THE IMPACTS ON DOUBLE CROPPING IN A WINTER WHEAT SYSTEM ON SOIL HEALTH AND CROP YIELDS

A Thesis

by

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ABSTRACT

Double cropping can increase farm profit and food availability, and may improve soil function by sustaining year-round vegetation and building soil organic matter. However, replacing summer fallow with warm-season double crops in an annual winter wheat cropping system may not sustain subsequent wheat yields due to increased water use with cropping intensification. Reducing tillage may abate soil water deficits generated by double cropping and could allow persistence in water limited environments. Our objectives were to evaluate cropping system and reduced tillage effects on soil physical properties and soil moisture, and to quantify these cropping systems using crop yields and herbage mass production. Following winter wheat harvest, a summer treatment of fallow, sesame, grain sorghum, cowpea, and a nine-species cover crop mix were evaluated under three tillage treatments (conventional, strip-till, and no-till). Study locations included Beeville, Thrall, and Lubbock and was implemented in fall 2015. At Lubbock, soil water deficits created by sesame and sorghum at the time of wheat planting were shown to decrease subsequent wheat yields by 12% and 45%, respectively, compared to fallow. Double crops impacted soil water during the growing season, and success of subsequent wheat crop was dependent on soil water profile recovery via precipitation/irrigation in time for wheat planting. Soil water differences became less evident as the wheat growing season progressed, and Thrall's subsoil was much sooner to recover than Lubbock. Tillage made less impact on crop yields and biomass production in Thrall and Beeville in relation to soil moisture, but it was evident that reduced tillage may be imperative in semi-arid regions such as Lubbock, as wheat yields were significantly affected by water deficits at time of planting. At Thrall, conventionally tilled plots averaged 42% for wet aggregate stability, this was 10% greater than minimally tilled plots’ average. Lubbock averaged 10% stability for wet aggregates, and differences were not observed between crop and tillage plots for simulated runoff events. As residue accumulation and organic matter increase from cropping intensification and reduced tillage, soil physical properties are likely to change over time.

DEDICATION

For the three most influential people in my life—my father Joel, my brother Ryan, and best friend Mikey.

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1. INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

Soil health is defined as the continued capacity of the soil to function as a living ecosystem and enhance water and air quality conditions while sustaining plant, animal and human productivity (Doran and Zeiss, 2000). The degradation of soil health can partly be attributed to decades of traditional farming practices, including mono-cropping, intensive tillage, and a heavy dependence on synthetic fertilizers, herbicides and pesticides (Gold, 1999). Conservation measures such as reduced tillage, diverse cropping rotations, and cover cropping all have the potential to remediate the health of a farmer’s soil by decreasing bulk density and erosion rate, as well as increasing/enhancing available water holding capacity, infiltration rate, aggregate stability, organic matter (OM), and microbial activity (Stubbs et al., 2004; Blanco-Canqui et al., 2013; Soil Health Institute, 2016). Reducing tillage has positive impacts on soil health by retarding soil erosion, carbon (C) loss, and by increasing soil moisture (Blanco-Canqui et al., 2004). However, in semi-arid regions, reduced tillage alone cannot combat soil erosion from water and especially wind (Hall et al., 1979). Implementation and management of ground cover, residue, and formed structures that control runoff should be coupled with reduced tillage (Hall et al., 1979). Adding cover crops to a system may break pest and diseases cycles, and enhance nutrient cycling by feeding soil microbial communities which facilitate that process (Grünwald et al., 2000). Double cropping may have similar benefits to cover cropping, and double cropping has a greater potential to increase annual farm revenue compared to cover cropping since generally, cover cropping is not harvested and sold.

In 2015, wheat was the most planted crop in Texas with 2.5 million hectares and ranks third in the United States for area planted (USDA-NASS, 2016). Winter wheat is a staple cash crop in Texas and throughout the United States, but often times fields are left fallow during the summer months until the next wheat planting, leaving the soil without cover and increasing its susceptibility to erosion and evaporative water loss (Massee and Cary; 1978). Planting a summer double crop after wheat harvest is not a common practice in the United States (Borchers et al., 2014). Currently, about 2% of United States farmland is double cropped. The hesitation could be tied to the lack of regional knowledge on the relative effects of these practices (Borchers et al., 2014). Currently, there is limited information on how the combined effects of conservation practices (i.e. conservation tillage and increased crop diversity) impact soil properties, wheat productivity, and profitability in this region.

This study investigated the relative impacts of decreasing tillage and increasing crop diversity and intensification within an annually planted wheat system. Cover cropping and double cropping managed with conventional, strip-, and no-tillage, were compared to the traditional summer fallow, conventionally tilled system. Since Texas is a sizable, and very ecologically diverse state with varying amounts of precipitation and differing soil types, this study was conducted in three ecoregions: Texas High Plains, Blackland Prairie Region, and the South Texas Plains.

1.2 Literature Review

1.2.1 Importance of Wheat

Wheat (*Triticum* spp.) is one of the primary commodity crops in the world, and is grown on more land than any other commercial crop. Wheat ranks third in the United States behind corn and soybeans for production acreage (FAO, 2016). The Triticum genus can be broken up into three primary species of domesticated wheat: *aestivum*, *durum*, and *spelta*. In 2015, 16 million hectares were planted in the United States, 2.5 million hectares were planted in Texas (USDA-NASS, 2015). Texas plants the third most wheat in the nation behind Kansas, and is ranked 5th in the United States for wheat production (USDA-NASS, 2015). In 2016, global production was approximated at 749 million metric tons, up 13 million metric tons from the previous year (FAO, 2016). The latest prices for total export came in at $49.4 billion USD, 21% of that coming from the United States (FAO, 2013).

Whole grain is defined as grain products that have relative proportions of grain, endosperm, germ and bran present (AACC, 1999). The nutritive value of grain increases with minimal refining, which produces whole grains that can contain ~80% more dietary fiber (Okarter and Liu, 2010). Beyond a greater supply of fiber in whole grain products, there are other nutritive components such as high levels of B vitamins (thiamin, niacin, riboflavin, and pantothenic acid) and minerals (Ca, Mg, K, P, Na and Fe) as well as high concentrations of amino acids and phytochemicals (Slavin, 2004). Out of the numerous whole grains, whole grain wheat specifically contains about 8-15% protein, ~12.7% fiber and 60-70% starch, and is also a source for iron and zinc (Shewry, 2009; Jonnalagadda et al., 2011). Consumption of whole grain based products are associated with reduced risk of coronary heart disease, cancer, type 2 diabetes, and obesity among other ailments (Farvid et al., 2016). Specifically, a study of breast cancer patients from 1991 to 2016 reported that women who incorporated greater amounts of whole grains into their diets had a statistically significant lower rate of premenopausal breast cancer (Farvid et al., 2016).

Wheat is also an important forage crop. Approximately 40-45% of the 2.47 million hectares of wheat in Texas in 2015 were grazed by livestock (USDA-NASS, 2015). Wheat herbage mass may contain more than 15% crude protein. Wheat forage is generally planted 4-6 weeks earlier than that grown for grain, and is grazed during the fall and winter months. Winter wheat has the potential to be a reliable dual-purpose crop for grazing and grain production. It has been shown that by dual-purposing winter wheat, there can be little to no impact on grain yields (Redmon et al., 1995; Edwards et al., 2011). In the southern Great Plains of Oklahoma, Edwards et al. (2011) investigated 18 to 19 cultivars of commercially released hard red winter wheat per year for dual-purposing from 1991 to 2010. Although dual-purpose management was observed to reduced grain yield by 14% compared to non-grazed management, in environments where yields did not exceed 1100 kg ha^{-1}, dual-purposing was shown to increase wheat grain yield (Edwards et al., 2011).

Another valuable incentive for planting wheat is the option of double cropping with warm-season annuals to potentially increase productivity and economic stability for the farmer. According to Alexandratos and Bruinsma (2012), total production of cereal crops will need to increase 45.5% by year 2050, which is roughly 0.9% per year, in order to feed an estimated nine billion people. Issues such as soil decline, salinization of irrigated land, and competition for land, reduce the chance of global food production meeting population demands in the future.

1.2.2 Double Cropping

The growing demand for food and feed brought on by the rapidly increasing world population and reduced number of farms and farmland, in addition to enhancing overall farm production and improved profits are motivations to focus on sustainable intensification of farming systems. Between 2015 and 2016, the number of farms in the United States decreased by 8,000, and the number of hectares owned decreased by 400,000 (USDA, 2017). A possible solution to the increased demand for crop production on less acreage could be the practice of double cropping. With continual cropping also comes an increased water demand for the subsequent crop. Continual cropping could provide an opportunity for farmers to not only increase farm profits and food availability, but could also lend itself to numerous soil health benefits if adequate moisture is available.

Double cropping is the agricultural practice of harvesting two or more successive crops on the same plot of land, in the same year. A USDA national survey evaluating double-cropping practices from 1999 to 2012, indicated that double cropping occurred on only 2.0% of all cropland, and similarly, only 2.1% of all cropland in the Southern Plains region of the United States was double cropped (Borchers et al., 2014). There has been little change in double crop acres between 1999 and 2012; this lack of change could possibly be linked to environmental and budgetary reasons (Borchers et al., 2014). Some of the main environmental constraints came from regional variation in length of growing season and issues concerning water availability and scarcity (Borchers et al., 2014). Some of the main economic reasons for lack in double crop planting comes from difficulty with insurance plans and obtaining coverage for the second crop, more expensive premiums, and commodity prices (Borchers et al., 2014). Commodity prices impact double cropping, since low prices can result in less crops planted due to potential for increased fertilizer, seed, and fuel costs.

According to National Agricultural Statistics between 1999 and 2012, an average of 53% of the total double-cropped land included soybeans (*Glycine max* L.) (Borchers et al., 2014). Soybean after wheat rotation is the most common practice, with winter wheat being used as the colder season rotation in southern states 84% of the time (Borchers et al., 2014). Winter wheat is the most common winter rotation crop in the southern United States, and aside from soybean, there are few summer rotation crops that have been evaluated (Borchers et al., 2014).

Options for warm-season crops within Texas differ from other parts of the United States. Choice in crop rotation should be based on growing conditions as well as market prices. Since winter wheat is generally harvested in May or June in Texas, summer crops that can get a full life cycle before wheat planting in November are best suited for this region of the country. A list of potential warm-season rotational crops for double cropping with winter wheat in Texas includes, but is not limited to, corn (*Zea mays* L.), cowpea (*Vigna unguiculata* L.), cotton (*Gossypium hirsutum* L.), guar (*Cyamopsis tetragonoloba* L.), sesame (*Sesamum indicum* L.), sorghum (*Sorghum bicolor* L.), or sunflower (*Helianthus annuus* L.). This experiment focuses on grain sorghum, sesame, cowpeas, and a warm-season cover crop mix.

1.2.2.1 Grain Sorghum.

Grain sorghum (*Sorghum bicolor* L.) is the third largest cereal grain in the United States, and fifth in the world (FAO, 2016). In the United States, grain sorghum's primary use is for livestock feed, but globally, it is used as grain for human and animal consumption as well as ethanol production. Grain sorghum can be grown under irrigation and also in dryland environments—a minimum of ~450.0 mm of water is needed during the growing season (FAO, 2018). Not only is grain sorghum drought tolerant, it is also tolerant to wet soils and flooding (Carter et al., 1989). Unger and Baumhardt's (1999) 58-year dryland sorghum study in the southern Great Plains region of Texas, determined that yield potential in a dryland setting was largely dependent on soil water content at the time of planting. Hybrid varieties are to be chosen based on yield potential parameters defined by the amount of degree days a region can offer (FAO, 2018). Average July temperatures of at least 27° C and 32° C day-time temperatures are needed for maximum photosynthesis by sorghum (Carter et al., 1989). A four year long-term crop rotation study in Tribune, Kansas found that grain sorghum yields, herbage mass, water productivity, and soil water, were all greater following winter wheat compared to following sorghum (Schlegel et al., 2017).

1.2.2.2 Sesame

Sesame (*Sesamum indicum* L.) is a heat tolerant crop grown in arid and semi-arid regions of the south, southeastern, and southwestern United States where the soils are well-drained (Sheahan, 2014b). The market for sesame import is exceeding the exportation market, leaving room for industry growth and potential to compete in the global market (Sheahan, 2014b). In the United States, 85% of sesame is grown under dryland conditions (Langham et al., 2008). It is grown primarily for oil production which is used in cooking oils, paints, soaps, cosmetics, insecticides, animal protein meal, and many other products (Myers, 2002). The whole seed is also used for food products. Sesame is highly drought, heat, insect, and disease tolerant and will cycle into termination and self-defoliation after heat units have been accumulated and moisture and fertility are spent (Langham et al., 2008). In locations such as the Rolling Plains of Texas and central Oklahoma, planting in the mid-May and up until mid-June generally leads to crop termination through fall freezes which promote even dry down (Langham et al., 2008). Sesaco Corporation (Austin, TX) has bred several non-dehiscent varieties that are shatter resistant for United States production, so time-to-harvest can be more easily managed and mechanized. An herbicidal harvest-aid could be an option for farmers in more southern regions which have later freeze potential. Sesame is recommended by Sesaco as a second crop after wheat in irrigated or high rainfall areas, reporting yields of up to 896 kg ha^{-1} in the San Angelo region of Texas (Langham et al., 2008). Planting sesame following a wheat harvest could provide additional income and soil benefits to the subsequent wheat crop from further OM inputs as well as remediating compaction with their taproots (Langham et al., 2008).

1.2.2.3 Cowpea

Cowpeas (*Vigna unguiculata* L.) are grown mainly in the southern regions of the United States as a crop for forage, green manure, dry or pulse. Cowpeas are grown in the sub-tropics of Asia and Oceania, the Middle East, southern Europe, Africa, the Southern U.S., and Central and South America (Singh, 2014). Cowpea is a drought and heat tolerant crop, with a total water requirement of about 200.0 to 350.0 mm (Singh, 2014). Cowpea is a legume, and associated rhizobium bacteria convert atmospheric nitrogen (N_2) into a plant available nitrogen (N). Cowpeas can be credited to adding up to 160 kg ha^{-1} of N to the soil in about 60 days, leaving behind about 40 kg ha^{-1} N to the subsequent crop like winter wheat (Singh, 2014). A 2010 study in Pakistan credits a legume-wheat rotation with increasing subsequent wheat yields by 18% compared to a sorghum-wheat rotation, this being largely explained by additional NO_3-N in the system (Hayat and Ali, 2010). The world average is about 500 kg ha^{-1} for cowpea grain yield but can range from 2000 to 3000 kg ha^{-1} and 2000 to 5000 kg ha^{-1} of forage with a mono-crop if grown in ideal conditions using a well-suited variety (Singh, 2014).

1.2.2.4 Cover Crop Mixes

Cover crops are grown in rotation with cash crops to improve soil quality by promoting nutrient cycling, reduced erosion, and enhanced soil structure. Green manure is often used interchangeably with the term cover crops, but the definitions are best thought of from the farmer’s perspective (Magdoff and Van Es, 2009). A green manure crop is usually grown and then plowed into the soil for the purpose of improving the soil by ways of soil organic matter (OM) and increased N availability, while cover crops are often grown for the purpose of ground cover for erosion prevention (Rogers and Giddens, 1957; Magdoff and Van Es, 2009).

