Soil & Tillage Research 206 (2021) 104823

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Soil water dynamics under a warm-season cover crop mixture in continuous wheat

Partson Mubvumba [a,*], Paul B. DeLaune [b], Frank M. Hons [c]

[a] USDA-ARS, Crop Production Systems Research Unit, P.O. Box 350, Stoneville, MS 38776, United States
[b] Texas A&M AgriLife Research, 11708 HWY 70 S, Vernon, TX 76384, United States
[c] Texas A&M University, 2474 TAMU, College Station, TX 77843, United States

ARTICLE INFO

Keywords:
Cover crops
Soil water
Infiltration
Wheat

ABSTRACT

Cover crop technology can potentially benefit monoculture wheat systems in the semi-arid US Southern Great Plains, but the biggest hurdle in such regions where evapotranspiration exceeds precipitation is soil water. Cover crop impact on soil water use and availability is a major cause for concern in water-limited environments. The objective of this study was to evaluate the impact of cover crops, grazing, and intercrops on soil water dynamics under rainfed conditions. Seven treatments were evaluated, including conventional tillage (CT) and combinations of no-tillage (NT) with a cover crop mixture, grazed cover crops, and/or cash crop intercropping. The three-year study was conducted on a long-term NT continuous wheat system in the Texas Rolling Plains. Despite dry periods, the cover crop mixture produced 2141 to 3503 kg ha^{-1} dry herbage mass. Stored soil water was significantly lower within 60 days after planting for cover crop compared to no cover crop treatments. Stored soil water was 22–26% lower in cover crop plots at time of termination. In the final two years of the study, the positive change in stored soil water from cover crop termination to wheat planting was two to four times greater for cover crop treatments compared to non-cover crop treatments. The greater infiltration and water capture after termination has the potential to make up for the loss in soil water that cover crops used.

1. Introduction

Water is usually the most limiting factor in crop production in semi-arid regions. Monoculture wheat (*Triticum aestivum* L.) production in the United States (US) Texas Rolling Plains leaves the land fallow during the summer, theoretically reserving the moisture captured during this period for the following winter wheat crop. Although conventional tillage (CT) winter wheat/fallow is a common practice in the southern and northern US Great Plains, low water use efficiencies have been reported with this practice (McGee et al., 1997). Switching fallowing with summer cover crops will potentially exhaust soil moisture which could be utilized by the dryland winter wheat. Often, dryland winter wheat production in semi-arid regions is hampered by characteristic low precipitation exacerbated by high evaporation and low stored soil moisture (Prihar et al., 1975; Soon et al., 2008). Norton (2007) reported that more than 75 % of the water from rainfall was lost where conservation management was not practiced. Conservation management eliminates tillage and fallowing. Cover crop adoption may further reduce available soil moisture and may be catastrophic to subsequent crops in drought periods (Dabney et al., 2001; Nielsen and Vigil, 2005; Balkcom et al., 2007; Nielsen et al., 2015).

Cover crop residue mitigates adverse soil temperatures and increases soil moisture storage (Rankoth et al., 2019; Blanco-Canqui et al., 2015, 2011; Kahimba et al., 2008). Smith et al. (1987) reported significant stored soil water reductions by winter cover crops, but reduced soil evaporation by the mulching provided by cover crops after termination. Cover crops create surface mulch that shades, insulates, and retards water vapor movement, allowing condensation inside the mulch and reducing evaporative losses (Blanco-Canqui et al., 2011; Steenwerth and Belina, 2008; Unger and Vigil, 1998; Phillips, 1984; Bond and Willis, 1969). Cover crop insulation of the soil surface also helps regulate soil temperature. Cover crops generally lower maximum soil temperatures in summer and raise minimum temperatures in winter. Research has shown a reduction of up to 5 °C and increase by 1 °C in hot and cold

Abbreviations: CT, conventional tillage; NT, no-tillage; NTC, no-tillage with cover crop; NTI, no-tillage with intercrops; NTCI, no-tillage with cover crops and intercrops; NTCG, no-till with grazed cover crop; NTCGI, no-tillage with intercrop and grazed cover crop.

* Corresponding author.
E-mail address: partson.mubvumba@usda.gov (P. Mubvumba).

https://doi.org/10.1016/j.still.2020.104823
Received 25 November 2019; Received in revised form 21 September 2020; Accepted 28 September 2020
Available online 23 October 2020
0167-1987/Published by Elsevier B.V.

climates, respectively (Teasdale and Mohler, 1993; Blanco-Canqui et al., 2011). Cover crops' reduction in soil temperature in summer reduces soil water evaporation and conserves soil moisture.

Cover crops were also found to decrease surface runoff, add organic matter and consequently improve soil structure (Blanco-Canqui et al., 2013a, 2012a; Rawls et al., 2003). Increased surface roughness due to cover crops facilitates soil water infiltration by reducing runoff velocity (Blanco-Canqui et al., 2013b; Krutz et al., 2009). The mulch also reduces rain drop impact on the soil surface, decreasing soil aggregate disruption and crusting that makes the soil surface less permeable and lowers evaporation (Blanco-Canqui et al., 2011). A mulch covering 90 % of the soil surface resulted in maximum infiltration into a dry soil (Felton et al., 1987).

Cover crops can reduce soil compaction through both surface and below ground effects on soil (Chen and Weil, 2010; Blanco-Canqui et al., 2012b; Steele et al., 2012). Brassicas like radishes, with deep tap roots, naturally till the subsoil, while more fibrous roots are more effective on the topsoil (Cresswell and Kirkegaard, 1995). Cover crop root systems create channels and macropores upon termination that improve soil hydraulic properties and increase water infiltration into the soil (Chen and Weil, 2010; Blanco-Canqui et al., 2011; Steele et al., 2012). Keisling et al. (1994) reported increased soil hydraulic conductivity, porosity and water holding capacity after 17 years of hairy vetch (*Vicia villosa* L.), winter rye (*Secale cereal*) and crimson clover (*Trifolium incarnatum* L.) cover crops. Cover crops, therefore, often increase soil macro porosity and connectivity and water movement into and within the soil system, improving precipitation capture and storage.

