |

[†] Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).

[§] CT, conventional-till; NT, no-till; C, cover crop; G, graze; I, intercropping.

Although no significant differences in SOC were detected after 3 years of CC, CC treatments showed a 3% increase in SOC compared to NT without CC and CT reduced SOC by 2% in the surface layer. Tillage destroyed soil aggregates exposing SOC to microbial activity and subsequent soil C loss (Gupta and Germida, 2015; Tian et al., 2015; Sa et al., 2001; Navarro-Garcia et al., 2012). Grazing CC however increased SOC by 4% compared to the traditional NT without CC. A related study using CC did not impact SOC and STN in the top 5 cm (Chalise et al., 2019). However, although no significant SOC were observed, STN treatment effects were detected. The no CC treatments CT, NT, and NTI recorded 16% lower STN compared to CC treatments ($p<0.05$; Table 4). Although not significant grazed CC treatments were 6% higher STN amongst the cover crop treatments despite a 58–67% (2014) and 47–55% (2015) lower biomass. Although not quantified animal waste may have contributed to the insignificant difference.

### 3.5. Correlation analysis

The Pearson's correlation analysis of the physicochemical parameters that were evaluated showed linear positive and negative relationships which were mainly significant at $p<0.05$ (Table 5). The positive relationship amongst parameters SOC vs. POX-C; SOC vs. STN; SOC vs. LM were strong ranging from $R^2 = 0.81–0.96$ ($p<0.05$). Other related studies detected similar correlation coefficients between SOC and POX-C of $R^2 = 0.76–0.93$ (Plaza-Bonilla et al., 2014; Duval et al., 2018; Jagadamma et al., 2019). Large macroaggregates showed positive strong relationships with SOC, POX-C and STN ranging $R^2 = 0.81–0.87$ ($p<0.05$; Table 5). Evaluating impact of tillage and residue management under cereal crop Somasundaram et al. (2017) showed how SOC and STN significantly correlated with large macroaggregates size in a long term (47 years) field experiment in Queensland, Australia. In this study the positive interactions and synergies exhibited were reflected in a very strong relationship between total porosity and soil water content ($R^2 = 0.96$, $p = 0.0005$; Table 5; Fig. 2).

### 3.6. Stored soil water

Stored soil water content was 39% higher for intercropped, grazed and ungrazed CC compared to CT and about 15% higher than NT without CC treatments ($p<0.05$; Table 4; Fig. 2). There were no significant differences in stored soil moisture due to intercropping or grazing among CC treatments. Grazing did not compact the soil significant enough to reduce porosity ($p<0.05$; Table 1), neither did turnips and radishes intercrops had an advantage over exclusive CC treatments as no differences were observed. The intercrops winterkill may have negatively affected anticipated treatment effects. Cover crops have been reported to increase stored soil water (Daigh et al., 2014; He et al., 2009; Nielson et al., 2016). Tillage reduced soil water storage by 16–24% compared to NT and NTI respectively. Tillage operations in the 3-year period significantly destroyed soil structure built over the 12-year

**Table 5**
Bivariate correlation matrix for soil physicochemical properties.

**Pearson Correlation Coefficients**

**Prob > |r| under H0: Rho=0**

| | BD | TP | SWC | SOC | POXC | STN | LM | SM | MA | SC | MWD |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **BD** | 1 | −0.9900 | −0.9632 | −0.8407 | −0.8516 | −0.9147 | −0.9299 | 0.9411 | 0.8920 | 0.8047 | −0.9299 |
| | | **<0.0001** | **0.0005** | **0.0178** | **0.0150** | **0.0039** | **0.0024** | **0.0016** | **0.0069** | **0.0291** | **0.0024** |
| **TP** | −0.9900 | 1 | 0.9631 | 0.8407 | 0.8515 | 0.9147 | 0.9300 | −0.9412 | −0.8921 | −0.8049 | 0.9300 |
| | **<0.0001** | | **0.0005** | **0.0178** | **0.0150** | **0.0039** | **0.0024** | **0.0016** | **0.0069** | **0.0290** | **0.0024** |
| **SWC** | −0.9632 | 0.9631 | 1 | 0.8171 | 0.8459 | 0.9264 | 0.8639 | −0.9020 | −0.8361 | −0.6561 | 0.8639 |
| | **0.0005** | **0.0005** | | **0.0248** | **0.0165** | **0.0027** | **0.0122** | **0.0055** | **0.0191** | **0.1095** | **0.0122** |
| **SOC** | −0.8407 | 0.8407 | 0.8171 | 1 | 0.8674 | 0.9659 | 0.8108 | −0.7927 | −0.8129 | −0.7451 | 0.8108 |
| | **0.0178** | **0.0178** | **0.0248** | | **0.0114** | **0.0004** | **0.0269** | **0.0335** | **0.0262** | **0.0546** | **0.0269** |
| **POXC** | −0.8516 | 0.8515 | 0.8459 | 0.8674 | 1 | 0.8993 | 0.8632 | −0.8310 | −0.8299 | −0.7149 | 0.8632 |
| | **0.0150** | **0.0150** | **0.0165** | **0.0114** | | **0.0058** | **0.0123** | **0.0205** | **0.0209** | **0.0710** | **0.0123** |
| **STN** | −0.9147 | 0.9147 | 0.9264 | 0.9659 | 0.8993 | 1 | 0.8702 | −0.8748 | −0.8532 | −0.7358 | 0.8702 |
| | **0.0039** | **0.0039** | **0.0027** | **0.0004** | **0.0058** | | **0.0109** | **0.0099** | **0.0146** | **0.0594** | **0.0109** |
| **LM** | −0.9299 | 0.9300 | 0.8639 | 0.8108 | 0.8632 | 0.8702 | 1 | −0.9889 | −0.9790 | −0.9308 | 0.9900 |
| | **0.0024** | **0.0024** | **0.0122** | **0.0269** | **0.0123** | **0.0109** | | **<0.0001** | **0.0001** | **0.0023** | **<0.0001** |
| **SM** | 0.9411 | −0.9412 | −0.9020 | −0.7927 | −0.8310 | −0.8748 | −0.9889 | 1 | 0.9791 | 0.8873 | −0.9889 |
| | **0.0016** | **0.0016** | **0.0055** | **0.0335** | **0.0205** | **0.0099** | **<0.0001** | | **0.0001** | **0.0077** | **<0.0001** |
| **MA** | 0.8920 | −0.8921 | −0.8361 | −0.8129 | −0.8299 | −0.8532 | −0.9790 | 0.9791 | 1 | 0.9138 | −0.9790 |
| | **0.0069** | **0.0069** | **0.0191** | **0.0262** | **0.0209** | **0.0146** | **0.0001** | **0.0001** | | **0.0040** | **0.0001** |
| **SC** | 0.8047 | −0.8049 | −0.6561 | −0.7451 | −0.7149 | −0.7358 | −0.9308 | 0.8873 | 0.9138 | 1 | −0.9308 |
| | **0.0291** | **0.0290** | **0.1095** | **0.0546** | **0.0710** | **0.0594** | **0.0023** | **0.0077** | **0.0040** | | **0.0023** |
| **MWD** | −0.9299 | 0.9300 | 0.8639 | 0.8108 | 0.8632 | 0.8702 | 0.9900 | −0.9889 | −0.9790 | −0.9308 | 1 |
| | **0.0024** | **0.0024** | **0.0122** | **0.0269** | **0.0123** | **0.0109** | **<0.0001** | **<0.0001** | **0.0001** | **0.0023** | |