The two mechanisms for soil rehabilitation would benefit more if combined, by creating a cover crop mix that would facilitate both advantages. Diverse rooting systems that can scavenge the soil for residual nutrients, especially easily leachable nitrates at varying depths, create a vast network of soil miners (Thorup-Kristensen, 2001). It is commonly hypothesized that increasing biological diversity promotes agroecosystem services that provide critical soil health inputs—such as soil quality, water-holding capacity, C sequestration, and pest control (Malézieux et al., 2009; Kremen and Miles, 2012; USDA-NRCS, 2014; Finney et al., 2017). A two year study performed in Pennsylvania by Finny et al. (2017) found that by combining diverse species mixtures based on differing functional groups (growth rates, C:N ratio), resulted in better performance compared to the monoculture cover crops, as well as increased the synergistic benefits of multiple agroecosystem services such as, biomass production, weed suppression, N retention compared to the no-cover crop control. Results following one of the studies facilitated by the USDA-NRCS Plant Materials Program (2014) in California found that after two years, there were no significant differences in improvement on soil health (bulk density, soil moisture, soil resistance, and total N) between two, four, and six component mixtures. However, canopy cover and herbage mass production were greatest with the four component mixtures compared to the two and six species mixes for all seeding rates (USDA-NRCS, 2014). Numerous studies facilitated by the USDA-NRCS Plant Materials Center across the United States have evaluated the effects of cropping system diversity with the use of cover crop mixes, and results differ widely from study to study. Still, the USDA-NRCS recommends the use of mixes over mono-culture covers (USDA-NRCS, 2014; USDA-NRCS, 2015c; USDA-NRCS, 2015d; USDA-NRCS, 2016b; USDA-NRCS, 2018).

Selecting cover crop species based on functionality can have large impacts on agroecosystem services (Finney et al., 2016; Finney et al., 2017). Creating a mixture with diverging functionality as well as attributes relevant to environmental capacities (drought and heat tolerance, etc.) would be ideal (Finney et al., 2016, USDA-NRCS, 2016a). For an optimal summer rotation in a winter wheat system in Texas, short-season, drought and heat tolerant cover crops with varying C:N ratios and differing herbage mass production were selected.

An overview of the cover crops selected for this study are as follows: Buckwheat (*Fagopyrum esculentum*) is a short-season annual that quickly establishes a fibrous root system and efficiently scavenges calcium (Ca) and low availability phosphorus (P) (Fig. 1.1; Robinson, 1980; SARE, 2007a; Cornell, 2017). Buckwheat is an ideal cover crop for low-fertility soils; not only for its nutrient scavenging abilities, but also for its rapid herbage mass decomposition which helps to promote soil aggregation. (SARE, 2007a; Cornell, 2017). Forage type cowpeas produce large quantities of herbage mass and are heat and drought tolerant after crop establishment (Fig. 1.1; SARE, 2007a; Singh, 2014). In addition to their weed smothering capabilities, cowpeas are fast growing and are adapted to low-fertility soils, as they fix atmospheric N (N_2) (SARE, 2007a). Foxtail millet is another fast-growing, heat tolerant crop that is primarily grown for hay, but can fit well into a wheat rotation as a weed suppresser and a smother crop (Fig. 1.1; Sheahan, 2014a). Guar is a warm-season legume that offers low C:N herbage mass (SARE, 2007b). Lablab is a warm-season legume that produces vigorous taproots and has expansive herbaceous vines (Fig. 1.1; Sheahan, 2012). It is also very drought tolerant and can be used as forage, hay, and silage crop for animals, as well as a pulse crop for humans (Sheahan, 2012). The runner peanut is another warm-season legume that can be compared to a perennial forage peanut (Fig. 1.1; Lemus, 2010). Both fix N_2, but forage will mainly supplement the diets of grazers, while the runner variety is used for production agriculture (Lemus, 2010). Pearl millet is a high herbage mass producing, drought resistant millet that can be used as a summer cover, or as a high nutritive-value forage (Fig. 1.1; Jennings et al., 2010). Short stature sunflowers were selected for their drought and heat tolerance as well as their large taproot that would be suited for lower-depth nutrient and moisture scavenging (Fig. 1.1; Meyers, 2010). Sunn hemp is a fast-growing tropical legume that is often planted as a green manure and soil improver as it adds soil OM, N, and suppresses root-knot nematode (Fig. 1.1; Rotar and Joy, 1983).

Figure 1. 1 Cover crop species within the cover crop mixture

1.2.3 Tillage Management

Tillage is an important tool farmers use to physically manipulate their soil, which impacts crop establishment, soil moisture availability, soil temperature, weed-management, and erodibility (Lal 2001; Baker et al., 2006). Conventional tillage is defined as tilling the entire field with one or more passes, leaving less than 15% visible residue on the soil surface (CTIC, 2002). The process of land preparation using conventional tillage has been fundamental for centuries, aiding in weed control, and promotion of surface levelness, aeration, and tilth for a desired seedbed (Baker et al., 2006). There were two conservation tillage types that were used in this study in addition to conventional tillage—strip-till and no-till. Strip-tillage implements churn the soil less than a conventional tillage swath, creating a thin plow layer parallel to the direction of the crop row. This less intensive tillage type is intended to disturb no more than 30% of the surface soil in preparation for the seedbed (Wolkowski et al., 2009). Keeping crop residue minimally disturbed but out of the planter's way are additional objectives for this farm practice. This ultimately promotes the continuity of the soil biome within the inter-rows by leaving the soil undisturbed and residue on top. Organic matter left as a nutritive buffer aids in the cycling of nutrients and the control of erosion among other soil health benefits (Brady and Weil, 1996). No-tillage systems lack mechanical tillage for field preparation and maintenance. In the instance of planting, the subsequent crop is drilled directly into the undisturbed soil amongst the residue remaining from the previous season.

From 2003-2006, the USDA surveyed cultivated crop land in the Texas Gulf Basin region to assess conservation practices, compare losses that would be had if these practices were not in use, and estimate the benefits if conservation efforts increased (USDA-NRCS, 2015b). The survey found current conservation efforts for water erosion were in place for 37% of farmland, with 66% of practices being structural, i.e. terraces, or tillage and residue management practices. However, only 5% met the criteria for no-till, mainly because of the heavy tillage needed for cotton production in the region (USDA-NRCS, 2015b).

Decreased tillage may also equate to dollars saved with decreased labor and fuel consumption from machinery not in use (Baker et al., 2006). The USDA calculated that a total of 3 billion liters of diesel was saved by national farm conservation efforts, which is roughly the amount of energy required annually by 3.2 million average households (USDA-NRCS, 2016c). (USDA-NRCS, 2016c). These efforts not only saved fuel energy, but also reduced carbon dioxide (CO_2) emissions—annual offset of nearly 1.9 million passenger cars (USDA-NRCS, 2016c).

Reduced tillage systems can decrease on-farm costs as well, but Texas farmers may be skeptical to adopt such practices because of the lack of information regarding risk and the benefits associated with reduced tillage (Ribera et al., 2004). An 18-year field experiment involving five crop rotations grow from 1984 to 2001 in the Brazos River floodplain indicated that although yield was unchanged, costs associated with fuel, labor, machine repairs, and equipment depreciation were less for a no-till system (Ribera et al., 2004). The risk ratings were varied, but ultimately, for the economically risk-averse farmer, no-till was a better option over conventional till in all five crop rotations (Ribera et al., 2004).

Additional benefits of reduced tillage include soil health benefits such as increases in soil OM, soil organic carbon (SOC), improved nutrient cycling, soil structure, micro and macro fauna, erosion protection, porosity (aeration), infiltration, and soil moisture (Karlen et al., 1994; Franzluebberz, 2002; Wright and Hons, 2005; Van Oost et al., 2006). It is estimated that additional conservation practices in the most severely needed areas in Texas would reduce sediment loss by 84%, N loss by 32%, and P by 63% (USDA-NRCS, 2015b). The primary source of erosion is due to wind and 97% of cropped acres in the region have a high or moderate need for additional conservation treatments (USDA-NRCS, 2015b). A study in Lubbock, Texas, found the presence of wheat stubble reduced wind erosion by 41% and water erosion by 49% as compared to land that was conventionally-tilled (Lascano et al., 1994). Another short-term benefit conservation tillage could provide is conserving soil water for adequate planting moisture (Dhuyvetter et al., 1996). In the eight studies evaluating multiple crop rotations and tillage systems in the Great Plains, Dhuyvetter et al. (1996) found that intensive crop rotations increased net returns for the farmer, especially when coupled with minimal tillage systems due to utilization of stored soil moisture conserved by minimal tillage.

Soil benefits of reduced tillage take years to manifest. In a 6-year Canadian tillage study, little to no change in soil OM and SOC was seen after switching to conservation management practices (Franzluebbers and Arshad, 1996). Physical changes often do not materialize until year seven or greater, and even then, the added addition of crop residue is key to increasing soil organic C and improved soil quality (Sapkota et al., 2017). After a 12-year continuous no-till study with varying cropping intensities, a decrease in bulk density, and an increase in porosity and macro-aggregates were observed as cropping intensity, crop residue, and soil OM increased (Shaver et al., 2002). A study conducted in Northwest France found that over a 7 to 8-year period the highest aggregate stability was found under no-till practices and lowest under conventional till practices due to the amount of OM accumulation (Bottinelli et al., 2017).

There are short-term challenges which impede conservation adoption by farmers. Early endorsers of reduced tillage practices, especially no-till, often acknowledge that adopting such techniques could result in greater short-term risk of reduced seedling emergence, crop yield, or worse, crop failure, in anticipation of long-term gains (Kirkegaard, 1995; Baker et al., 2006). Seedling emergence and crop loss are two of the most cited issues associated with no-till and strip-till, but Ribera et al. (2004), found no statistical yield differences for soybean, sorghum, and wheat between no-till and conventionally tilled plots in Burleson County, TX (Ribera et al., 2004). Similarly, Lithourgidis et al. (2006) did not observe differences across conventional, minimal, and no-till plots for winter wheat in northern Greece. A decrease in summer soil temperatures as well as decreases in weed germination, runoff, and leaching of N can also have strong agronomic benefits (Baker et al., 2006). All of the above factors are capable of increasing crop yields for the farmer.

1.2.4 Soil Health

Soil quality as a concept has been continuously evolving amongst soil scientists (Papendick and Parr, 1992; Doran and Parkin, 1994; Karlen and Stott, 1994), and in 1997 efforts of the Soil Science Society of America and Karlen et al. (1997) proposed legislative standards for soil quality. Soil quality can be defined as the capacity of soil to function (Karlen et al., 1997). The concept of using indirect measures (indicators) to evaluate soil quality was first proposed in 1991 by Larson and Pierce and since then, the idea of using these indicators to yield numerical values as placeholders on the soil quality scale has been adopted (Andrews et al., 2002). The conversation then shifted to soil health, which can be defined as the continued capacity of the soil to function as a living ecosystem that promotes water and air quality and sustains plants, animals and humans (Doran and Zeiss, 2000). Soil health attributes are determined by evaluations of the three domains of soil function: physical, chemical, and biological properties (USDA-NRCS, 2015a). More recently, the urgency of soil as a finite resource—similar to water and food—has been promoted, and is referred to as soil security (McBratney et al., 2014).

Numerous methods have been suggested since the 1990's to develop a sound system of soil grading, and since then, some have been devised, including the Soil Quality Index (SQI), (Doran et al., 1994; Karlen et al., 1997; Nakajima et al., 2015) and more recently the Soil Management Assessment Framework Design (SMAF) (Andrews et al., 2004) and the Comprehensive Assessment of Soil Health (CASH) (Moebius-Clune et al., 2016) for soil quality. Giving a soil a numerical grade may aid in the evaluation of the soil's current standing, and give indication as to its potential, all in hopes that it could be translated into specific farm management decisions (Andrews et al., 2004; Beniston et al., 2015; Nakajima et al., 2016). The latest list of soil health indicators released from the Soil Health Institute are as follows: organic C, pH, water-stable aggregation, crop yield, texture, penetration resistance, cation exchange capacity, electrical conductivity, N, P, potassium (K), C mineralization, erosion rating, base saturation, bulk density, available water holding capacity, infiltration rate, and micronutrients (Soil Health Institute, 2016). In the interest of time, research funds, and labor abilities, we pursued a select number of these indicators that were within the three major soil health components; soil moisture, infiltration rate, and wet aggregate stability (physical component).

Physical soil properties that were evaluated are soil moisture, time-to-runoff, and wet aggregate stability. Soil moisture is usually measured as volumetric water content. It is a major factor determining crop establishment at time of planting, as well as yield potential based on soil moisture available for crop growth and production (Nielsen, 2006). For this study, we choose to monitor soil moisture over time, as an indirect measure of soil health, by looking at correlations in yield or other soil health indicators brought on by differing crop and tillage implementation.

Soil infiltration is defined as the ability of water to move through the soil profile allowing temporary storage of water for plant and soil organism uptake (USDA-NRCS, 2017). There are several factors that affect soil infiltration with soil texture being a major component. When a soil has a high percentage of clay, water may infiltrate slower compared to larger textured soils unless cracks are present or structure is well defined. In less compacted, well-structured soils with greater porosity, infiltration rates tend to be greater and instances of runoff less severe (Franzleubbers, 2002). Factors impacting infiltration rate that can be affected by management practices are compaction, surface soil structure, residue cover, and crusting. Decreasing the frequency of tillage can be directly linked to improvement of infiltration rate due to control of these factors, namely, increased residue and OM (Franzluebbers, 2002). By increasing infiltration rates, total stored water has a greater potential to increases as well, which could further promote increased productivity of that field (Dao, 1993).

From the infiltration measurements, several soil hydrologic properties can be determined, one such being time-to-runoff (T_{ro}) (van Es and Schindelbeck, 2003). Time of ponding is a more common measurement often recorded alongside infiltration research, as it is the point at which the infiltration gradient transitions from a rate smaller than the infiltration capacity to infiltration at capacity rate (Diskin and Nazimov, 1996). Ponding is the precursor to runoff. Time-to-runoff is dependent on the rainfall rate as well as initial soil water conditions (Diskin and Nazimov, 1996; van Es and Schindelbeck, 2003).

Wet aggregate stability is defined as the cohesive forces between soil particles withstanding applied disruptive forces and is a measure of the resistance of soil aggregates to slaking by water (Kemper and Rosenau, 1986). It is measured using a standardized simulated rainfall event on a sieve containing soil aggregates between 0.25 and 2.0 mm (van Es et al., 2003). The fraction of soil that remains on the sieve determines the percent aggregate stability (van Es et al., 2003). Stable aggregates can be indicative of OM, biological activity, and nutrient cycling, influencing the presence of micro and macro pores, which ultimately perpetuates high infiltration, and appropriates soil aeration for plant life.