Significant stored soil surface water recharge was reported following cover crops in Alabama (Balkcom et al., 2007), often resulting in similar or higher yields of following crops. Other studies in the Texas Rolling Plains, however, have shown no impact of cover crops on cotton [*Gossypium hirsutum* (L.)] lint yields (DeLaune and Sij, 2012; Sij et al., 2003). Baughman et al. (2007) reported a reduction in cotton lint yield in NT cotton with cover crops in the Rolling Plains. Nielsen et al. (2015) demonstrated how cover crops, either single or mixed species, negatively affected subsequent crop yields through soil moisture depletion in the Central Great Plains and reported an average 10 % reduction in wheat yields following cover crops compared to fallow. In semi-arid regions, cover crops deplete stored soil moisture but can potentially enhance soil chemical, physical and biological processes, contributing to sustainable soil ecosystem service functions and productivity. No-tillage (NT) and cover crops synergies are frequently more beneficial compared to the combination of CT and cover crops (Olson et al., 2014). CT is a common practice in the Texas Rolling Plains.

Research geared toward mitigating of challenges and enhancing the benefits of sustainable practices is critical for producers to fully embrace new technology under dryland agriculture in semi-arid areas. In the case of cover crop adoption, balancing the pros and cons of their effects on soil moisture availability poses a huge challenge to farmers. However, there is still limited information on the impact of cover crops in wheat systems in the Texas Rolling Plains. We hypothesized that cover crops would deplete reserved soil moisture compared to summer fallow but enhance infiltration after cover crop termination. The objectives of this study were to determine the impact of NT, cover crops, intercropping and grazing on soil water dynamics in continuous wheat systems and the subsequent viability of cover crop implementation in the Texas Rolling Plains.

2. Materials and methods

Field plots were located at a rainfed research site at the Texas A&M AgriLife Research Smith Walker Research Unit (34°03′28.7″N 99°14′35.8″W) near Vernon, Texas (Fig. 1). Continuous wheat had been in NT production at this site since 2001 and was utilized as a dual-purpose grain/grazing system whenever conditions allowed for adequate forage. The soil type is Rotan clay loam (Fine, mixed, superactive, thermic Pachic Paleustolls). The average annual precipitation in this region is 711 mm and mean annual temperature is 17.1 °C (U.S. climate data, 2017).

The experimental design was a randomized complete block design with seven treatments replicated four times. Each replicate research plot was 0.2 ha (2000 m^2) in size. The following treatments were evaluated:

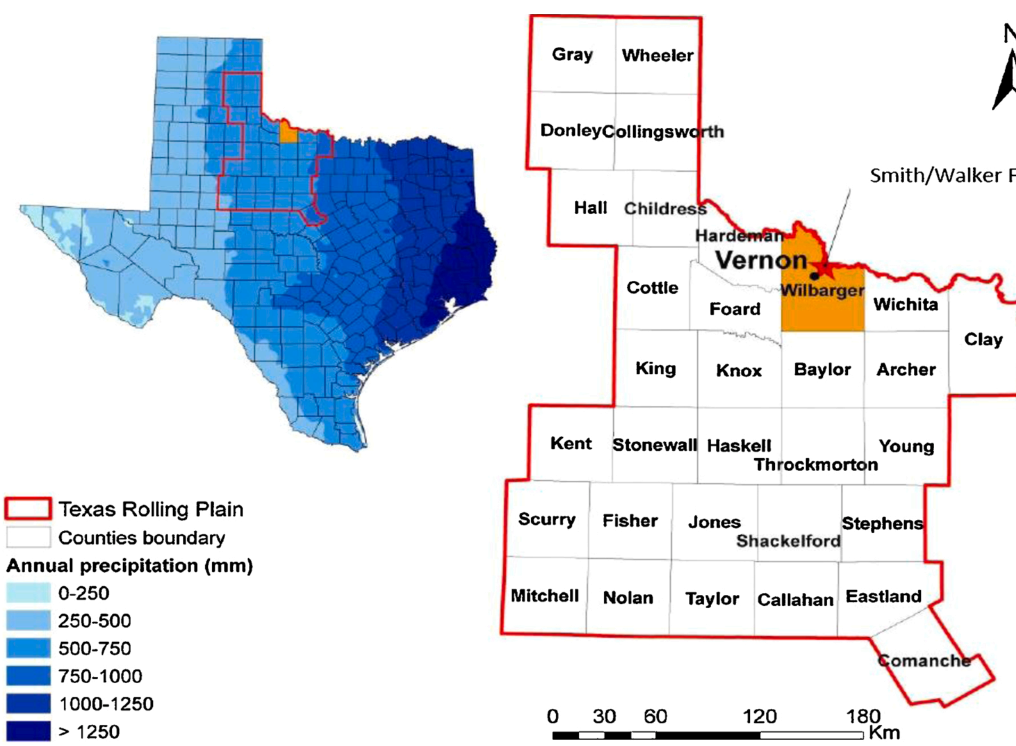

Fig. 1. Study location at Smith/Walker Research Farm, Texas Rolling Plains near Vernon, TX.

1) conventional tillage without a cover crop (CT); 2) no-till without a cover crop (NT); 3) no-till without a cover crop and intercropped with turnip/radish (NTI); 4) no-till with a cover crop (NTC); 5) no-till with a grazed cover crop (NTCG); 6) no-till with a cover crop plus intercropping (NTCI); and 7) no-till with a grazed cover crop plus intercropping (NTGCI). Cover crops were all grown during summer months, while intercropped species were seeded with wheat. As the entire field had been in no-till wheat production since 2001, CT plots were reverted to tillage in summer 2013. A disc and chisel sweep were used to a depth of 15 cm two to three times each summer. A multi-species mix of legumes and grasses (Table 1) was planted as a warm-season cover crop, closely following guidelines used by local USDA-NRCS Field Office Staff (NRCS, 2011).

The multi-species cover crop mix was custom mixed by a regional seed company and modified in the second year based on availability and performance in the first year. Inoculant (Micronoc, Sono Ag, Hale Center, TX) for legumes was added during mixing. Cover crops were planted in June every year after wheat harvest using a no-till drill at a row spacing of 19 cm (Table 2). Cover crops were chemically terminated after grazing in August/September each year. Glyphosate was primarily used for cover crop termination each year with an additional application of paraquat dichloride in 2015.