Db, bulk density; TP, total porosity; SOC, soil organic carbon; POX-C, permanganate oxidizable carbon; STN, soil total nitrogen; LM, large macroaggregate; SM, small microaggregate; MA, micro-aggregate; S + C, silt + clay; MWD, mean weight diameter; SWC, soil water content. Top number showing $R^2$ value and below, significance level, declared significant at $p<0.05$ (**bold**).

Db, bulk density; TP, total porosity; SOC, soil organic carbon; POX-C, permanganate oxidizable carbon; STN, soil total nitrogen; LM, large macroaggregate; SM, small microaggregate; MA, micro-aggregate; S + C, silt + clay; MWD, mean weight diameter; SWC, soil water content. Top number showing $R^2$ value and below, significance level, declared significant at $p<0.05$ (**bold**).

period through crushing of large maroaggregates into small macroaggregates increasing bulk density and reducing total porosity and capacity of soil to store soil water ($p<0.05$; Tables 1 and 2). Similarly, Kool et al. (2019) observed reduced water retention due to tillage, altering of soil structure and diminished hydraulic properties. Elsewhere reduced soil water storage under tillage was due to alteration of pore size distribution (Bescansa et al., 2006).

## 4. Summary and conclusion

This study supported our hypothesis that NT with CC would improve soil physical and chemical properties, and in that way enhancing soil ecosystem services and function for sustainable production. The no CC treatments (CT, NT and NTI) measured parameters trended negatively compared to NT with CC and CT often recording the lowest POX-C, large macroaggregates, MWD and total porosity, a manifestation of negative effects of tillage after 12 years of NT practice. No till and CC improved soil aggregate stability by increasing aggregate sizes by 34–64%, significantly for surface large-macro aggregates and MWD by 13–35% compared to CT, NT and NTI, thereby reducing soil vulnerability to wind erosion, a common problem in the semiarid drylands of Texas and improved soil bearing capacity to resist potential negative effects due to flash grazing. Physio-chemical synergies showed how CC increased POX-C enhancing soil macro-aggregation and subsequently reducing surface bulk density, increasing total porosity and stored soil moisture by up to 39% compared to CT. Conventional tillage physically destroyed soil structure, compacting the soil, and leaving it susceptible to both wind and water erosion. Conventional tillage soil compaction effects were reflected in increased bulk density of 9–11% compared to NT treatments without CC, whilst inclusion of CC to NT reduced bulk density by 8–13%. Soil compaction due to tillage and improved soil quality owing to inclusion of CC to long term NT was mirrored in porosity measurements. Tillage reduced porosity by 12% whilst CC increased porosity by 10–18% compared to the long-term NT practice. The combination of CC and NT significantly improved soil quality. Observed changes were more pronounced in the soil surface layer, due to the complex interaction between the soil surface layer and the atmosphere through radiation, temperature, rainfall, evaporation, humidity, wind, and anthropogenic effects. Intercropping with radishes and turnips did not show any significant effects that stood out. This was attributed to extensive winterkill of the intercrops that was observed each year. Flash grazing CC did not negatively affect any measured parameter. Whilst CC improved soil quality under monoculture system, flash grazing is worth considering as a way of recouping associated CC production costs for sustainable productivity in semi-arid regions. The relatively rapid treatment impact that was observed in this investigation is important considering the cost/benefit dilemma associated with cover crops adoption in semi-arid regions for soil security attainment.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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