1.3 Research Objectives

The overall objective of the proposed research was to evaluate the impacts of warm-season double cropping and reducing tillage on crop productivity and soil health in an annual winter wheat cropping system in three different ecoregions of Texas. Summer double crops were grain sorghum, sesame, cowpea, and a nine-species cover crop mix (buckwheat [‘Mancan’, *Fagopyrum esculentum* L.], cowpea [‘Texas Pinkeye Purple Hull’ for 2016 and ‘Iron and Clay’ for 2017, *Vigna unguiculata* L.], German foxtail millet [*Setaria italic* L.], pearl millet hybrid [*Pennisetum glaucum* L.], guar [‘Kinman’, *Cyamopsis tetragonoloba* L.], lablab [‘Rio Verde’, *Lablab purpureus* L.], runner peanut [‘Tamrun OL11’, *Arachis hypogaea* L.], short stature sunflower [‘8H668S’, *Helianthus annuus* L.], and Sunn hemp [*Crotalaria juncea* L.]) in addition to the traditional summer fallow (control). Each cropping system was evaluated under conventional, strip-till and no-till. Specific objectives were to:

1. Evaluate the impact of double cropping and reduced tillage on grain yield and herbage mass in annual winter wheat cropping systems
2. Quantify the benefits of double cropping and reduced tillage in an annual winter wheat cropping system on soil moisture throughout the growing season as well as physical soil properties that relate to the accumulation and conservation of soil moisture

2. EFFECTS OF REDUCED TILLAGE AND DOUBLE CROPPING ON GRAIN YIELDS AND BIOMASS PRODUCTION IN A WINTER WHEAT SYSTEM

2.1 Introduction

The goal of increasing agriculture production of food and fuel is a top priority worldwide, however, many farmers still annually plant a single crop. Double cropping, harvesting two or more successive crops on the same land in the same year, has the ability to increase crop production and income for the farmer. According to a USDA national survey, double cropping occupied only 2% of all cropland in the United States from 1999 to 2012 (Borchers et al., 2014). There are many economic and environmental reasons for the low rate of double cropping, regional variability and limited access to water in dryland or minimal precipitation zones are two main reasons for low adoption (Unger et al., 2006; Borchers et al., 2014).

The traditional summer fallow period in a winter wheat (*Triticum aestivum* L.) system is often implemented in regions of the United States that tend to experience less and/or more erratic precipitation events (Hinze and Smika, 1983). Ensuring success of the primary crop (winter wheat) is the reason for this practice, as winter wheat displays a strong linear response to available soil moisture at the time of planting (Nielsen et al., 1999; Nielsen et al., 2002; Nielsen, 2005; Stone and Schlegel, 2006). Wheat yields in the Great Plains were reportedly reduced by 7.9 kg ha^{-1} for every millimeter of soil water absent at time of wheat planting in a wheat-sunflower (*Helianthus annuus* L.) rotation (Nielsen et al., 1999). Similarly, Stone and Schlegel (2006) found that grain yields in the water limited environment of the west-central Great Plains were significantly related to available soil water at emergence. Grain yields increased 22.1 kg ha^{-1} in sorghum and 9.8 kg ha^{-1} in wheat per millimeter of additional available soil water from the 0-183.0 cm depth at the time of emergence (Stone and Schlegel, 2006). Double cropping in winter wheat has potential to deplete soil moisture otherwise reserved for the subsequent wheat crop, however, summer fallow may also decrease soil moisture due to evaporation. Massee and Cary (1976) pointed out that less than 30% of precipitation was stored during the summer fallow period. They attribute this in part to the exposure of bare soil to evaporation along with erosion from wind and water (Massee and Cary, 1978). Stewart and Burnett (1987) found that 36% of precipitation was lost as evaporation during the summer fallow period in a continuous wheat system. By replacing summer fallow with crop intensification, soil moisture will need to be supplemented either with precipitation, irrigation, or moisture conserving management practices.

Reduced tillage has potential to benefit a double cropping system, due to its impact on soil moisture conservation (Unger, 1984; Baumhardt et al., 1985; Dhuyvetter et al., 1996). Stored soil moisture increases when tillage is reduced and surface residue is present (Unger and Stewart, 1983). If residue is maintained on the soil's surface as a physical barrier, soil water evaporation lessens and wind and water erosion are reduced (Massee and Cary, 1976; Gill and Jalota, 1995; Shangning and Unger, 2001; Baumhardt and Jones, 2002). Ribera et al. (2004) concluded that no-till farming was the more economical choice over conventional tillage in all five of the crop rotations tested in the Brazos River floodplain from 1984 to 2001. Although they found yields to be unchanged, costs including fuel, labor, equipment repairs, and depreciation decreased (Ribera et al., 2006). Dhuyvetter et al. (1996) found that in seven of the eight studies evaluating crop rotations and tillage systems in the Great Plains that more intensive crop rotations increased net returns for the farmer when coupled with minimal tillage prior to double crop planting. The ability to double crop in a water limited environment like the Great Plains, is due in part to the utilization of stored soil moisture conserved by minimal tillage (Dhuyvetter et al., 1996).

Despite the research and claims made on the plausibility of double cropping with reduced tillage in a winter wheat system, the option of which crop to rotate with and method of tillage is ambiguous. Soybean (*Glycine max* L.) rotated with winter wheat is the most common double cropping rotation in the United States but is mainly limited to the Midwest and Southeast because of crop adaptation and water usage (Lobell and Asner, 2003; Borchers et al., 2014; University of Missouri Extension Irrigation, 2018). Currently in Texas and in the Great Plains, a three-year rotation of wheat – warm-season crop – fallow predominate (Hansen et al., 2012; Tarksalson et al., 2006; Schlegal et al., 2017). Corn (*Zea mays* L.) and then grain sorghum (*Sorghum bicolor* L.) are the second and third most common warm-season crop for rotation with winter wheat, respectively (Borchers et al., 2014). Fallowing is often introduced to help recover the water deficient post warm-season crop harvest (Tarkalson et al., 2006; Hansen et al., 2012; Schlegal et al., 2017). Aside from soybean, corn, and sorghum, there are few summer rotation crops that have been evaluated in a winter wheat system. Options for a warm-season rotation crop in Texas differ from other regions in the United States (Borchers et al., 2014). Winter wheat is generally harvested in May or June in Texas, so a summer crop must reach full maturity before wheat planting in November. Potential warm-season rotational crops for double cropping with winter wheat in Texas include, but is not limited to, corn, cowpea (*Vigna unguiculata* L.), cotton (*Gossypium hirsutum* L.), guar (*Cyamopsis tetragonoloba* L.), proso millet (*Panicum miliaceum* L.), sesame (*Sesamum indicum* L.), sorghum, and sunflower.

Farmers and researchers alike would benefit from research on previously under-evaluated warm-season winter wheat rotations. Precipitation storage and use efficiency has been shown to increase with tillage reduction and residue maintenance in dryland crop production (Dhuyvetter et al., 1996; Nielsen et al., 2002; Nielsen et al., 2005; Stone and Schlegal, 2006). By understanding the impacts of combining various summer double crops and reduced tillage with winter wheat, the overall productivity of the system can then be analyzed in terms of grain yields and biomass produced. Therefore, the objectives of this study were to 1) evaluate the effects of integrating double cropping and reduced tillage on winter wheat and double crop yields; and 2) evaluate the impact of wheat-double crop rotation and tillage on wheat and double crop herbage mass production.

2.2 Materials and Methods

2.2.1 Study Sites

The study was conducted at three locations—Beeville, Lubbock and Thrall, TX. The Beeville (28° 27’N 97° 42’W) research site was supplementary irrigated with a sprinkler system, and the study was implemented on a Parrita sandy clay loam (loamy, mixed, superactive, hyperthermic, shallow Petrocalcic Paleustoll) in the South Texas Plains ecoregion. Average annual rainfall for this location is 789.0 mm (NCDC, 2018), with average air temperatures of 29^{o}C (high) and 17^{o}C (low) (National Oceanic and Atmospheric Administration, 2018). The plots were 9.1 m long by 3.0 m wide with four rows per summer double crop plot (76.0 cm row spacing). The Lubbock, Texas (33° 41’N 101° 49’W), research site was supplementary flood irrigated, and the study was implemented on an Olton clay loam (fine, mixed, superactive, thermic Aridic Paleustolls) in the High Plains ecoregion. Average annual rainfall for this location is 489.0 mm yr^{-1}, with average air temperatures of 24^{o}C (high) and 8^{o}C (low) (National Oceanic and Atmospheric Administration, 2018). The plots were 12.2 m long by 4.1 m wide with four rows per summer double crop plot (102.0 cm row spacing). The dates and amount of irrigation for Beeville and Lubbock sites are listed on Table 2.1. The Thrall, Texas (30° 36’N 97° 18’W), research site was dryland, and the study was implemented on a Burleson clay (fine, smectitic, thermic Udic Haplusterts) in the Blackland Prairie ecoregion. Average annual rainfall for this location is 893.0 mm yr^{-1}, with average air temperatures of 26^{o}C (high) and 13^{o}C (low) (National Oceanic and Atmospheric Administration, 2018). The plots were 22.9 m long by 7.6 m wide with ten rows per summer double crop plot (76.0 cm row spacing). The experimental design was a three replicate, split-plot within a randomized complete block design. Tillage treatments were the main plots and summer double crop treatments were the subplots. The tillage treatments consisted of conventional till, strip-till, and no-till. Conventional till was performed before double crop and winter wheat planting to a ~15.2 cm depth with a 1.5 meter offset disc (Hay King, OPDM 28-22, K and M Manufacturing Company Inc., Taylor, TX, USA), to a ~15.2 cm depth with a 4.2 meter wide tandem disk (John Deere, Moline, IL), followed by a custom built five bottom lister plow, and a ~15.2 cm depth with a 6.1 meter tandem plow (Case IH, RMX370, Sturtevant, WI, USA), at Beeville, Lubbock, and Thrall respectively. Tillage was performed just prior to planting which did not allow soil to settle or mellow and could have affected emergence in some locations and years. Strip-till was performed once a year, just before double crop planting using an Orthman 1tRIPr implement (Lexington, NE) with no-till planting of wheat for this treatment. No-till main plots were undisturbed besides summer fertilizer applications that were often knifed in at Thrall and Lubbock. Summer double crops and winter wheat were planted using a no-till planter for the summer double crops and a no-till drill for the winter wheat. The summer double crop treatments consisted of fallow, sesame, grain sorghum, cowpea, and a nine-species cover crop mix.

2.2.2 Cropping System Management

For each location, region specific winter wheat varieties were selected. In Beeville 'TAM 305' was planted, in years 1 and 2. In Lubbock, 'TAM 304' was planted in years 1 and 2. In Thrall 'TAM 304' was planted in year 1, and 'WB Cedar' in year 2 (Table 2.2). At Thrall, a conventional drill was used to plant winter wheat in 2016 rather than a no-till drill due to equipment failure. The seeding rate for winter wheat 'TAM 304' at Lubbock in 2017 was increased to secure yield goals potentially compromised by late-season planting. Winter wheat was planted on 19.0-cm row spacing at all locations.

Table 2. 1 Irrigation dates and amount (mm) at Beeville and Lubbock

	Beeville	
Year	Date	Irrigation (mm)
2016	04 Aug	25
	11 Aug	25
	16 Sept	25
	04 Oct	25
	28 Nov	25
2017	02 Jan	25
	05 July	25
	14 July	25
	25 July	25
2018	15 Jan	25
	Lubbock	
2016	12 Jul	89
	03 Aug	91
	19 Aug	104
2017	20 June	104
	17 July	117

Table 2. 2 Seeding rate and planting and harvest dates for cultivars (winter and summer) included in the experiment in years 1 and 2 for each location. Seeding rate is pure live seed in kg ha^{-1}.

Year	Crop	Variety	Planting date	Harvest date	Seeding rate (PLS, kg ha^{-1})
Beeville					
2016	Wheat	TAM 305	19 November	21 March (terminated)	67.3
	Cover Crop		9 June	25 August	48.6
	Cowpea	Texas Pinkeye Purple Hull	9 June	15 August	27.1
	Sesame	S32	9 June	1 November	3.3
	Sorghum	DKS 37-07	28 June (replant)		3.7
2017	Wheat	TAM 305	1 December	15 May	67.3
	Cover Crop		8 June	13 September	49.5
	Cowpea	Golden Eye Cream	8 June	14 August	56.1
	Sesame	S32	8 June	27 October	3.3
	Sorghum	SP 7715	17 July (replant)	3 November	4.9
Lubbock					
2016	Wheat	TAM 304	12 December	9 June	67.3
	Cover Crop		20 June	26 August	48.6
	Cowpea	Texas Pinkeye Purple Hull	20 June	26 September	27.1
	Sesame	S32	20 June	16 November	3.3
	Sorghum	DKS 37-07	20 June	24 October	3.7
2017	Wheat	TAM 304	7 December	7 June	114.4
	Cover Crop		14 July	12 October	49.5
	Cowpea	Golden Eye Cream	14 July	12 October	56.1
	Sesame	S32	14 July	10 November	2.5
	Sorghum	DKS 37-07	14 July	10 November	4.1
Thrall					
2016	Wheat	TAM 304	2 December	13 May	78.5
	Cover Crop		14 June	9 September, 12 October	48.6
	Cowpea	Texas Pinkeye Purple Hull	14 June	9, 15 September	27.1
	Sesame	S32	14 June	14 November	3.3
	Sorghum	DKS 37-07	14 June	12, 15, 22 September, 7 October	3.7
2017	Wheat	WB Cedar	15 November	28 May	78.5
	Cover Crop		13 June	15 September	49.5
	Cowpea	Golden Eye Cream	13 June	22 September	56.1
	Sesame	S32	13 June	19 October	3.3
	Sorghum	SP 7715	13 June	26 October	4.9

Lubbock and Thrall’s N fertilizer source was urea ammonium nitrate (UAN, 32-0-0), and Beeville’s was urea (46-0-0) (Table 2.3). Fertilizer applications were applied based on yield potential for each region and nutrient concentrations of soil samples taken prior to planting at a 0-15.0 cm depth. In Beeville all fertilizer was broadcast applied in granular form. In Lubbock, UAN was diluted with water at a 1:1 ratio. Nitrogen (N) was applied to wheat at each location at planting (1/3 of total N) followed by a topdress application before jointing (2/3 of total N). Fertilizer at Lubbock was applied to double crops using a four-row sidedress applicator (4 meters) with knives mounted behind coulters. Wheat planted at Lubbock in 2017 was fertilized using an eight-row boom (8.1 meters) on a tractor, applied using TeeJet StreamJet, 7-way fertilizer spray nozzles (TeeJet Technologies, Glendale Heights, IL, USA). Fertilizer in Thrall was applied using a combination of methods. For the summer crops, UAN (32-0-0) was sidedress applied using a 4-row knife rig to dribble fertilizer 10.2 cm below the soil surface and 7.6 cm away from the root zone. In addition, an application of granular phosphorus (P; triple superphosphate, 0-46-0) and Potassium (K; muriate of potash 0-0-60) was broadcast applied using a hand spreader. Winter wheat was fertilized using TeeJet StreamJet, 7-way nozzles.

Table 2. 3 Fertilizer applications by crop for 2016 and 2017 at all locations.