2.1. Soil moisture

A neutron moisture meter (NMM) was used to measure soil water storage (Evett, 2008). Aluminum access tubes, about 5-cm in diameter and 180 cm long were placed by the plant row in each plot to a depth of 150 cm. The installation was done using a Giddings hydraulic coring machine (Giddings Machine Company, Windsor, CO). Soil water stored in the profile was measured about twice a month at 20 cm depth increments from 0 to 140 cm. The NMM readings were converted to volumetric soil water content with three calibration equations determined for the soil type under investigation at one of the experimental sites for the NMM that was used (Model 503DR, CPN International Inc, Martinez, CA, Serial No. H350607921). The calibration process and derivation of soil moisture computation equations are documented by Evett (2003). The three equations were based on the soil profile characteristics of the soil under investigation. Historical average temperature and precipitation was accessed through U.S Climate data online (U.S. climate data, 2017), while the values observed during the study were recorded on site using two all-weather rain gauges on the farm (Productive Alternatives Inc.; Fergus Falls, Minnesota)(Table 3).

Table 1
Composition of cover crop mixture used during the study period 2013-2015.

Cover Crop Species	Seeding Rate (kg ha^{-1})	
	2013	2014 - 2015
Iron & Clay Cowpea (*Vigna unguiculate L.*)	6.7	5.6
Guar (*Cyamopsis tetragonoloba L.*)	–	6.7
Mung beans (*Vigna radiate L.*)	–	6.7
Pearl Millet (*Pennisetum glaucum L.*)	–	2.2
German Foxtail Millet (*Setaria italic L.*)	1.7	1.1
Sorghum Sudangrass (*Sorghum bicolor × S. bicolor var. sudanense*)	2.8	–
Forage Sorghum *(Sorghum bicolor (L.) Moench.)*	–	3.4
Buckwheat (*Fagopyrum esculentum*)	3.4	2.2
Sesame (*Sesamum indicum*)	0.6	–
Browntop Millet (*Urochloa ramosa (L.) Nguyen*)	1.7	–
Catjang Pea *(Vigna unguiculata subsp. Cylindrica)*	6.7	–
Lablab Bean (*Lablab purpureus*)	1.1	–
Forage Soybean (*Glycine max (L.) Merr.*)	9.0	–
Total Rate	33.6	28.0

Table 2
Cover crop planting and termination dates for the study period 2013-2015.

Year	Date	
	Planted	Terminated
2013	06.08.13	08.30.13
2014	06.23.14	08.18.14
2015	06.25.15	09.15.15

2.2. Grazing

Two adjacent grazed cover crop treatment plots were combined and fenced into a single 4000 m^2 paddock, resulting in a total of four grazing paddocks. The first year, 15 cow/calf pairs with an estimated live weight of 9525 kg were rotated through the paddocks from August 26–30, 2013. Each paddock was grazed for 24 consecutive hours before moving into the next paddock. Hence, each 4000 m^2 paddock received grazing over a single 24-hr period. In 2014, seven cow/calf pairs, nine heifers and nine cows with an estimated live cattle weight of 13,270 kg were rotated through the paddocks from August 11th to 12th. Each paddock was grazed for 6-hrs with two paddocks grazed per day. In 2015, 31 available cattle (18 cows and 13 calves) with an estimated live cattle weight of 11,340 kg were rotated through the four paddocks, six hours per paddock, on the 9th to the 10th of September. Grazing of winter wheat occurred in one of three study years, when 15 stocker calves grazed wheat across the entire study site from January 6 to February 25, 2014.

2.3. Biomass

Summer cover crop biomass production was determined by clippings taken 2 cm above ground level from two randomly placed 1 m^2 grids per plot immediately prior to cover crop termination. For grazed cover crop treatments, above ground biomass clippings were taken before and after grazing to estimate the amount of biomass removed by grazing and/or trampling. Removal was estimated by the difference between pre-grazed and post-grazed biomass measurements. Biomass samples were oven dried at 65 °C for 48 h or longer as necessary and dry weights were recorded.

2.4. Statistical analysis

Data were analyzed using Proc GLIMMIX using SAS Version 9.4 (SAS Institute Inc., Cary, NC). Generalized linear mixed models such as the GLIMMIX procedure combine the characteristics of generalized linear models and mixed models (SAS Institute, 2017). Treatment was considered a fixed effect and block (nested within year) was considered random when analyzed by year. As climate, planting date, and termination date varied by year, data were analyzed by year. Means of significant effects were separated using Fisher's protected LSD at $P < 0.05$.

3. Results and discussion

3.1. Climatic conditions

The study area was classified as enduring exceptional drought conditions, which is the most intense drought rating, during the cover crop growing season for the first two years of the study (http://droughtmonitor.unl.edu/). Average annual rainfall for the study site is 711 mm (U.S. climate data, 2017). Precipitation for the wheat fallow season (June-October) during the study was 419, 482, and 272 mm for years 1–3, respectively (Table 3). These values are higher than the historical average of 374 mm for all but the final summer, which received below normal precipitation (Table 3). The high amounts of precipitation during the summers of 2013 and 2014 were due to significant rainfall events in July, which were approximately four times above normal for the

Table 3
Historical and observed average temperature and precipitation during wheat fallow period for the study location near Vernon, TX USA 2013-2015.

Month	Historical		Observed 2013		Observed 2014		Observed 2015	
	Avg. Temp (°C)	Precip (mm)	Avg. Temp (°C)	Precip (mm)	Avg. Temp (°C)	Precip (mm)	Avg. Temp (°C)	Precip (mm)
June	27	108	29	50	15	110	27	58
July	29	53	29	226	28	208	30	64
August	29	62	29	47	29	57	29	38
September	24	80	26	68	25	51	27	12
October	18	71	18	28	20	56	19	100
Total		374		419		482		272

month. Average temperatures were also equal to or greater than the historical average for much of the study period (Table 3).

3.2. Cover crop biomass

Annual dry biomass yields from cover crops ranged from 1796 kg ha^{-1} to 3644 kg ha^{-1} (Table 4). Averaged across treatments, mean biomass production was 2141 kg ha^{-1} in 2013, 3503 kg ha^{-1} in 2014, and 2861 kg ha^{-1} in 2015. Although limited information is available for warm-season mixed species cover crop performance, our data were comparable to recent observations in Nebraska and Colorado, where a mixture of cool- and warm-season cover crops produced variable biomass from year to year ranging from 2020 to 4790 kg dry biomass ha^{-1} (Nielsen et al., 2015), although seeding rates were much higher than used in our study (57.1 vs. 28 kg ha^{-1}). Biomass levels in 2013 were lower than observed in other years (Table 4), although seeding rates were 5.6 kg ha^{-1} greater than 2014 and 2015, with a greater number of cover crop species used in the mix (10 vs. 8). Total stored soil water was generally lower for the first 32 days after planting (DAP) due to erratic precipitation on site after planting in 2013 compared to 2014 and 2015 (Fig. 2), exacerbated with higher temperatures (Table 1), which may have contributed to the lower cover crop biomass levels observed in the first year of the study.

Although not quantified, grass species in our cover crops mix, millets and sorghum, performed better than legumes. Approximately 16 mm rainfall was received on June 9, 2013, the day after the cover crop mixture was planted. This provided sufficient moisture for germination. However, after emergence, temperatures exceeding 38 °C occurred over the next two to three weeks, which negatively affected legume species. Millets (*Pennisetum glaucum* L.; *Setaria italic* L. *and Urochloa ramosa (*L.*) Nguyen)* and sorghum Sudan grass (*Sorghum bicolor* × *S. bicolor* var. *sudanense*) became the dominant planted species in late summer. Related research has shown that cover crop mixtures can be dominated by 1–2 species, where 2 species of a 10-species mix comprised 69–92 % of the total biomass (Nielsen et al., 2015; Sanderson et al., 2018). Like legumes, no sesame (*Sesamum indicum*) or buckwheat (*Fagopyrum esculentum*) were noted in any cover crops stands at termination during the first year and modifications to the mix were made in subsequent years. A better representation of legumes was noted in 2014 and 2015.

Table 4
Annual cover crop dry biomass produced in grazed and ungrazed systems near Vernon, TX USA 2013-2015.

Treatments	Cover crop biomass production (kg ha^{-1})					
	2013		2014		2015	
	Pre-Graze	Post-Graze	Pre-Graze	Post-Graze	Pre-Graze	Post-Graze
NTCG[‡]	2169b[†]	–	3133b	1305a	3120a	1391b
NTC	2129b	–	3629a	–	2381c	–
NTCGI	1796c	–	3590a	1190b	2961b	1557a
NTCI	2474a	–	3644a	–	2987b	–

[†] Means within a column followed by the same letter are not different at $P < 0.05$.
[‡] CT, conventional-till; NT, no-till; C, cover crop; G, graze; I, intercropping.

Grazing resulted in 58–67 % lower biomass in 2014 and 47–55 % lower biomass in 2015 (Table 4). Thus, we can conclude that 47–67 % of standing biomass was removed or trampled into the soil due to grazing over relatively short grazing periods, which is comparable to the recommendations of USDA-NRCS to leave 50 % of cover crop biomass after grazing (local soil health workshops). However, grazing did not have a significant effect on the amount of stored soil water.

3.3. Growing season stored soil water

Comparisons of the amount of soil water stored by depth showed more significant effects in the top 60 cm of soil compared to 60−140 cm. Generally, the stored soil water content for the 60-140 cm depth did not interact significantly with treatments during the first, second or third growing seasons (data not shown). However, significant differences in stored soil water were observed between cover crop and non-cover crop treatments each year of the study, with cover crop plots displaying lower stored soil water beginning at 39–52 DAP each year of the study (Fig. 2).

In the first year of the study (2013), stored soil water was statistically the same for all treatments for initial readings taken 32 DAP, averaging 76 mm across all treatments in the top 60 cm (Fig. 2). Due to 226 mm of precipitation recorded between July 15–25, no significant differences in soil water were observed among treatments 52 DAP (30 July). However, these rainfall events resulted in vigorous cover crop growth. Consequently, cover crop treatments had significantly lower soil water compared to NT and CT treatments without cover crops by 60 DAP (Fig. 2). At time of termination, cover crops had at least 22 % less stored soil water than treatments without cover crops (Fig. 2). Nielsen et al. (2015) concluded that a multi-species cover crop mixture, like those used in the current study, in the Central Great Plains used water similarly to cover crops grown as single-species plantings. Additionally, cover crop water use was found to be 1.78 times greater than evaporative water loss from a NT fallow treatment with residue from the previous growing season's proso millet (*Panicum miliaceum*) crop (Nielsen et al., 2015), an observation that is consistent with other studies in the Great Plains (Nielsen and Vigil, 2005; Burgess et al., 2014; Holman et al., 2012 and Holman et al., 2018). Similar to findings by Nielsen et al. (2015), cover crop water use in the current study was greater than evaporative water losses in NT with wheat residue and bare fallow conditions resulting from CT. Klocke et al. (2009) determined that 100 % cover with corn residue was required for significant reductions in soil evaporation compared to bare fallow.

In 2014, there were no significant differences among treatments 3 DAP (Fig. 2). Comparable to observations in 2013, cover crop treatments showed significantly lower stored soil water 58 DAP (Fig. 2). Three weeks after seeding cover crops, cover crop treatments had lower soil water than NT without cover crops (NT and NTI). Between readings 21 and 39 DAP, 117 mm precipitation was recorded, which led to variable recharge of soil water among treatments. However, cover crop treatments, except for NTCI, had lower stored soil water than non-cover crop treatments due to the timing of the rainfall corresponding with a period of rapid growth and development of the cover crops. At cover crop termination, stored soil water was at least 26 % lower due to cover crop treatments than non-cover crop treatments (Fig. 2).