				Nutrient (kg ha^{-1})			
Year	Crop	Product	Date Applied	N	P_2O_5	K_2O	S
			Beeville				
2016	Wheat	Urea, TSP†, K_2O	February (topdress)	84.0	31.4	9.5	-
	Cover Crop			-	-	-	-
	Cowpea	TSP		-	39.2	-	
	Sesame	Ammonium sulfate, Urea	June	33.6	61.6		26.9
	Sorghum	Ammonium sulfate, Urea	June	33.6	39.2		26.9
2017	Wheat	Urea, P_2O_5	January (topdress)	84.0	52.6	-	-
	Cover Crop			-	-	-	-
	Cowpea			-	-	-	-
	Sesame	UAN		84.0	-	-	-
	Sorghum	UAN		62.7	-	-	-
			Lubbock				
2016	Wheat	UAN	March (topdress)	127.2	-	-	-
	Cover Crop			-	-	-	-
	Cowpea			-	-	-	-
	Sesame		July	43.8	-	-	-
	Sorghum		July	79.5	-	-	-
2017	Wheat	UAN	March (topdress)	127.3			
	Cover Crop			-	-	-	-
	Cowpea			-	-	-	-
	Sesame			-	-	-	-
	Sorghum			-	-	-	-
			Thrall				
2016	Wheat	UAN	26 January (topdress)	78.5	-	-	-
	Cover Crop	7-21-2	19 July	16.4	49.2	4.7	-
	Cowpea	7-21-2	19 July	16.4	49.2	4.7	-
	Sesame	7-21-2, UAN	19 July	60.8	65.2	5.4	-
	Sorghum	7-21-2, UAN	19 July	60.3	30.0	2.6	-
2017	Wheat	UAN	16 December	80.7	-	-	-
	Cover Crop			-	-	-	-
	Cowpea	Potash, TSP	11 July	-	44.9	78.4	-
	Sesame	UAN, Potash, TSP	11 July	81.8	44.9	78.4	-
	Sorghum	UAN, Potash, TSP	11 July	76.2	44.9	78.4	-

†TSP: triple super phosphate, triple superphosphate, 0-46-0.

The summer double crop treatments were sesame, grain sorghum, cowpea, and a cover crop mixture (buckwheat, cowpea, German foxtail millet, guar, lablab, runner peanut, pearl millet, short stature sunflower, and sunn hemp; Fig. 2.1 and Table 2.4). The seed ratio was determined based on crop water tolerance, heat adaptiveness, vigor, and biomass production (Fig. 2.1 and Table 2.4; USDA-NRCS, 2011; USDA-NRCS, 2014; USDA-NRCS, 2016d). Figure 2.1 depicts a ratio of the cover crop species within the mixture. Seeding depth by species was considered, and an average seeding depth of 2.5 cm was chosen for cover crop species planted in bulk. The cowpea variety used in 2016 was the same variety used in the cowpea double crop, Texas Pinkeye Purple Hull. In 2017, a forage type cowpea variety was selected, Iron and Clay. Iron and Clay cowpeas are 120-day maturity, twice as long as Texas Pinkeye Purple Hull (54-60 days).

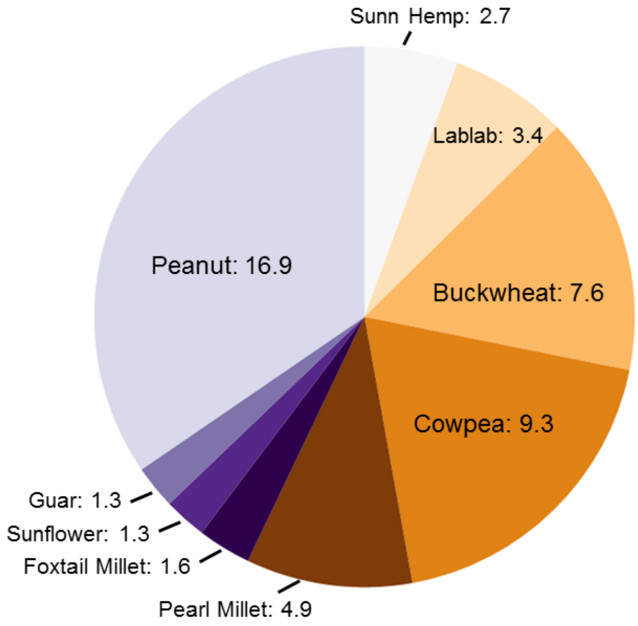

Figure 2. 1 Ratio of seeding rate for cover crop mix in kg pure live seed (PLS) ha^{-1}.

Table 2. 4 Cover crop cultivars included in the experiment for 2016 and 2017, their functional group classification, and seeding rate of pure live seeds (PLS).

Year	Functional Group	Species name and cultivar	Seeding rate (PLS)	
			kg ha^{-1}	seeds m^{-2}
2016	Legume	Cowpea, 'Texas Pinkeye Purple Hull'	11.2	10
	Legume	Guar, 'Kinman'	1.2	4
	Legume	Lablab, 'Rio Verde'	3.6	1
	Legume	Peanut, 'Tamrun OL11'	14.6	3
	Legume	Sunn Hemp	2.8	9
	C_4 Grass	German Foxtail Millet	1.6	73
	C_4 Grass	Pearl Millet Hybrid	4.9	88
	C_3 Broadleaf	Sunflower, '8H668S'	1.2	2
	C_3 Broadleaf	Buckwheat, 'Mancan'	7.6	26
Total			48.7	216
2017	Legume	Cowpea, 'Iron and Clay'	7.4	12
	Legume	Guar, 'Kinman'	1.3	5
	Legume	Lablab, 'Rio Verde'	3.3	2
	Legume	Peanut, 'Tamrun OL11'	19.3	6
	Legume	Sunn Hemp	2.7	13
	C_4 Grass	German Foxtail Millet	1.6	90
	C_4 Grass	Pearl Millet Hybrid	4.9	122
	C_3 Broadleaf	Sunflower, '8H668S'	1.3	3
	C_3 Broadleaf	Buckwheat, 'Mancan'	7.6	35
Total			49.4	288

Summer fallow was implemented as a treatment for comparison. Summer double-crops were planted with a John Deere Max Emerge planter (John Deere, Moline, IL) unit with ALMACO cone seeders (ALMACO, Nevada, IA) on a 76.0-cm row spacing in Thrall and Beeville. At Lubbock, double crops were planted with a John Deere Max Emerge Plus (John Deere, Moline, IL) unit with ALMACO cone seeders (ALMACO, Nevada, IA) on 102.0 cm row spacing in Lubbock to follow common row spacing for the areas.

Cowpea seed was pre-treated with Apron XL (a.i. Mefenoxam) fungicide (Syngenta, Greensboro, NC) and Cruiser 5FS (a.i. Thiamethoxam) insecticide (Syngenta, Greensboro, NC) and species specific powdered *Bradyrhizobium* (N-Dure, Verdesian, Cary, NC). Sorghum seed was pre-treated with Apron XL fungicide and Cruiser 5FS insecticide, and a safener (Concep III

Seed Treatment, Syngenta, Greensboro, NC). The cover crop seed mixture was pre-treated with Apron XL fungicide and Cruiser 5FS insecticide, as well as Concept III safener. The mixture was treated at the time of planting with a *Bradyrhizobium* species inoculant, combining—powdered *Rhizobium* (same as cowpea) and granular (Primo GX2, Verdesian, Cary, NC) to help with larger seed inoculation (Flynn, 2015).

Weed control was enacted in the summer double crop using a burndown and pre-emergent herbicide combination before planting and in-season control was done with a hooded sprayer and broad-spectrum herbicide. Chemical termination of the cover crops was enacted post subsampling harvest of herbage mass (Table 2.5). Crop specific post-emergence herbicides were used when needed. Products used were identified with minimal plant-back restrictions. At Beeville, herbicide applications were applied using a backpack sprayer as well as a hooded sprayer and boom sprayer (Table 2.5). At Lubbock, bulk herbicide applications were applied to the entire trial with an eight-row boom on a tractor (Table 2.5). Plots that were individually sprayed, used the Milo-Pro with a four-row boom out of CO_2 canisters on a tractor. A four-gallon backpack sprayer with a hand-held, two-row boom was used to spray volunteer wheat in 2016, as well as fallow plots and termination of cowpea plots in 2017. Fallow plots and alleys in 2017 were also sprayed using a four-gallon backpack sprayer with a hand-held, two-row boom.

Sugar-cane aphids (*Melanaphis sacchari*) and bird predation were observed at all locations. Both sorghum hybrids used were sugar-cane aphid tolerant, yet insecticide was applied in August of 2016 (Sivanto 200 SL, a.i. Flupyradifurone, a.i. 0.82 kg ha^{-1}, Bayer Crop Science LP, Research Triangle Park, NC) at the recommended threshold to protect yield at Thrall and at Lubbock (Besiege, a.i. Lambda-cyhalothrin, a.i. 0.29 kg ha^{-1} and a.i. Chlorantraniliprole, a.i. 0.59 kg ha^{-1}, Syngenta, Greensboro NC). At Thrall and Lubbock in 2017, a.i. 0.94 kg ha^{-1} of Sivanto

200 SL was applied at both locations and at Beeville, Transform WG (a.i. sulfoxaflor, a.i. 0.05 kg ha^{-1}, Dow AgroSciences LLC, Indianapolis, IN) was applied when sugar-sane aphids reached the population threshold in October of 2017. Heavy bird predation at Beeville resulted in a complete crop loss for the grain sorghum in 2016, thus yields were not taken for Beeville that year. Bird predation occurred at Lubbock and Thrall as well, but to a lesser extent. Wire mesh crop cages were centralized in each sorghum plot at all locations in 2017 to eliminate impacts from bird depredation. In Thrall and Beeville, cages were 1.5 m wide (across two rows) by 1.2 m long and in Lubbock were 2 m wide (across two rows) by 1.2 m long. In 2016 at Lubbock, conventionally tilled plots had visible bird damage rated greater than 85% for some grain heads. On-going bird damage called for multiple subsample grain sorghum harvests in Thrall in 2016. Bird damage ratings were determined by visual assessment of each sorghum head within the subsample harvest; it is recognized that estimates increase error in the study. Sorghum heads that were rated above 40% were thrown out of the data set. In 2017, Beeville experienced issues with sorghum ergot disease which was caused by the fungus *Claviceps Africana*; all plots were infected.

Table 2. 5 Herbicide applications for 2015-2017 at all locations.

Year	Plots	Product	Active Ingredient	Method	Date Applied	Rate (L ha^{-1})	Active Ingredient (kg ha^{-1})
				Beeville			
2015	All (Wheat)	Sharpen	saflufenacil	Spray	19 Nov	0.15	0.05
	All (Wheat)	RoundUp WeatherMax	Glyphosate, 540g/L potassium salt	Spray	19 Nov	3.51	1.90 a.e.
	All (Wheat)	Outrider	Sulfosulfuron	Spray	17 Dec	0.05	0.04
2016	All (Wheat)	MCPA	2-methyl-4-chlorophenoxyacetic acid isooctyl (2-ethylhexyl) ester	Spray	04 Feb	0.88	0.53
	All (Wheat)	Harmony Extra SG	Thifensulfuron-methyl Tribenuron-methyl	Spray	04 Feb	0.04	0.01 0.01
	All (Wheat, termination)	RoundUp WeatherMax	Glyphosate, 540g/L potassium salt	Spray	21 Mar	3.51	1.90 a.e.
	All (Pre-emergent)	RoundUp WeatherMax	Glyphosate, 540g/L potassium salt	Spray	13 May	3.51	1.90 a.e.
	All (Summer crops)	RoundUp WeatherMax	Glyphosate, 540g/L potassium salt	Spray	16 June	3.51	1.90 a.e.
	All (minus cover)	Dual Magnum II	S-metolachlor	Spray	16 June	1.64	1.50
	Between rows	Ignite	Glufosinate-ammonium	Hooded	14 July	2.12	0.59
	Between rows	RoundUp WeatherMax	Glyphosate, 540g/L potassium salt	Hooded	19 Aug	4.94	2.67 a.e.
	All (minus sesame)	RoundUp WeatherMax	Glyphosate, 540g/L potassium salt	Backpack	02 Sept	2.34	1.26 a.e.
	Sesame	RoundUp WeatherMax	Glyphosate, 540g/L potassium salt	Backpack	08 Nov	5%	0.3 a.e.
	Cover Crop (Sunn Hemp)	2,4-D	2,4-dichlorophenoxy butyric acid	Backpack	08 Nov	10%	0.04 a.e.
	All (pre-emergent)	RoundUp WeatherMax	Glyphosate, 540g/L potassium salt	Spray	14 Dec	3.51	1.90 a.e.
2017	All (minus cover)	Dual II Magnum	S-metolachlor	Spray	12 June	1.64	1.50
	All	RoundUp PowerMax	Glyphosate, 540g/L potassium salt	Spray	12 June	3.51	1.90 a.e.
	Fallow, alleys	RoundUp PowerMax	Glyphosate, 540g/L potassium salt	Backpack	12 July	5%	0.03
	All	RoundUp PowerMax	Glyphosate, 540g/L potassium salt	Spray	21 Nov	2.34	1.26 a.e.
			Lubbock				
2016	All (Pre-emergent)	RoundUp	Glyphosate, 540g/L potassium salt	Spray	14 June	3.51	1.90 a.e.
	All (Post-emergent)	Dual II Magnum	S-metolachlor	Spray	24 June	1.52	1.40
	Sorghum	Milo-Pro	2-Chloro-4,6-bis(isopropylamino)-s-triazine	Spray	24 June	2.34	1.12
2017	All	Tomahawk	fluroxypyr as the methyl heptyl ester 200 g/l	Spray	17 June	3.51	0.70
	All	Ammonium Sulfate		Spray	17 June	1.91 kg ha^{-1}	1.91
	All	RoundUp	Glyphosate, 540g/L potassium salt	Spray	27 June	3.51	1.90 a.e.

Table 2.5 Continued 1

Year	Plots	Product	Active Ingredient	Method	Date Applied	Rate (L ha^{-1})	Active Ingredient (kg ha^{-1})
Lubbock							
2017	All	Gramoxone SL 2.0	Paraquat dichloride (1,1’-dimethyl-4,4'-bipyridinium dichloride	Spray	14 July	2.34	0.77 a.e.
	All	Dual II Magnum	S-metolachlor	Spray	14 July	1.54	1.41
	Fallow, Alleys	RoundUp	Glyphosate, 540g/L potassium salt	Spray	09 Aug	3.51	1.90 a.e.
	Fallow, Alleys	Liberty 280 SL	Glufosinate-ammonium	Backpack	09 Aug	3.15	0.88
	Cowpea, Fallow	RoundUp	Glyphosate, 540g/L potassium salt	Backpack	13 Oct	3.51	1.90 a.e.
	All	Tomahawk	200 g/l fluroxypyr	Spray	15 Nov	3.51	0.70
	All	Ammonium Sulfate		Spray	15 Nov	1.91 kg ha^{-1}	1.91
Thrall							
2016	All	Huskie	Pyrasulfotole	Spray	06 Jan	1.1	0.04
			Bromoxynil octanoate	Spray	06 Jan		0.23
			Bromoxynil heptanoate	Spray	06 Jan		0.23
	All	Gly Star Plus	Glyphosate, 356g/L isopropylamine salt	Spray	15 June	2.34	0.83 a.e.
	All (minus sesame)	Dual II Magnum	S-metolachlor	Spray	15 June	1.17	1.07
	Fallow, Cowpea, Cover	Gly Star Plus	Glyphosate, 356g/L isopropylamine salt	Spray	09 Sept	2.34	0.83 a.e.
	Cover (Conventional till only)	Gly Star Plus	Glyphosate, 356g/L isopropylamine salt	Spray	12 Oct	2.34	0.83 a.e.
	All (Post-emergent)	Gly Star Plus	Glyphosate, 356g/L isopropylamine salt	Spray	20 Dec	2.34	0.83 a.e.
	All (Post-emergent)	Sharpen	saflufenacil	Spray	20 Dec	1.17	0.40
2017	All	Harmony Extra SG	Thifensulfuron-methyl	Spray	01 Feb	0.04	0.01
			Tribenuron-methyl	Spray	01 Feb		0.01
	All (Pre-emergent)-Tank Mix	Gly Star Plus	Glyphosate, 356g/L isopropylamine salt	Spray	23 June	2.34	0.83 a.e.
	All (Pre-emergent) – Tank Mix	Dual II Magnum	S-metolachlor	Spray	23 June	1.17	1.07
	Fallow, Cowpea, Cover –Tank Mix	Gly Star Plus	Glyphosate, 356g/L isopropylamine salt	Spray	01 Aug	2.34	0.83 a.e.