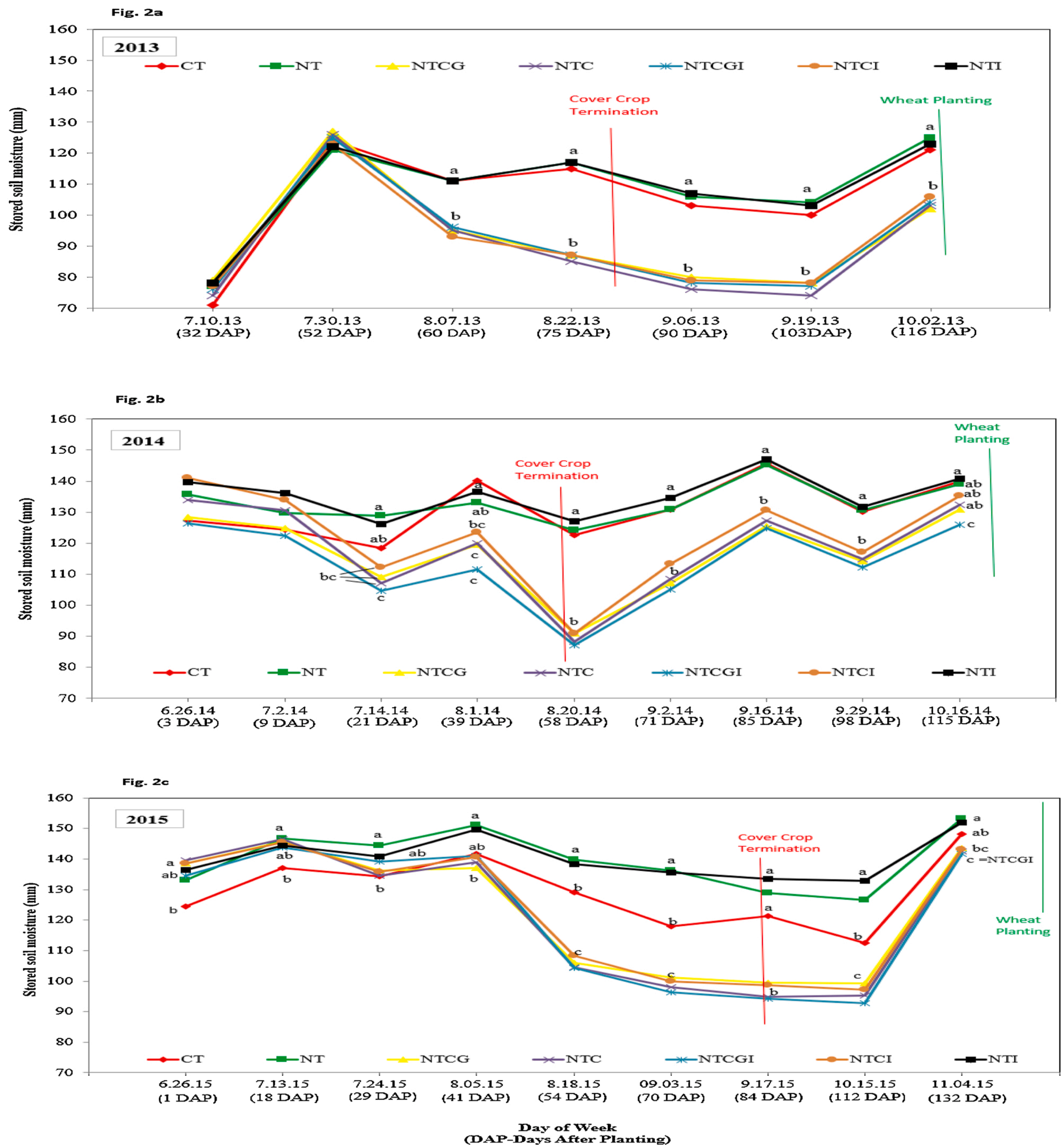

Fig. 2. Stored soil water at 0-60 cm depth during 2013, 2014 and 2015 cover crop growing season near Vernon, TX. Different letters within day after planting indicate significant differences at P < 0.05. CT, conventional-till; NT, no-till; C, cover crop; G, graze; I, intercropping.

At the time of cover crop planting in 2015, there were no significant differences in stored soil water between cover crop treatments and NT treatments without a cover crop (Fig. 2), when 51 mm precipitation was received just prior to planting. Except for NTCGI, all other cover crop treatments resulted in significantly higher soil water than CT at cover crop planting. Tillage also affected stored soil water 54–70 DAP, when it was lower for CT than NT and NTI (Fig. 2). Tillage has been shown to reduce soil aggregation and infiltration rates (Elliott et al., 1987). Surface soil sealing, degraded soil structure and mesoporosity (soil pores with <60 μm diameter) have also been reported in tilled soil (Fabrizzi et al., 2005; Elliott, 1986). Thus, potential benefits of NT for 12 years may have been lost after three years of tillage in our study. Stored soil water was significantly lower in cover crops than all other treatments beginning at 54 DAP, with this trend continuing through termination. Soil water measurements collected immediately after cover crop termination showed that cover crops reduced stored soil water by at least 22 % compared to NT and NTI. Although not significantly different, CT resulted in 12 % lower soil water than NT and NTI at cover crop termination (Fig. 2).

3.4. Post termination soil water

Soil water use by cover crops was expected; however, it is also important to evaluate the subsequent impact of cover crops on soil water storage after termination. Soil water use is a top concern in environments of the US Great Plains, but recovery of soil moisture in the system prior to cash crop planting is critical. Unger and Vigil (1998) concluded that timely termination of cover crops is essential in semi-arid environments due to soil water use. As previously discussed, cover crop treatments resulted in lower stored soil water at time of termination. After cover crop termination, the study site received a total precipitation of 68 mm in 2013, 118 mm in 2014, and 110 mm in 2015 prior to winter wheat planting.

The first year of the study received the least amount of rainfall between termination (8.30.13) and winter wheat planting (10.03.13). The first year also had the least amount of time between termination and cash crop planting and thus a shorter recovery time. Only 68 mm precipitation (Table 3) was recorded in September post cover crop termination with 62 mm of it in a couple days; 40 mm (9.20.13) and 22 mm (9.28.13). This therefore left a large soil moisture deficit which was carried over into the wheat period. Blanco-Canqui et al. (2012a) acknowledged that cover crops can reduce the amount of available water to the following crops but reiterated their capacity to increase water capture and curb runoff. The increase in stored soil water between termination timing and cash wheat planting ranged from 22–28 mm for cover crop treatments compared to 15–19 mm for non-cover crop treatments (Fig. 3).

Years 2014 and 2015 of the study differed in recorded precipitation (Table 3) but resulted in similar soil moisture recharge among treatments (Figs. 2b, c & 3). Cover crop treatments resulted in a significantly greater increase in stored soil water than non-cover crop treatments in both 2014 and 2015. In 2014, soil water did not differ between cover crop treatments and CT or NT just prior to cash crop planting (Figs. 2b & 3). Stored soil water increased by 39–44 mm for cover crop treatments in 2014 after 118 mm of precipitation that occurred between cover crop termination (8.18.14) and wheat planting (10.20.14). This positive change in stored soil water was two to four times greater for cover crop treatments compared to fallow treatments, indicating that stored soil water levels recovered from the greater amounts used by cover crops during the summer. In 2015, the stored soil water increase for cover crop treatments was like that observed in 2014, with 110 mm precipitation recorded between termination (9.15.15) and planting (11.09.15). Precipitation patterns differed between years, with the heaviest storm events occurring on August 28th (33 mm) and September 12th (29 mm) for 2014 compared to two similar events that produced 56 and 40 mm on October 22nd and 30th for 2015, respectively. The final year of the study showed significantly higher soil water increases, with the recharge of stored soil water in cover crop treatments being at least 46 % greater than in non-cover crop treatments from termination to winter wheat seeding, indicating a positive cumulative effect of cover crops on soil moisture dynamics (Fig. 3). Potential mechanisms of this cumulative effect are indicated by Basche and DeLonge (2017), who showed that adoption of cover crops for more than 10-year improved soil hydrological properties such as total porosity and water retained at field capacity.

Although cover crops resulted in significantly lower soil water at termination, infiltration and retention of precipitation post-termination was enhanced with cover crops. In Indiana and Iowa during a severe drought in 2012, a rye cover crop reportedly increased stored soil water for the following corn crop (Daigh et al., 2014). A long-term study in China comparing CT without surface residues to NT with surface residues showed how the latter improved soil physical properties and soil water transmission in a monoculture winter wheat system (He et al., 2009). Nielsen et al. (2016) reported greater precipitation storage efficiency where cover crops were present compared with a fallow treatment of pearl millet (*Pennisetum glaucum L)* residue. Specifically, they reported precipitation storage efficiency between cover crop termination and wheat planting averaged 29.8 % for five evaluated cover crop treatments compared to 10.4 % for a proso millet residue fallow treatment. The available water at wheat planting was always numerically greater for the fallow treatment compared with the cover crop treatment, but only significantly so for five of the eight data sets (Nielsen et al., 2016).

The addition of grazing of cover crops and intercropping in wheat had no effect on stored soil water compared to other cover crop treatments (Fig. 2–3). DeLaune et al. (2013) reported that graze out systems increased runoff by as much as 1.5-fold and decreased infiltration by as much as 1.3-fold compared to the graze/grain wheat system. However, a short-duration high density flash grazing did not impact soil water storage. Nielsen et al. (2015, 2016) proposed that grazing of cover crops may be considered to provide an economic benefit of cover crops, although removal of biomass would have to be carefully considered in light of the increased potential for soil loss by wind erosion. Although grazing resulted in significant removal of cover crops biomass, no significant negative effects were observed from this practice regarding soil water. Holman et al. (2018) concluded that the best way for producers to

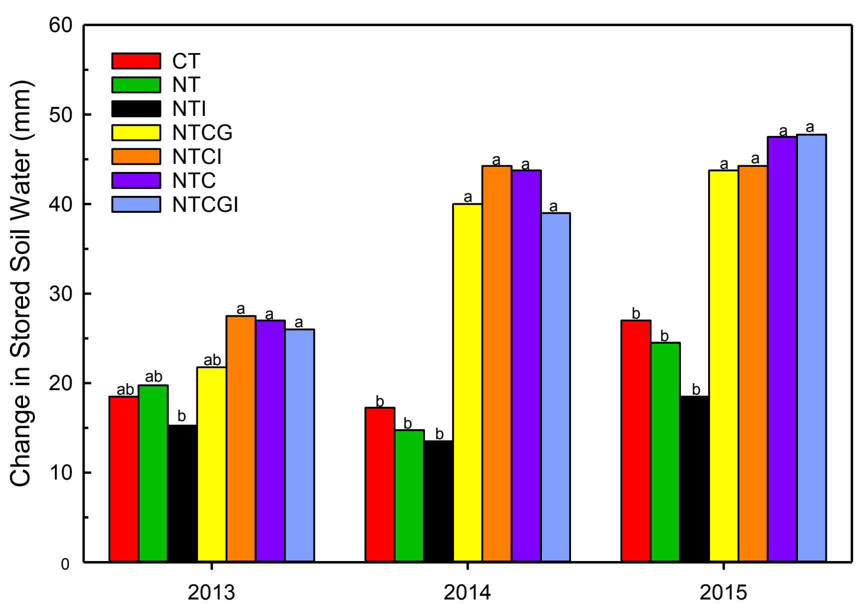

Fig. 3. Change in stored soil water from time of cover crop termination to time of wheat planting at 0-60 cm depth during the study period 2013-2015 near Vernon, TX. Different letters within each year indicate significant differences at P < 0.05. CT, conventional-till; NT, no-till; C, cover crop; G, graze; I, intercropping.

potentially improve soil properties over time and be profitable is to grow a forage crop and not a summer cover crop in the semi-arid Central Great Plains region. In the scenario evaluated in our study, factors such as infrastructure and logistics, would have to be considered to successfully implement flash grazing.

4. Conclusion

Cover crops grown during the summer fallow period in continuous wheat systems produced biomass throughout the study period, even during the drought period, although some species in the mix failed each season. Grazing cover crops at a high density over a short duration resulted in significant herbage mass removal. However, grazing cover crops did not affect stored soil water compared to ungrazed treatments. Intercropping radishes and turnips with wheat did not affect stored soil moisture during the off-season as establishment was poor. Stored soil water was significantly reduced by cover crops starting within 60 DAP and continuing through termination of the cover crop. Meanwhile, after three years of being removed from NT management, CT plots were beginning to show the negative effects and disruptive consequences of tillage to the soil ecosystem and adverse impact on water infiltration and holding capacity. The post-termination increase in stored soil water was greater in the final two years of the study than it was in the first year, which had the shortest recovery time between cover crop termination and wheat planting. At the time of planting wheat, NT treatments without cover crops had higher stored soil water compared to cover crop treatments, although this was only highly significant in the first year of investigation which experienced the lowest rainfall. Hence, cover crop management in water-limited environments should be carefully managed and longer recovery times between cover crop termination and crop planting may be required to allow soil moisture recharge for a successful following crop under dryland conditions. Overall, the results of this three-year study period indicate the potential for cover crops to recover the soil water they used during their peak growth. Although it was not always sufficient to fully recover soil water to levels seen in NT without cover crops, these results provide insight that could be used to successfully implement cover crops into wheat systems while mitigating their negative effects on soil water in the Texas Rolling Plains region.