Table 2.5 Continued 2

Year	Plots	Product	Active Ingredient	Method	Date Applied	Rate (L ha^{-1})	Active Ingredient (kg ha^{-1})
			Thrall				
2017	Fallow, Cowpea, Cover –Tank Mix	Outlook	Dimethenamid-P	Spray	01 Aug	1.54	1.11
	Sesame	Gly Star Plusredmon	Glyphosate, 356g/L isopropylamine salt	Spray	27 Sept	1.17	0.42 a.e.
	Fallow, Cowpea, Cover	Liberty 280 SL	Glufosinate-ammonium	Spray	27 Sept	2.12	0.59
	All (Pre-emergent)	Gly Star Plus	Glyphosate, 356g/L isopropylamine salt	Spray	16 Nov	2.34	0.83 a.e.
	All (Pre-emergent)	Sharpen	saflufenacil	Spray	16 Nov	1.17	0.40
	Rep 1 only	Axial XL	Pinoxaden (5.05%)	Spray	16 Dec	1.2	0.06
	All (Post-emergent)	Buctril	Bromoxynil octanoate	Spray	16 Dec	1.76	0.40 a.e.
	All (Post-emergent)	MCPE Phenoxy	2-methyl-4-chlorophenoxyacetic acid isooctyl (2-ethylhexyl) ester	Spray	16 Dec	1.17	0.52 a.e.

2.2.3 Grain Yield

Grain harvesting for wheat, cowpea, sorghum, and sesame at Thrall was done using a Wintersteiger (Wintersteiger Ag, Ried, Austria) classic plot combine (1.5 m header) and harvested by hand at the other two locations. Grain sorghum was hand harvested from inside cages using a linear meter row. The herbage mass plus grain was dried at 50° C until constant weight. Samples were threshed and grain weighed. The grain weight was then subtracted from the total dry subsample weight to estimate herbage mass weight. Grain moisture (Dickey-john, Minneapolis, MN) was measured to standardize grain yields to 13.5% moisture.

2.2.4 Herbage Mass and Stand Counts

Herbage mass samples were collected for each summer double crop and wheat. For wheat, herbage mass samples were collected before combine harvest by hand harvesting 1-m row length at ground level in three random locations per plot at the Thrall, and two random locations at Beeville and Lubbock. Wheat heads were separated from the herbage mass. Samples were threshed using a stationary Almaco LPR thresher (Nevada, IA) to separate grain from the heads. Head weight without grain was weighed and added back into the overall herbage mass weight for each wheat subsample. Stand counts for winter wheat were performed at Beeville and Lubbock by counting the number of plants per linear meter, four meters per plot. Random, yet representative regions within the plot were selected and a meter stick was laid down twice per plot, counting the plants on either side. For wheat stand counts at Thrall, a meter stick was laid down in four random, but representative regions per plot and the number of plants were counted on either side of the meter stick for a total of eight linear meter rows.

For summer double crops in 2016, not including cover crops, samples were collected post combine harvest at Thrall and for sesame in Beeville. In 2017, herbage mass was collected precombine harvest at all locations. Four linear row meter cuttings were taken within each plot. Cover crop herbage mass samples were taken before a desiccant was applied by cutting four linear meter rows at ground level. Two linear meter cuttings were sorted by species for botanical composition. Sesame herbage mass was too few to collect post combine harvest at Beeville in 2016. Samples were collected and dried in a forced-air oven at 50°C to a constant weight to determine dry matter yield. Stand counts for double crops were performed at Beeville and Lubbock by counting the number of plants per linear meter, four meters per plot. Random, yet representative regions within the plot were selected and a meter stick was laid down twice per plot, counting the plants on either side. For double crop counts at Thrall, a meter stick was laid down in three random, yet representative regions per plot and the number of plants were counted on either side of the meter stick for a total of six linear meter rows. For stand counts by species within the cover crop plots, a meter stick was laid down (twice at Beeville and Lubbock and three times at Thrall) and species counted per linear meter row. At this stage in the cover crop's growth, it is difficult to differentiate between "German Foxtail Millet" and "Pearl Millet", thus, the species are grouped together and labeled "millet".

2.2.5 Statistical Analysis

Statistical analyses were conducted using SAS version 9.4 (SAS Institute Inc., Cary, NC). Analysis of variance (ANOVA) was conducted using PROC GLIMMIX (See Appendix). Location, tillage, and summer crop were treated as fixed effects. Year and replication were implemented as random effects using the RANDOM statement. There were significant location × tillage and location × crop interactions, so data is presented by location. The function LS-means with the PDIFF option was used to determine mean separation among the various effects at $P <$

0.05 significance. Calculated probabilities or differences among treatments are presented in Appendix B.

2.3 Results and Discussion

2.3.1 Wheat Grain Yields

Tillage impacted wheat stand counts at Beeville and Thrall, and at Lubbock, strong trends were observed. Greater emergence was observed at Beeville and Thrall in plots that were conventionally tilled, and at Lubbock, greater emergence was observed in the strip-tilled plots. Summer crop affected wheat stand counts at Thrall, but did not the other locations. Greater emergence was observed in the plots that previously contained cover crops, emergence was lesser in the plots that previously contained sesame and sorghum.

Summer crop and tillage affected wheat yield at Lubbock and tillage impacted wheat yield at Thrall (Fig. 2.2). At Beeville, warm winter temperatures in 2017 caused poor vernalization for hard red winter wheat variety, ‘TAM 305’, which resulted in a low yield average across treatments—136 kg ha^{-1}. Similar yields of 148 kg ha^{-1} for ‘TAM 305’ were reported for uniform variety trials in the South Texas region, specifically Wharton, TX (Neely et al., 2017). Poor vernalization was observed for most of the South Texas region in 2017 (Neely et al., 2017). Yields at Beeville were unaffected by tillage and previous season’s double crops. Impacts from tillage on stand counts may have been ameliorated by irrigation just after planting (November 28th, 2016, ~35.0 mm) as well as irrigation and precipitation events throughout the growing season. This may coincide with Stone and Schlegel’s (2006) findings, where wheat yields were more closely tied to soil moisture at emergence as well as throughout the growing season.

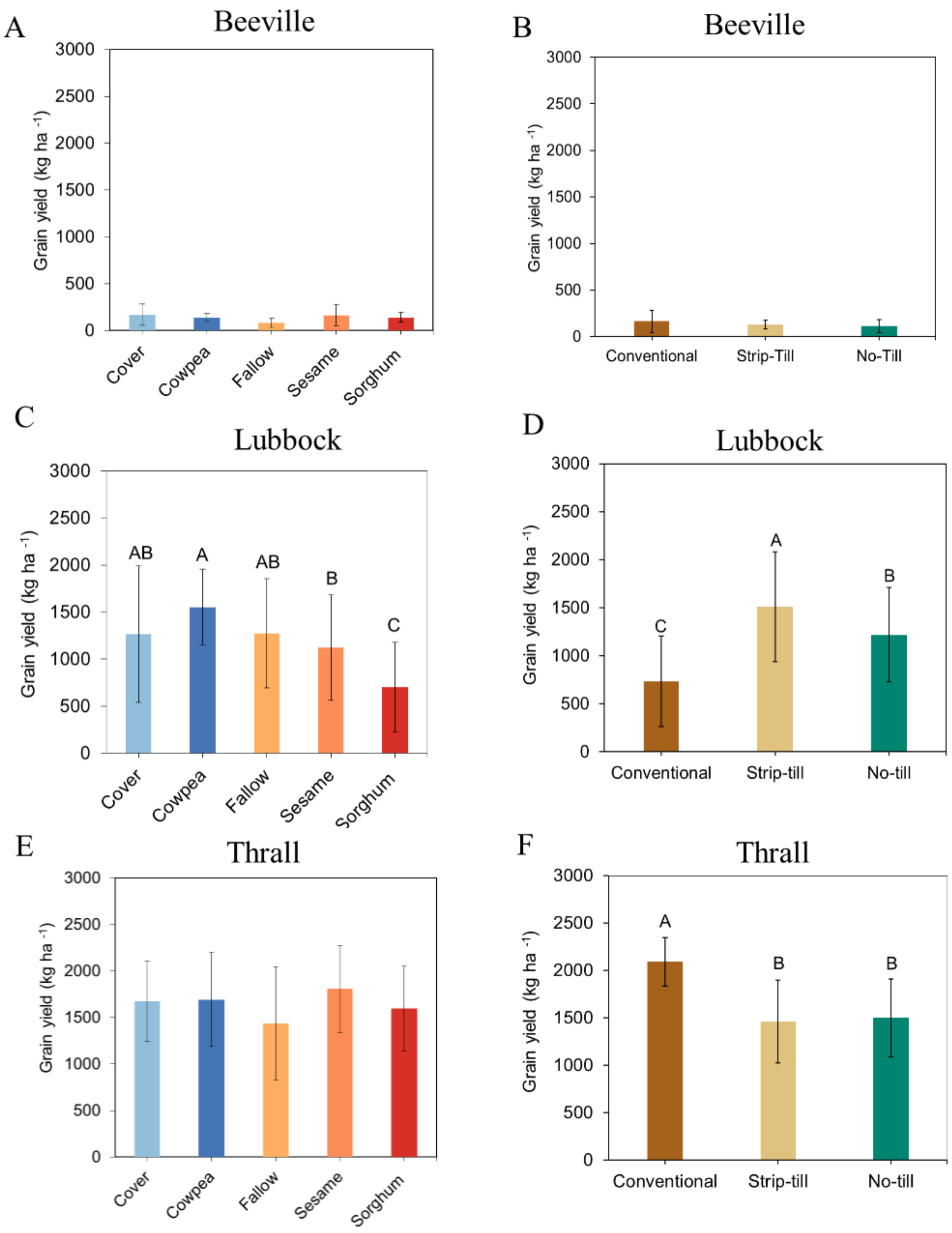

Figure 2. 2 Wheat grain yield (kg ha^{-1}) in 2017 as affected by previous years' double crops (a, c, e) and tillage treatments (b, d, f) at Beeville (a, b) Lubbock (c, d) and Thrall (e, f). Bars represent standard deviation and different letters indicate tillage and summer crop treatment significance within location ($P < 0.05$).

Lubbock displayed low yields compared to uniform variety trial averages for ‘TAM 304’ dryland—2464 kg ha^{-1} (Neely et al., 2017). Yields were affected by previous season’s summer double crops (Fig. 2.2). Sorghum reduced wheat yields at Lubbock by 45% compared to fallow. Yields were also significantly affected by tillage and resemble stand count trends, with strip-tillage producing the highest yields (Fig. 2.2). Greater stand counts and grain yields were observed for wheat grown in the spring strip-till plots. It could be hypothesized that since winter wheat and double crops were planted in the same direction, that spring strip-tillage alleviated some subsoil compaction and the soil’s friability carried through until winter wheat planting in the fall.

At Thrall, poor vernalization was observed due to warm winter temperatures in 2017, which resulted in low yields for ‘WB Cedar’ (97 kg ha^{-1}). Uniform variety trials for hard winter wheat in Thrall, TX for 2017 were abandoned due to vernalization issue and bird predation (Neely et al., 2017). Average yields for ‘WB Cedar’ planted at 97 kg ha^{-1} across the Blacklands in 2017 were 3215 kg ha^{-1} (Neely et al., 2017). In Thrall, minimally tilled treatments decreased stands, which may have reduced wheat yields (Fig. 2.2). Stand establishment in Thrall may be reduced due to the use of a conventional drill instead of a no-till drill due to equipment failure. Seed in the minimally tilled plots (strip-till and no-till) was drilled very shallow, as the drill was adapted to planting in tilled soils. Double crops did not affect yields despite affecting stands. For stand counts, there were significantly fewer plants m^{-2} in the sorghum and fallow plots. Residue may have decreased stands in the plots that previously contained sorghum, as the conventional drill was unequipped to plant in plots with heavy residue. Sorghum residue was observed to persist well into the wheat growing season (data not shown).

2.3.2 Wheat Herbage Mass

Tillage did not impact wheat herbage mass production at any of the three locations. Wheat herbage mass production at Beeville was not impacted by the previous season's double crop, but produced more herbage mass than the other two locations and averaged 4160 kg DM ha^{-1}. The wheat grain yields were also not impacted by summer crop.

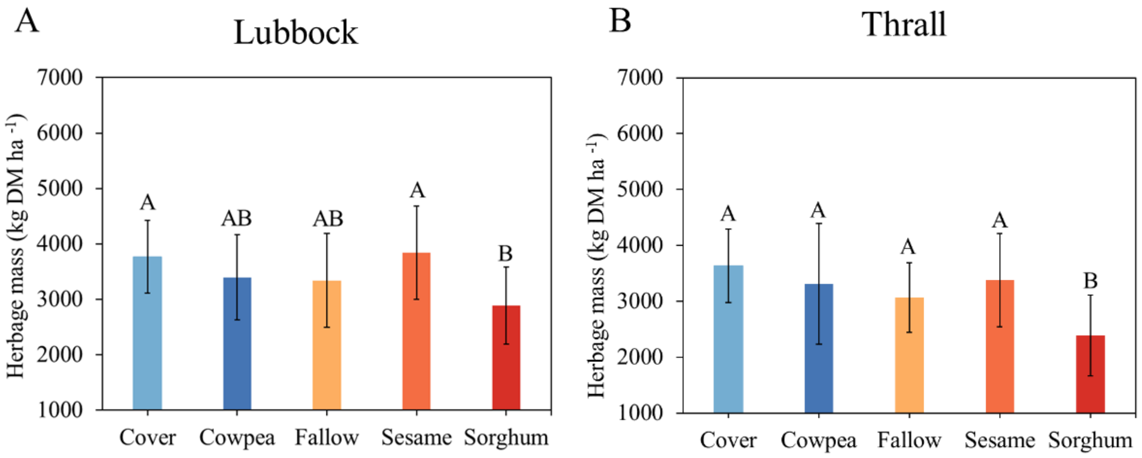

Figure 2. 3 Herbage mass (kg DM ha^{-1}) for wheat in 2017 at Lubbock (a) and Thrall (b) as affected by double crop treatments. Bars represent standard deviation and different letters with tillage and summer double crop treatments indicate significance ($P < 0.05$) at each location.