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.

Acknowledgement

This research was funded by Texas USDA-NRCS CIG Program. Grant ID#69-7442-13-980.

References

Balkcom, K., Schomberg, H., Reeves, W., Clark, A., Baumhardt, L., Collins, H., Delgado, J., Duiker, S., Kaspar, T., Mitchell, J., 2007. Managing cover crops in conservation tillage systems. Managing Cover Crops Profitably, pp. 44–61.
Basche, A., DeLonge, M., 2017. The impact of continuous living cover on soil hydrologic properties: a meta-analysis. Soil Sci. Soc. Am. J. 81, 1179–1190.
Baughman, T.A., Keeling, J.W., Boman, R.K., 2007. On-farm Conservation Tillage Programs to Increase Dryland Cotton Profitability. Project 05-643TX. Final Report to Cotton Inc., 25 January 2007.
Blanco-Canqui, H., Mikha, M.M., Presley, D.R., Claassen, M.M., 2011. Addition of cover crops enhances no-till potential for improving soil physical properties. Soil Sci. Soc. Am. J. 75 (4), 1471–1482.
Blanco-Canqui, H., Claassen, M.M., Presley, D.R., 2012a. Summer cover crops fix nitrogen, increase crop yield, and improve soil–crop relationships. Agron. J. 104 (1), 137–147.
Blanco-Canqui, H., Claassen, M.M., Presley, D.R., 2012b. Summer cover crops fix nitrogen, increase crop yield, and improve soil–crop relationships. Agron. J. 104, 137–147. https://doi.org/10.2134/agronj2011.0240.
Blanco-Canqui, H., Shapiro, C.A., Wortmann, C.S., Drijber, R.A., Mamo, M., Shaver, T.M., Ferguson, R.B., 2013a. Soil organic carbon: the value to soil properties. J. Soil Water Conserv. 68, 129A–134A. https://doi.org/10.2489/jswc.68.5.129A.
Blanco-Canqui, H., Holman, J.D., Schlegel, A.J., Tatarko, J., Shaver, T., 2013b. Replacing fallow with cover crops in a semiarid soil: effects on soil properties. Soil Sci. Soc. Am. J. 77, 1026–1034. https://doi.org/10.2136/sssaj2013.01.0006.
Blanco-Canqui, H., Shaver, T.M., Lindquist, J.L., Shapiro, C.A., Elmore, R.W., Francis, C. A., Hergert, G.W., 2015. Cover crops and ecosystem services: insights from studies in temperate soils. Agron. J. 107, 2449–2474. https://doi.org/10.2134/agronj15.0086.
Bond, J.J., Willis, W.O., 1969. Soil water evaporation: surface residue rate and placement effects 1. Soil Sci. Soc. Am. J. 33 (3), 445–448.
Burgess, M., Miller, P., Jones, C., Bekkerman, A., 2014. Tillage of cover crops affects soil water, nitrogen, and wheat yield components. Agron. J. 106 (4), 1497–1508.
Chen, G., Weil, R.R., 2010. Penetration of cover crop roots through compacted soils. Plant Soil 331 (1-2), 31–43.
Cresswell, H.P., Kirkegaard, J.A., 1995. Subsoil amelioration by plant-roots-the process and the evidence. Arid. Soil Res. Rehabil. 33 (2), 221–239.
Dabney, S.M., Delgado, J.A., Reeves, D.W., 2001. Using winter cover crops to improve soil and water quality. Comm. Soil Sci. Plant Anal. 32 (7-8), 1221–1250.
Daigh, A.L., Helmers, M.J., Kladivko, E., Zhou, X., Goeken, R., Cavdini, J., Barker, D., Sawyer, J., 2014. Soil water during the drought of 2012 as affected by rye cover crops in fields in Iowa and Indiana. J. Soil Water Conser. 69 (6), 564–573.
DeLaune, P.B., Sij, J.W., 2012. Impact of tillage on runoff in long term no-till wheat systems. Soil Till. Res. 124, 32–35.
DeLaune, P.B., Sij, J.W., Krutz, L.J., 2013. Impact of soil aeration on runoff characteristics in dual-purpose no-till wheat systems. J. Soil Water Conserv. 68 (4), 315–324.
Elliott, E.T., 1986. Aggregate structure and carbon, nitrogen, and phosphorus in native and cultivated soils. Soil Sci. Soc. Am. J. 50 (3), 627–633.
Elliott, L.F., Papendick, R.I., Bezdicek, D.F., 1987. Cropping Practices Using Legumes With Conservation Tillage and Soil Benefits.
Evett, S.R., 2003. Soil water measurement by neutron thermalization. Encyclopedia of Water Science, pp. 889–893.
Evett, S.R., 2008. Neutron moisture meters. In: Evett, S.R., Heng, L.K., Moutonnet, P., Nguyen, M.L. (Eds.), Field Estimation of Soil Water Content: A Practical Guide to Methods, Instrumentation, and Sensor Technology. IAEA-TCS-30. International Atomic Energy Agency, Vienna, Austria, pp. 39–54.
Fabrizzi, K.P., Garcıa, F.O., Costa, J.L., Picone, L.I., 2005. Soil water dynamics, physical properties and corn and wheat responses to minimum and no-tillage systems in the southern Pampas of Argentina. Soil Till. Res. 81 (1), 57–69.
Felton, W.L., Freebairn, D.M., Fettell, N.A., Thomas, J.B., 1987. Crop residue management. In: Cornish, P.S., PratJey, J.E. (Eds.), Tillage: New Directions in Australian Agriculture. Inkata Press, Melbourne, Australia, pp. 171–193.
He, P., Li, S., Jin, J., Wang, H., Li, C., Wang, Y., Cui, R., 2009. Performance of an optimized nutrient management system for double-cropped wheat-maize rotations in North-Central China. Agron. J. 101 (6), 1489–1496.
Holman, J., Dumler, T., Roberts, T., Maxwell, S., 2012. Fallow Replacement Crop Effects of Wheat Yield. Rep. Progr. 1070. Kansas State Univ. Coop. Ext. Serv., Manhattan.
Holman, J.D., Arnet, K., Dille, J., Maxwell, S., Obour, A., Roberts, T., Roozeboom, K., Schlegel, A., 2018. Can cover or forage crops replace fallow in the semiarid Central Great Plains? Crop Sci. 58 (2), 932–944.
Kahimba, F.C., Sri Ranjan, R., Froese, J., Entz, M., Nason, R., 2008. Cover crop effects on infiltration, soil temperature and soil moisture distribution in the Canadian prairies. Appl. Eng. Agric. 24, 321–333. https://doi.org/10.13031/2013.24502.
Keisling, T.C., Scott, H.D., Waddle, B.A., Williams, W., Frans, R.E., 1994. Winter cover crops influence on cotton yield and selected soil properties. Comm. Soil Sci. Plant Anal. 25 (19-20), 3087–3100.
Klocke, N.L., Currie, R.S., Aiken, R.M., 2009. Soil water evaporation and crop residues. Trans. ASABE 52 (1), 103–110.
Krutz, L.J., Locke, M.A., Steinriede, R.W., 2009. Interactions of tillage and cover crop on water, sediment, and pre-emergence herbicide loss in glyphosate-resistant cotton: Implications for the control of glyphosate-resistant weed biotypes. J. Environ. Qual. 38, 1240–1247. https://doi.org/10.2134/jeq2008.0342.
McGee, E.A., Peterson, G.A., Westfall, D.G., 1997. Water storage efficiency in no-till dryland cropping systems. J. Soil Water Conserv. 52 (2), 131–136.
Nielsen, D.C., Vigil, M.F., 2005. Legume green fallow effect on soil water content at wheat planting and wheat yield. Agron. J. 97 (3), 684–689.
Nielsen, D.C., Lyon, D.J., Hergert, G.W., Higgins, R.K., Calderón, F.J., Vigil, M.F., 2015. Cover crop mixtures do not use water differently than single-species plantings. Agron. J. 107 (3), 1025–1038.
Nielsen, D.C., Lyon, D.J., Higgins, R.K., Hergert, G.W., Holman, J.D., Vigil, M.F., 2016. Cover crop effect on subsequent wheat yield in the Central Great Plains. Agron. J. 108, 243–256.
Norton, J.B., 2007. No-till grain production in Wyoming: status and potential. In: Proceedings Vol. 7: Western Nutrient Management Conference. Salt Lake City, UT: University of Utah, pp. 182–187.
NRCS, 2011. Conservation Practice Standard: Cover Crop, Code 340. NRCS National Handbook of Conservation Practices, p. 3 pg (accessed 23 Jan.2016). http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1046845.pdf.
Olson, K., Ebelhar, S.A., Lang, J.M., 2014. Long-term effects of cover crops on crop yields, soil organic carbon stocks and sequestration. Open J. Soil Sci. 4, 284–292. https://doi.org/10.4236/ojss.2014.48030.
Phillips, R.E., 1984. Soil moisture. In: Phillips, R.E., Phillips, S.H. (Eds.), Notillage Agriculture: Principles and Practices. Van Nostrand Reinhold Co., New York, pp. 66–86.