At Lubbock, sorghum negatively impacted wheat herbage mass production, similar to sorghum's impact on wheat grain yield (Fig 2.3). Herbage mass production in plots that previously contained sesame produced greater herbage mass compared to plots that previously contained grain sorghum (Fig 2.3). Sorghum has the greatest water requirements out of the four double crops, which may explain the effect on subsequent wheat grain yields and herbage mass production (Assefa et al., 2010). Soil moisture at time of planting has been reported to reduce wheat grain yields (Nielsen et al., 2002), and may also affect subsequent wheat herbage mass yields.

At Thrall, less herbage mass was produced in the plots that previously contained sorghum (Fig. 2.3). This differs from wheat yield, as grain yields were not affected by the previous season's sorghum crop. Since soil moisture was likely similar in all double crop plots at the time of planting, differences in herbage mass production could likely be due to method of collection for herbage mass (sub-sampled with linear meter row) compared to method of grain harvest (five-foot plot combine swath).

2.3.3 Double Crops

Double crop stand count was not impacted by tillage, and average stands are displayed by location (Table 2.6).

Table 2. 6 End-of-season (or Pre-harvest) stand counts of summer double crops by location.

Location	Double Crops	Plants m^{-2}
Beeville	Cover	8.2
	Cowpea	6.9
	Sesame	9.0
	Sorghum	4.9
Lubbock	Cover	11.5
	Cowpea	11.0
	Sesame	12.0
	Sorghum	7.5
Thrall	Cover	5.7
	Cowpea	8.2
	Sesame	9.7
	Sorghum	9.0

2.3.3.1 Cowpea Yields

Lubbock had greater cowpea yields than Beeville or Thrall, which were not different (Fig. 2.4). Tillage did not impact cowpea yield at any location.

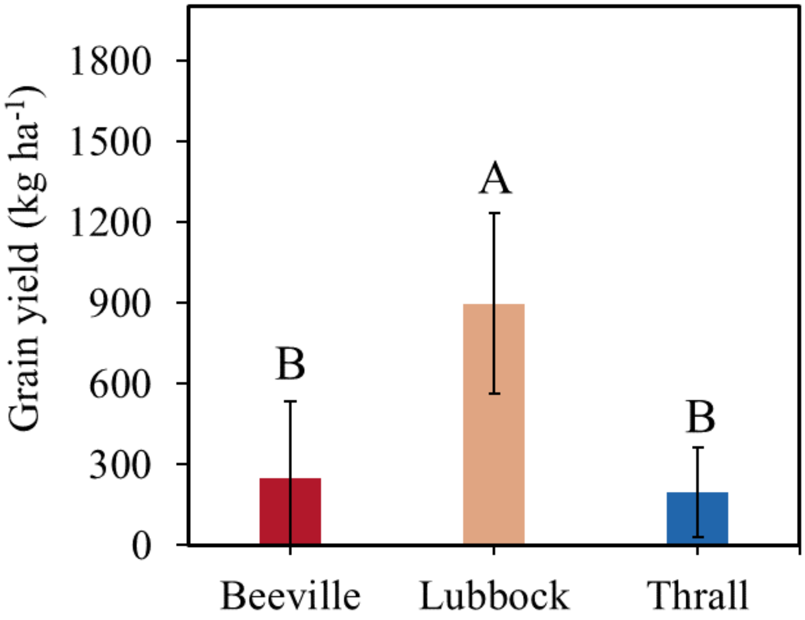

Figure 2. 4 Cowpea grain yield (kg ha^{-1}) by location. Bars represent standard deviation and different letters indicate significance ($P<0.05$) at each location within each year.

Lubbock had statistically greater yields compared to Beeville and Thrall across years (Fig. 2.4). Lubbock produced similar yields (average yield: 897 kg ha^{-1}) to averages in the High Plains that was noted by Roberts (2000), which was 673 to 897 kg ha^{-1}. The yield difference by location could be due to day and night temperature fluctuations that occur in Lubbock during the summer season. Roberts (2000) mentioned that optimum growing conditions ranged from 29 to 35°C during the day and 16 to 18°C at night. Late season plantings for the two southern locations could explain the location effect, as high summer daytime and nighttime temperatures are not conducive to maximum yields (Roberts, 2000). Low yields in Beeville can partly be attributed to predation by wildlife (rabbits and deer). In 2017, the cowpea variety was changed from Texas Pinkeye Purple Hull to Golden Eye Cream, the objective being greater yields.

2.3.3.2 Sesame Yields

Tillage did not impact sesame yields at any location. Sesame yields at Beeville were low (388 kg ha^{-1}) compared to 2016 regional averages in South Central Texas (515 kg ha^{-1}; Sesaco, 2016). Low yields in 2017 could be explained by environmental complications from Hurricane Harvey. The hurricane brought heavy precipitation (142.0 mm) and rapid soil saturation to the research site. Excessive irrigation or late-season rain in development stages past late bloom has been noted to be harmful to sesame plants (Langham et al., 2010; Sheahan, 2014b). Sesame was planted on June 8, 2017, and was in late bloom or was just entering ripening phase (days 78-85 after planting) during the time of the hurricane. Tillage effects on stand counts were not observed when analyzed across years at Beeville (Table 2.6).

Although the Edwards Plateau district is regionally different than the Southern High Plains, it was the closest and most comparable area based on available data from Sesaco. Sesame yields at Lubbock (837 kg ha^{-1}) were comparable to 2016 dryland averages for Edwards Plateau (678 kg ha^{-1}), although statistics were not analyzed to compare study averages to regional averages achieved by Sesaco (Sesaco, 2016). Lubbock had a shorter growing season with earlier freeze potential, sesame was not an ideal fit into the rotation due to late harvests in November just before wheat planting.

Sesame yields at Thrall on average appeared to be lesser (655 kg ha^{-1}) compared to 2016 regional averages for the Blacklands (998 kg ha^{-1}), although statistics were not analyzed to compare study averages to regional averages achieved by Sesaco (Sesaco, 2016). A lower yield average across years could be due to emergence issues in 2016 and weather complications in 2017. At Thrall in 2016, sesame emergence was delayed by over a month in the conventionally tilled plots. In 2017, Thrall experienced 227.0 mm of precipitation in three days during Hurricane Harvey. Late season rains during sesame's late bloom phase could be the reason for lower yields in 2017 (Langham et al., 2010). Tillage effects on stand counts were not observed when analyzed across years at Thrall (Table 2.6).

2.3.3.3 Grain Sorghum Yields

Sorghum did not produce grain at Beeville in 2016 due to bird predation, so data was analyzed by year and only two locations were included in 2016. Tillage did not impact yield at any location. Average yields for grain sorghum in Gregory, TX, for 2017 was 5049 kg ha^{-1} which was similar to yields obtained in Beeville in 2017 of 4600 kg ha^{-1} (Schnell et al., 2017). The average yield for grain sorghum in Lubbock across years was 3738 kg ha^{-1}. The yields were comparable to irrigated High Plains averages for Lubbock in 2016 (2817 kg ha^{-1}) although there was yield damage noted in that year by the performance testing group (Schnell et al., 2016). Irrigated yield averages reported by performance testing in 2017 (4923 kg ha^{-1}) for Hale County appeared to be greater than average yields across years in Lubbock, although statistics were not analyzed to compare study averages to regional averages achieved by Schnell et al. (2017). Hale County neighbors Lubbock County on the north and is where variety trails were held in 2017.

2.3.3.4 Double Crop Herbage Mass

There were differences in herbage mass production across summer crops, though tillage did not impact summer crop herbage mass. Data is presented across tillage treatments and year by crop for each location (Fig. 2.5).

The cover crop mix and grain sorghum produced the greatest amount of herbage mass at Beeville. Although herbage mass production was not significantly affected by crop type at Lubbock and Thrall, both locations had strong trends. There was a tendency for sorghum to produce the most herbage mass at Lubbock. Sesame at Thrall in 2017 tended to produce great amounts of herbage mass despite having lower grain yields that year; this could be due to the late season rains brought in by Hurricane Harvey. Cowpeas tended to produce the least herbage mass at Lubbock and Thrall.

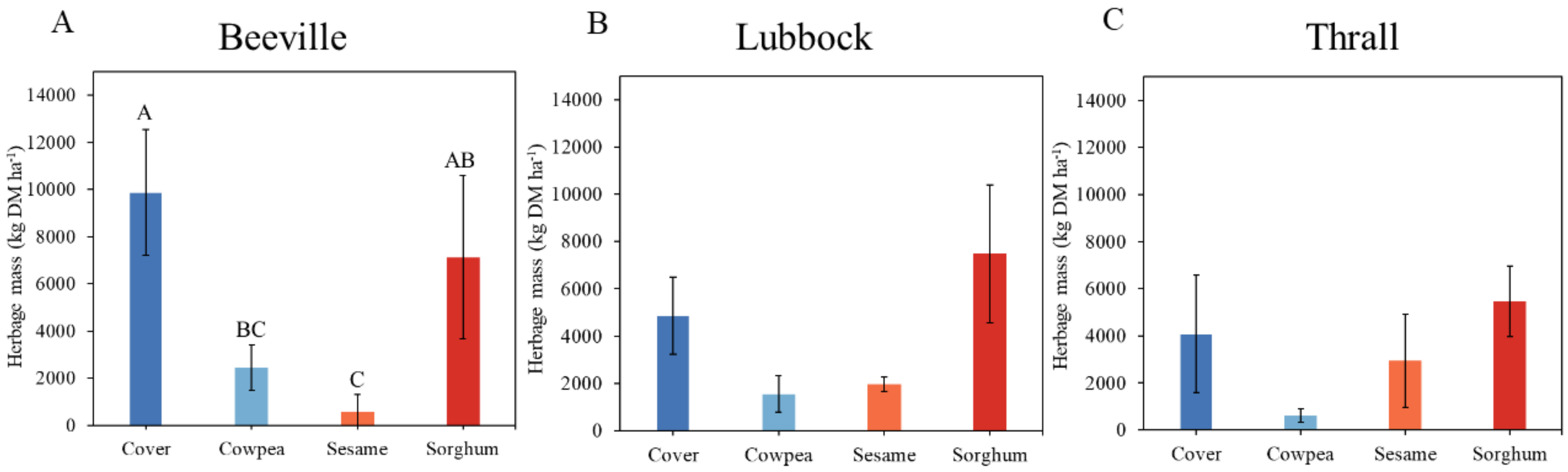

Figure 2. 5 Herbage mass (kg DM ha^{-1}) for all summer double crops by location, across years and tillage treatments. Bars represent standard deviation and different letters indicate significance at $P < 0.05$.

2.3.3.5 Cover Crops

Tillage did not impact cover crop species stand counts at any location though there were more millet plants than the other species at Beeville and a tendency at Lubbock (Table 2.7). Cowpea was often the second most counted plant within the cover crop species stand counts at all locations. Lubbock not only had greater species diversity at stand, but also had greater numbers of plants counted. Besides millet and cowpea, each location had frequency differences for observed species stands.

Table 2. 7 Cover crop species stand counts at each location across years.

	Species within cover crop mixture							
	Buckwheat	Cowpea	Guar	Lablab	Millet†	Peanut	Sunflower	Sunn hemp
Location	------------------------ Plants m^{-2}------------------------							
Beeville	0.04 b‡	1.2 b	0.2 b	0.04 b	4.3 a	0.3 b	0.06 b	0.2 b
Lubbock	5.6	4.4	1.1	0.2	9.0	0.5	0.8	3.0
Thrall	0.4	1.8	0.5	0.2	3.4	0.6	0	0.1

† Millets cannot be distinguished at this stage in development; foxtail millet and pearl millet were counted together

‡Different letters indicate stands significance ($P < 0.05$)

All locations had significant differences in herbage mass production by species in the cover crop mix, but tillage did not impact herbage mass production at any location (Table 2.8).

Table 2. 8 Cover crop herbage mass production in kg ha^{-1} by location.

	Species within cover crop mixture								
	Buckwheat	Cowpea	Foxtail Millet	Guar	Lablab	Peanut	Pearl Millet	Sunflower	Sunn hemp
Location	------------------------Herbage mass kg ha^{-1}------------------------								
Beeville	0.0 b†	174.7 b	2.3 b	96.5 b	3.2 b	0.6 b	1733.9 a	7.9 b	36.2 b
Lubbock	28.9 b	349.4 b	0.9 b	22.6 b	43.2 b	1.9 b	1730.3 a	742.6 b	197.2 b
Thrall	1.3 b	449.5 a	2.7 b	3.9 b	84.1 b	50.5 b	694.2 a	1.0 b	10.9 b

†Different letters indicate significance ($P < 0.05$) within location

At cover crop harvest, buckwheat was not often present because of its short season (8-10 weeks) (Pavek, 2016). However, at Lubbock in 2017, it appeared buckwheat produced a second generation, sprouting from the seeds produced in the first generation. We believe this to be possible based on timing of second emergence (11.6 weeks after initial planting) and the abundance of germinating buckwheat seeds on top of the soil outside the planted row. Lablab was often absent from stand counts and final herbage mass harvest, possibly due to a low seeding rate (Table 2.4). The proportion of lablab in the cover crop mix was kept at a low percentage because of the redundant functional group and physical similarities it shared with cowpea as well as the increased potential for known smothering of other crops. Guar did not compete well in a mixed species setting, as it did not produce great amounts of herbage mass compared to the other species in the mix but grew more vigorously (visually exceeding ~1.5 m) in a single species test row that was planted at Beeville. The peanut’s herbage mass presence in the cover crop mix may have been at a disadvantage due to competition for sunlight, as pearl millet may have shaded out may of the other species in the cover crop mix, peanut included. Although the seeding rate was much lower than most of the other crops, its presence was still accounted for in stands as well as herbage mass. The only issue with peanut that we encountered was at planting. Often times, peanut would plug the cone planter because of its size. Pearl millet significantly produced the most herbage mass at all locations and was also the species with the greatest crop establishment for stand counts at Beeville (Table 2.7 and 2.8). Sunflowers would not be recommended in years where there is limited soil moisture at planting due to the water requirements for germination (Kansas State University, 2009). Sunflowers in the cover crop mix had trouble emerging at Thrall in 2017 because of that, as did the monocrop of sunflowers planted in the same study field for a different project. Poor stand establishment of sunflower was likely the result of inadequate soil moisture at planting, as there is usually a high requirement for sunflower establishment (Kansas State University, 2009). Sunn hemp performed well in the mixed species cover crop, producing high amounts of herbage mass. Sunn hemp was also noted for being a proficient shade crop throughout the season. However, chemical termination of sunn hemp was difficult, as it was the only species in the mix resistant to glyphosate and had to be further controlled with 2,4-D (2,4-Dichlorophenoxyacetic acid, Dow AgroSciences, Indianapolis, IN).

The species that primarily dominated stand counts as well as herbage mass produced were pearl millet and cowpea (Table 2.8). Based on unaffected wheat yields (Fig. 2.2) and wheat herbage mass (Fig. 2.3), cover crops may integrate well in a winter wheat rotation at all locations. There are a few species in the cover crop mix that could be eliminated due to lack of competition and low herbage mass production, most notably, German foxtail millet, lablab, sunflower and guar.

2.4 Conclusions

It may be concluded that after two years of research, double cropping in a winter wheat rotation may be possible at all locations, but with considerations. Sorghum and sesame were observed to have negative impacts on wheat production at Lubbock, but more years of study are needed to conclude results from double cropping in winter wheat with sesame and sorghum at that location. Reduced tillage appears to positively impact wheat grain yields at Lubbock. Location impacted cowpea yields, as production was greater in Lubbock, possibly due to optimal nighttime temperatures. Reduced tillage may be of a greater importance to the sustainability of a wheat–double crop rotation in water limited environments.

3. IMPACTS OF TILLAGE AND DOUBLE CROPPING ON SOIL MOISTURE DYNAMICS, INFILTRATION, AND AGGREGATE STABILITY

3.1 Introduction

A fallow period following winter wheat is commonplace in Texas agriculture, as water is often limited. The practice of double cropping, continual cultivation on agriculture land, minimizes the fallow period. By keeping the ground covered year-round, erosion is reduced and OM is increased, which may ultimately lead to improved soil structure (Blanco and Lal, 2008). Despite the many benefits double cropping can offer, there is still reluctance to full adoption of the practice. Some of the hesitance to double cropping is due to environmental uncertainties—weather and adequate soil moisture for the following rotational crop (Dhuyvetter et al., 1996; Borchers et al., 2014).

A possible way to reduce additional moisture lost during the second growing season is reduced tillage (Dhuyvetter et al., 1996). Disturbance of the soil through tillage increases evaporative moisture loss and because residue cover is buried, instances of runoff worsen (Baker et al., 2006; Lal 2001). No-till systems have potential to build soil organic matter (OM) and sequester C through slowed decomposition of crop residues, resulting in increased water holding capacity (Unger and Wiese, 1979; Franzluebbers et al., 1995b) and enhanced aggregation and structural stability (Six et al., 2000). Additionally, reduced tillage systems capture and retain more water when precipitation events occur (Baumhardt and Jones, 2002), and specifically no-till has been credited with improving infiltration rates and increasing water holding capacity (Franzluebbers et al., 1995a-b; Franzlubbers, 2002).

Integration of crop rotations and cover crops into cropping systems magnifies the beneficial effects of tillage reduction (Keeling et al., 1989; Havlin et al., 1990; Bordovsky et al., 1994). Keeping the soil covered also captures rainfall more effectively through preferential flow patterns from root systems, thereby reducing runoff (McVay et al., 1989; Dabney, 1998; Unger and Vigil, 1998). It would be expected that double cropping will have some of the same soil health benefits that cover cropping offers. What is not entirely known are the combined effects reduced tillage and double cropping have on soil moisture and physical soil properties in potentially water-limited regions like Texas. Lack of such knowledge is an issue, as adequate soil moisture is often linked to the success or failure of a crop.

By understanding the combined impacts of double cropping and tillage on soil moisture and the physical properties that promote water procurement, then conservation efforts may be tailored to management practices within different climates and soil types. Thus, the objectives of this research were to 1) evaluate the effects of double cropping and tillage in a winter wheat cropping system on soil moisture throughout the growing season; and 2) evaluate wheat-double crop rotation and tillage influences of soil physical properties including wet aggregate stability and infiltration.

3.2 Materials and Methods

3.2.1 Study Sites

The study was conducted at three locations—Beeville, Lubbock and Thrall, TX. The Beeville (28° 27’N 97° 42’W) research site was supplementary irrigated with a sprinkler system, and the study was implemented on a Parrita sandy clay loam (loamy, mixed, superactive, hyperthermic, shallow Petrocalcic Paleustoll) in the South Texas Plains ecoregion. Average annual rainfall for this location is 789.0 mm (NCDC, 2018), with average air temperatures of

29^{o}C (high) and 17^{o}C (low) (National Oceanic and Atmospheric Administration, 2018). The plots were 9.1 m long by 3.0 m wide with four rows per summer double crop plot (76.0 cm row spacing). The Lubbock, Texas (33° 41'N 101° 49'W), research site was supplementary flood irrigated, and the study was implemented on an Olton clay loam (fine, mixed, superactive, thermic Aridic Paleustolls) in the High Plains ecoregion. Average annual rainfall for this location is 489.0 mm yr^{-1}, with average air temperatures of 24^{o}C (high) and 8^{o}C (low) (National Oceanic and Atmospheric Administration, 2018). The plots were 12.2 m long by 4.1 m wide with four rows per summer double crop plot (102.0 cm row spacing). The Thrall, Texas (30° 36'N 97° 18'W), research site was dryland, and the study was implemented on a Burleson clay (fine, smectitic, thermic Udic Haplusterts) in the Blackland Prairie ecoregion. Average annual rainfall for this location is 893.0 mm yr^{-1}, with average air temperatures around 26^{o}C (high) and 13^{o}C (low) (National Oceanic and Atmospheric Administration, 2018). The plots were 22.9 m long by 7.6 m wide with ten rows per summer double crop plot (76.0 cm row spacing). The dates and amount of irrigation at Beeville and Lubbock sites are listed on Table 2.1 in Section 2.

The experimental design was a three replicate, split-plot within a randomized complete block design. Tillage treatments were the main plots and summer double crop treatments were the subplots. The tillage treatments consisted of conventional till, strip-till, and no-till. Conventional till was performed before double crop and winter wheat planting to a ~15.2 cm depth with a 1.5 meter offset disc (Hay King, OPDM 28-22, K and M Manufacturing Company Inc., Taylor, TX, USA), to a ~15.2 cm depth with a 4.2 meter wide tandem disk (John Deere, Moline, IL), followed by a custom built five bottom lister plow, and a ~15.2 cm depth with a 6.1 meter tandem plow (Case IH, RMX370, Sturtevant, WI, USA), at Beeville, Lubbock, and Thrall respectively. Often conventional tillage was performed the same day as planting at

Beeville and Thrall due to logistical complexities. Strip-till was performed once a year, just before double crop planting with no tillage occurring prior to wheat planting. No-till main plots were undisturbed besides summer fertilizer applications that were often knifed in at Thrall and Lubbock. Summer double crops and winter wheat were planted using a no-till planter for the summer double crops and a no-till drill for the winter wheat. The summer double crop treatments consisted of fallow, sesame, grain sorghum, cowpea, and a nine-species cover crop mix.

3.2.2 Cropping System Management

For each location, region specific winter wheat varieties were selected. At Beeville, 'TAM 305 was planted in 2016 and 2017. At Lubbock, 'TAM 304' was planted, in both years. In Thrall 'TAM 304' was planted in year 1, and 'WB Cedar' in year 2 (Section 2, Table 2.2). At Thrall, a conventional drill was used to plant winter wheat in 2016 rather than a no-till drill. This last-minute change was made due to equipment breakdown and approaching rains. The seeding rate for winter wheat 'TAM 304' at Lubbock in 2017 was increased to secure yields goals potentially compromised by late season planting. Winter wheat was planted on 19.0-cm row spacing at all locations. In the strip-till treatment, wheat was planted the same as the no-till treatment—strip tillage was performed once a year before double crop planting using an Orthman 1tRIPr implement (Lexington, NE). Tillage was performed just prior to planting which did not allow soil to settle or mellow and could have affected emergence in some locations and years.

Lubbock and Thrall's N fertilizer source was urea ammonium nitrate (UAN, 32-0-0), and Beeville's was urea (46-0-0) (Section 2, Table 2.3). Fertilizer applications were applied based on yield potential for each region and nutrient concentrations of soil samples taken prior to planting at the 0-15.0 cm depth. At Beeville all fertilizer was broadcast applied in granular form. In Lubbock, UAN was diluted with water at a 1:1 ratio. Nitrogen (N) was applied to wheat at each location at planting (1/3 of total N) followed by a topdress application before jointing (2/3 of total N). Fertilizer at Lubbock was applied to double crops using a four-row sidedress applicator (4 meters) with knives mounted behind coulters. Wheat planted at Lubbock in 2017 was fertilized using an eight-row boom (8.1 meters) on a tractor, applied using Teejet StreamJet, 7-way fertilizer spray nozzles (TeeJet Technologies, Glendale Heights, IL, USA). Fertilizer at Thrall was applied using a combination of methods. For the summer crops, UAN (32-0-0) was sidedress applied using a 4-row knife rig to dribble fertilizer 10.2 cm below the soil surface and 7.6 cm away from the root zone. In addition, an application of granular P (triple superphosphate, 0-46-0) and K (muriate of potash, 0-0-60) was broadcast applied using a hand spreader. Winter wheat was fertilized using TeeJet StreamJet, 7-way nozzles.

The summer double crop treatments were sesame, grain sorghum, cowpea, and a cover crop mixture (Section 2, Fig. 2.2 and Table 2.4). The seed ratio was determined based on crop water tolerance, heat adaptiveness, vigor, and biomass production (Section 2, Fig. 2.1 and Table 2.4; USDA-NRCS, 2011; USDA-NRCS, 2014; USDA-NRCS, 2016d). Figure 2.1 in Section 2 depicts a ratio of the cover crop species within the mixture. Seeding depth by species was considered, and an average seeding depth of ~2.5 cm was chosen for cover crop species planted in bulk. The cowpea variety used in 2016 was the same variety used in the cowpea double crop, Texas Pinkeye Purple Hull. In 2017, a forage type cowpea variety was selected, Iron and Clay. Iron and Clay cowpeas are 120-day maturity, twice as long as Texas Pinkeye Purple Hull (54-60 days).

Summer fallow was implemented as a treatment for comparison. Summer double-crops were planted with a John Deere Max Emerge planter (John Deere, Moline, IL) unit with ALMACO cone seeders (ALMACO, Nevada, IA) on a 76.0-cm row spacing in Thrall and Beeville. At Lubbock, double crops were planted with a John Deere Max Emerge Plus (John Deere, Moline, IL) unit with ALMACO cone seeders (ALMACO, Nevada, IA) on 102 cm row spacing in Lubbock to follow common row spacing for the areas. The cowpea variety was changed at all locations after year 1 from a determinate variety (Texas Pinkeye Purple Hull) to an indeterminate variety (Golden Eye Cream) to increase yield potential (Section 2, Table 2.2). Cowpea seed was pre-treated with Apron XL (a.i. Mefenoxam) fungicide (Syngenta, Greensboro, NC) and Cruiser 5FS (a.i. Thiamethoxam) insecticide (Syngenta, Greensboro, NC) and species specific powdered *Bradyrhizobium* (N-Dure, Verdesian, Cary, NC). Sorghum seed was pre-treated with Apron XL fungicide and Cruiser 5FS insecticide, and a safener (Concep III Seed Treatment, Syngenta, Greensboro, NC). The cover crop seed mixture was pre-treated with Apron XL fungicide and Cruiser 5FS insecticide, as well as Concept III safener. The mixture was treated at the time of planting with a *Bradyrhizobium* species inoculant, combining—powdered *Rhizobium* (same as cowpea) and granular (Primo GX2, Verdesian, Cary, NC) to help with larger seed inoculation (Flynn, 2015).

Weed control was enacted in the summer double crop using a burndown and pre-emergent herbicide combination before planting and in-season control was done with a hooded sprayer and broad-spectrum herbicide. Chemical termination of the cover crops was enacted post subsampling harvest of herbage mass (Section 2, Table 2.2 and 2.5). Crop specific post-emergence herbicides were used when needed. Products used were identified with minimal plant-back restrictions. At Beeville, herbicide applications were applied using a backpack sprayer as well as a hooded sprayer and boom sprayer (Section 2, Table 2.5). At Lubbock, bulk herbicide applications were applied to the entire trial with an eight-row boom on a tractor (Section 2, Table 2.5). Plots that were individually sprayed, used the Milo-Pro with a four-row boom out of CO_2 canisters on a tractor. A four-gallon backpack sprayer with a hand-held, two-row boom was used to spray volunteer wheat in 2016, as well as fallow plots and termination of cowpea plots in 2017. Fallow plots and alleys in 2017 were also sprayed using a four-gallon backpack sprayer with a hand-held, two-row boom.

Sugar-cane aphids (Melanaphis sacchari) and bird predation were observed at all locations. Both sorghum hybrids used were sugar-cane aphid tolerant, yet insecticide was applied in August of 2016 (Sivanto 200 SL, a.i. Flupyradifurone, a.i. 0.82 kg ha-1, Bayer Crop Science LP, Research Triangle Park, NC) at the recommended threshold to protect yield at Thrall and at Lubbock (Besiege, a.i. Lambda-cyhalothrin, a.i. 0.29 kg ha-1 and a.i. Chlorantraniliprole, a.i. 0.59 kg ha-1, Syngenta, Greensboro NC). At Thrall and Lubbock in 2017, a.i. 0.94 kg ha-1 of Sivanto 200 SL was applied at both locations and at Beeville, Transform WG (a.i. sulfoxaflor, a.i. 0.05 kg ha-1, Dow AgroSciences LLC, Indianapolis, IN) was applied when sugar-sane aphids reached the population threshold in October of 2017. Heavy bird predation at Beeville resulted in a complete crop loss for the grain sorghum in 2016, thus yields were not taken for Beeville that year. Bird predation occurred at Lubbock and Thrall as well, but to a lesser extent. Wire mesh crop cages were centralized in each sorghum plot at all locations in 2017 to eliminate impacts from bird depredation. In Thrall and Beeville, cages were 1.5 m wide (across two rows) by 1.2 m long and in Lubbock were 2.0 m wide (across two rows) by 1.2 m long. In 2016 at Lubbock, conventionally tilled plots had visible bird damage rated greater than 85% for some grain heads. On-going bird damage called for multiple subsample grain sorghum harvests in

Thrall in 2016. Bird damage ratings were determined by visual assessment of each sorghum head within the subsample harvest; it is recognized that estimates increase error in the study. Sorghum heads that were rated above 40% were thrown out of the data set. In 2017, Beeville experienced issues with sorghum ergot disease which was caused by the fungus Claviceps Africana; all plots were infected.

3.2.3 Temporal Soil Moisture

After summer double crop emergence in 2016, 5.1 cm outer diameter aluminum access tubes, 1.8 m length, with a 10.0-cm long (5.4 cm outer diameter) collar at the top of the tube were installed near the center of each plot within a row. At planting and tillage, tops were removed, and the bottom portion protected from equipment and entry of soil into the tube. Soil moisture content was taken throughout both growing seasons using a neutron moisture meter (503 ELITE Hydroprobe, InstroTek, Inc.) at 20.0, 40.0 cm depths at Thrall and Beeville, and 15.0, 30.0, 45.0, 60.0 cm at Lubbock. Neutron moisture meter measurements were taken approximately every two weeks during double crop growth cycle to capture the timing of crop growth stages for the wide-variety of crops. During the wheat growing season, measurements lessened to once a month until stem elongation in the spring, since growth and evapotranspiration are reduced during the winter months.