Prihar, S.S., Singh, Y., Singh, R., Singh, P., 1975. Effect of N fertilization on yield and water use efficiency of dryland winter wheat as affected by stored water and rainfall. Agron. J. 67, 599–603.
Rankoth, L.M., Udawatta, R.P., Gantzer, C.J., Jose, S., Nelson, K.A., 2019. Cover crop effects on Corn Plant Sap Flow Rates and soil water dynamics. Crop Sci. 59 (5), 2227–2236.
Rawls, W.J., Pachepsky, Y.A., Ritchie, J.C., Sobecki, T.M., Bloodworth, H., 2003. Effect of soil organic carbon on soil water retention. Geoderma 116, 61–76. https://doi.org/10.1016/S0016-7061(03)00094-6.
Sanderson, M., Johnson, H., Hendrickson, J., 2018. Cover crop mixtures grown for annual forage in a semi-arid environment. Agron. J. 110 (2), 525–534.
SAS Institute, 2017. SAS/STAT Software–the GLIMMIX Procedure. SAS Institute, Cary, NC. In: https://support.sas.com/rnd/app/stat/procedures/glimmix.html.
Sij, J., Ott, J., Olson, B., Baughman, T., Bordovsky, D., 2003. Dryland cropping systems to enhance soil moisture capture and water-use efficiency in cotton. In: Proc. 2003 Beltwide Cotton Conference. Nashville, TN. 6-10 Jan. 2003. [CD].
Smith, M.S., Frye, W.W., Varco, J.J., 1987. Legume winter cover crops. In: Stewart, B.A. (Ed.), Advances in Soil Science, Vol. 7. Springer, New York, pp. 95–139. https://doi.org/10.1007/978-1-4612-4790-6_3.
Soon, Y.K., Malhi, S.S., Wang, Z.H., Brandt, S., Schoenau, J.J., 2008. Effect of seasonal rainfall, N fertilizer and tillage on N utilization by dryland wheat in a semi-arid environment. Nutr. Cycl. Agroecosyst. 82 (2), 149–160.
Steele, M.K., Coale, F.J., Hill, R.L., 2012. Winter annual cover crop impacts on no-till soil physical properties and organic matter. Soil Sci. Soc. Am. J. 76, 2164–2173. https://doi.org/10.2136/sssaj2012.0008.
Steenwerth, K.L., Belina, K.M., 2008. Cover crops and cultivation: impacts on soil N dynamics and microbiological function in a Mediterranean vineyard agroecosystem. Agric., Ecosyst. Environ., Appl. Soil Ecol. 40, 370–380. https://doi.org/10.1016/j.apsoil.2008.06.004.
Teasdale, J.R., Mohler, C.L., 1993. Light transmittance, soil temperature, and soil moisture under residue of hairy vetch and rye. Agron. J. 85 (3), 673–680.
U.S. climate data, 2017. Temperature – Precipitation – Sunshine – Snowfall. Programming & Design by Your Weather Service. World Climate. Retrieved from. http://www.usclimatedata.com/climate/vernon/texas/united-states/ustx1404.
Unger, P.W., Vigil, M.F., 1998. Cover crop effects on soil water relationships. J. Soil Water Conserv. 53, 200–207.