Soil moisture was reported as ‘total water’ in mm within the 0-60.0 cm portion of the top soil which is equivalent to volumetric water content if the total amount of water is divided by the total amount of soil within the top 60.0 cm. The largest differences in moisture deficits are often confined to the upper 60.0 cm for crop water use (Unger and Vigil, 1998). Neutron counts taken at various depths are converted into total water for a designated volume of soil by using a calibrated slope and intercept specific to each instrument. Calibrations were obtained for each location’s neutron moisture meter. The laboratory calibration method using a barrel of sand saturated with water was used to calibrate instruments at Beeville and Lubbock (InstroTek, Inc., 2018). For calculating total water at Thrall, a previous field calibration was used. The calibration was performed using the same neutron moisture meter on a different field, but on the same soil type (Burleson clay).

3.2.4. In-situ Infiltration

Sprinkler infiltration tests were carried out using the Cornell sprinkle infiltrometer at the Thrall and Lubbock locations (van Es, H.M., and R.R. Schindelbeck. 2003). This instrument is a portable rainfall simulator that was placed onto a single, 24.1 cm infiltration ring. The height of water was recorded every three minutes after the initial time of runoff. The simulated rainfall rate was set to 30.0 cm hr^{-1}. This method was performed in 18 plots with three replications per plot. Fallow, sorghum, and cover crop subplots in no-till and conventional till main plots were measured. Water that was degassed the previous night was poured into the infiltrometer until it reached the 40.0-cm mark. The unit was depressurized before each measurement was taken while on a flat platform away from the ring, as to not disturb the area of measurement. Surface soil moisture measurements were made at the time of infiltration measurements using a Theta Probe (ML3 ThetaProbe Soil Moisture Sensor, Delta-T Devices, Cambridge, UK). Three measurements around each ring were taken. The percent clay was determined in the lab for Thrall using the Bouyoucos hydrometer method for particle size analysis (Bouyoucos, 1962). Lubbock’s clay percentage was obtained from soil web survey (Soil Survey Staff, 2018).

Infiltration readings in Lubbock 2017 were taken over two days starting on June 13th. There was a 25.0 mm rain event on the 15th of June and two measurements in a no-till sorghum plot were affected and were not included in the data. This time frame is not ideal, as more days could increase error in the study and can leave room from environmental effects.

3.2.5 Wet Aggregate Stability

Aggregates were gathered at each location from the surface soil layer. Three samples from each plot were composited. Using a trowel, a soil surface sample measuring 10.0 x 3.0 x 2.0 cm was removed and placed into a paper bag. Samples were then air dried. The dried soil aggregates were sent to The Cornell Soil Health Testing Laboratory in Ithaca, NY, where wet aggregate stability was tested using the Cornell sprinkle infiltrometers (van Es and Schindelbeck, 2017).

3.2.6 Statistical Analysis

Soil moisture over time was statistically analyzed as an ANOVA with measurement day as a repeated measure in PROC GLM (SAS Institute Inc., Cary, NC, version 9.4, 2013). The LS-MEANS function was used to determine mean separation of repeated measures among the various effects at $P < 0.05$ significance. When using PROC GLM an additional F-test was used to account for the nonstandard error structure, using Tillage as the hypothesis effects and replication × tillage as the error term. Soil moisture was analyzed for all three locations for tillage (main plot) and by double crop (sub plots).

Statistical analysis for time-to-runoff and wet aggregate stability were conduced using SAS using SAS version 9.4. Analysis of variance (ANOVA) was conducted using PROC GLIMMIX. Location, tillage, and summer crop were treated as fixed effects. Replication was considered random using the RANDOM statement. There were significant location × tillage and location × crop interactions, so data is presented by location. The function LS-means with the

PDIFF option was used to determine mean separation among the various effects at $P < 0.05$ significance.

3.3 Results and Discussion

3.3.1 Temporal Soil Moisture

3.3.1.1 Soil Moisture in Beeville, Texas

Soil moisture was measured on 13 occasions (days) between August of 2016 and January of 2018 (Fig. 3.1).

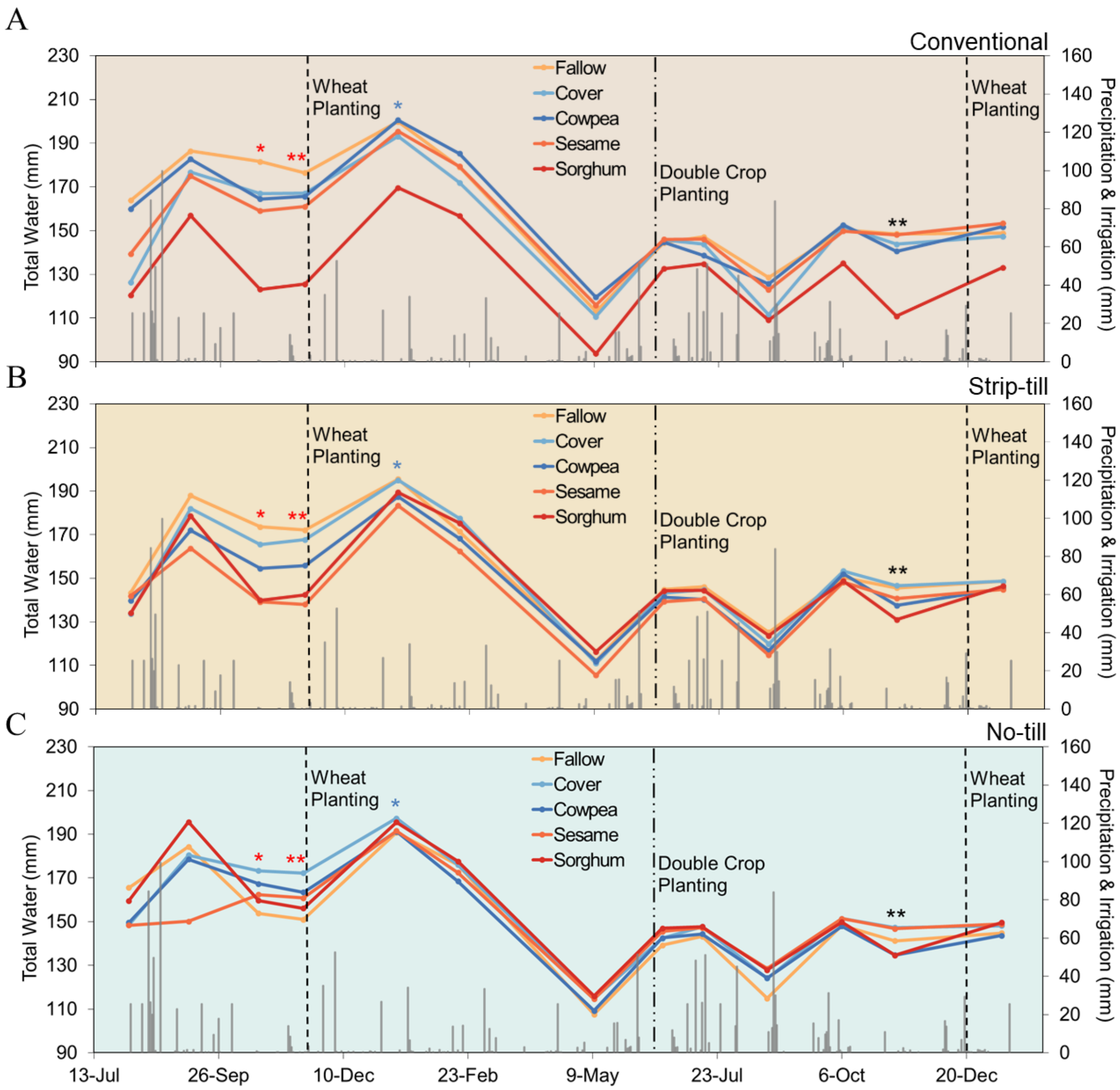

Figure 3. 1 Soil moisture (mm) over time by tillage (a = conventional till, b = strip-till, and c = no-till) as affected by double crop treatments in Beeville for the 0-60 cm soil layer. * (*P* value < 0.05) and ** (*P* value < 0.01). Red asterisks indicate tillage × crop interaction and blue asterisks indicate significant tillage effects at the same levels of significance. Precipitation and irrigation are displayed as grey bars at the bottom.

Temporal soil moisture at Beeville had one measurement day (day 12) that was significantly affected by the double crop treatment (Fig. 3.1). A tillage × summer crop interaction was observed for day 3 (October 20th, 2016) and day 4 (November 16th, 2016; Fig. 3.1)

Rain events in November (30.0 mm) and irrigation (35.0 mm) on November 28th just before wheat planting could have ameliorated the interactions between the tillage treatments and the double crop plots that existed earlier in the double crop growing season (Fig. 3.1). On day 5 (January 11th, 2016, the measurement after wheat planting), there were no differences observed between different crop treatments despite conventional till grain sorghum. Day 5 was the only day of measurement in the study where all crops were impacted the same by tillage. Adequate rain and irrigation events appeared to replenish the soil profile, bringing the soil moisture up to one of the greatest points throughout the study. There was one irrigation event throughout the 2016 wheat growing season just before day 5, January 11th, 2017 (27.0 mm). A steep decline from the point of peak soil moisture (day 5) to around harvest (day 7) was observed. The changes in soil water use while winter wheat was in season resembled the cumulative water use graphs reported in a dryland winter wheat study conducted by Brown (1971) near Bozeman, Montana. Both graphs display trends from winter wheat soil moisture use (Brown, 1971). On day 7 (May 10th, 2017), the soil moisture was at its lowest point during the study, this was just before wheat harvest (May 15th, 2017) and right before double crop planting (June 8th, 2017). After wheat harvest in May 2016, seasonal rains appeared to increase total water in all crop profiles just before double crop planting in 2017.

Fallow plots were observed to contain the greatest amount of soil moisture in the conventional till and strip-till plots in the 2016 double crop growing season and continuing on into winter wheat (Fig. 3.1). However, under no-till, fallow plots were contained less soil moisture than some of the other double crop plots, but there were smaller magnitudes of difference comparatively to the strip-till and conventional till plots. The presence of weeds (data not presented) in the no-till plots could have influenced the decrease in soil moisture, as this study location had continuous weed competition. The summer crop treatments in 2017 have less magnitudes of difference than the previous year.

After cover crops were terminated on August 25th, 2016, the plots previously containing the mixture were observed to contain some of the most soil moisture compared to the other cropped plots. With the precipitation events that occurred after cover crop harvest, likely residue cover reduced runoff from the plots. When runoff is impeded by physical crop barriers, increased infiltration in the areas of greater residue is often observed as well as decreases in soil water evaporation from soil shading (Nielsen, 2006). For example, Nielson (2006) found that with increases in wheat residue ranging from 0 to 10,088 kg ha^{-1} that precipitation storage efficiency increased from 15% to 35%.

Plots containing cowpeas tended to contain the third least amount of soil moisture during the 2016 double crop growing season. After winter wheat was planted, soil moisture differences became less pronounced and double crops plots tended to average out continuing on into the 2017 double crop growing season. The switch to a greater yielding cowpea variety appeared to not affect soil moisture at this location in 2017 double crop growing season.

The sesame plots tended to have the second lowest soil moisture out of many of the measurement days amongst the three tillage treatments. On measurement day 2 (September 8th, 2016), sesame plots in the no-till treatments were observed to be at the lowest moisture level compared to the other double crop plots, however, this was not a statistically significant. Sesame can have water use demands ranging from about 304.0 mm to 406.0 mm (Landham et al., 2010).

From 2016 to 2018, plots with grain sorghum under conventional tillage had consistently lower soil moisture than the other conventional tillage double crop plots as well as double crop plots under strip-till and no-till. There was an increase in moisture observed post herbicide treatment on September 2nd, 2016, which is to be expected with crop senescence. The moisture deficits often observed in both sesame and sorghum plots were likely driven by crop water use. Sorghum can exhibit water requirements from 450.0 to 650.0 mm (Assefa et al., 2010). Both are relatively high when compared to cowpea which is around 200.0 to 350.0 mm (Singh, 2014). Based on consistently lower soil moisture in the conventional grain sorghum plots, reduced tillage could be better suited for grain sorghum production in the South Texas Plains ecoregion.

Soil moisture deficits occurring at time of planting are often reflected in subsequent wheat grain yields (Nielsen and Vigil, 2005). Nielsen and Vigil (2005) found that dryland wheat yields were linearly related to soil moisture availability at the time of planting. Often, double cropping or cover cropping influences these differences of soil moisture at time of planting (Zentner et al., 1996; Nielsen and Vigil, 2005; Nielsen et al., 2016; Schlegel et al., 2017). Soil moisture at the time of wheat planting in 2017 was lower than the previous year, possibly due to the intensification of cropping. Yields could be affected for the 2018 harvest.

At the Beeville location in years 1 and 2, tillage had little effect on soil moisture (Fig. 3.1). There were no statistical differences between tillage treatments except on day 5, January 11th, 2017 (no-till > conventional > strip-till). Although statistical differences were not frequently observed, the no-till plots generally had less variability between the different double crop plots than did strip-till and conventional, conventional having the greatest variation. Similar findings were observed by Potter and Chishester (1993) on a Vertisol in Temple, TX, where soil moisture in conventionally tilled plots below the 0 –7.5 cm surface of soil were not statically different compared to the 6 year no-till and the 10 year no-till plots. Additionally, Munawar et al. (1990) had similar findings for their conservation tillage study in Lexington, Kentucky—no significant differences in soil moisture for all sampling dates were observed, but no-till soil moisture was generally greater compared to conventional tillage (Munawar et al., 1990). Tillage does not appear to greatly impact soil moisture at this location and on this particular soil under minimal irrigation.

For the Beeville location, with a mean annual precipitation of 789.0 mm year^{-1} (NCDC) with additional irrigation, double cropping may be possible as soil moisture post wheat planting in both years appear to recover. After wheat planting, differences were not observed between plots for 2016 and 2017. Despite supplemental irrigation, the soil moisture profile during the double cropping season for 2017 was lower than in 2016 and differences fewer. Soil moisture at time of planting wheat in 2017 was lower than the previous year and could have negative effects on wheat grain yields for the 2018 harvest. Overall, planting double crops had a much larger impact on total water than tillage type (Fig. 3.1). Sorghum consistently used the most soil moisture especially in the conventional tillage. Plots planted with grain sorghum had the least amount of water while fallow and cover crop plots had the most. If the soil profile can recover from moisture depletion brought on by the double crops, then it is predicted that grain yields will not be affected. From the farmer’s perspective, cover crops could appear to be a viable option in a winter wheat rotation in terms of soil moisture conservation in this region of Texas under these environmental conditions. However, double cropping in Beeville might only be possible with supplemental irrigation combined with average precipitation.

3.3.1.2 Soil Moisture in Lubbock, Texas

Soil moisture was measured on 17 occasions between August of 2016 and December of 2017 (Fig. 3.2). Tillage × crop interactions were observed for days 10 (March 20th, 2017), 11 (April 11th, 2017), and 12 (April 12th, 2017). Some of the double crop treatment plots were misplanted in 2017, and a second ANOVA for repeated measures was analyzed separate for days 15-17.

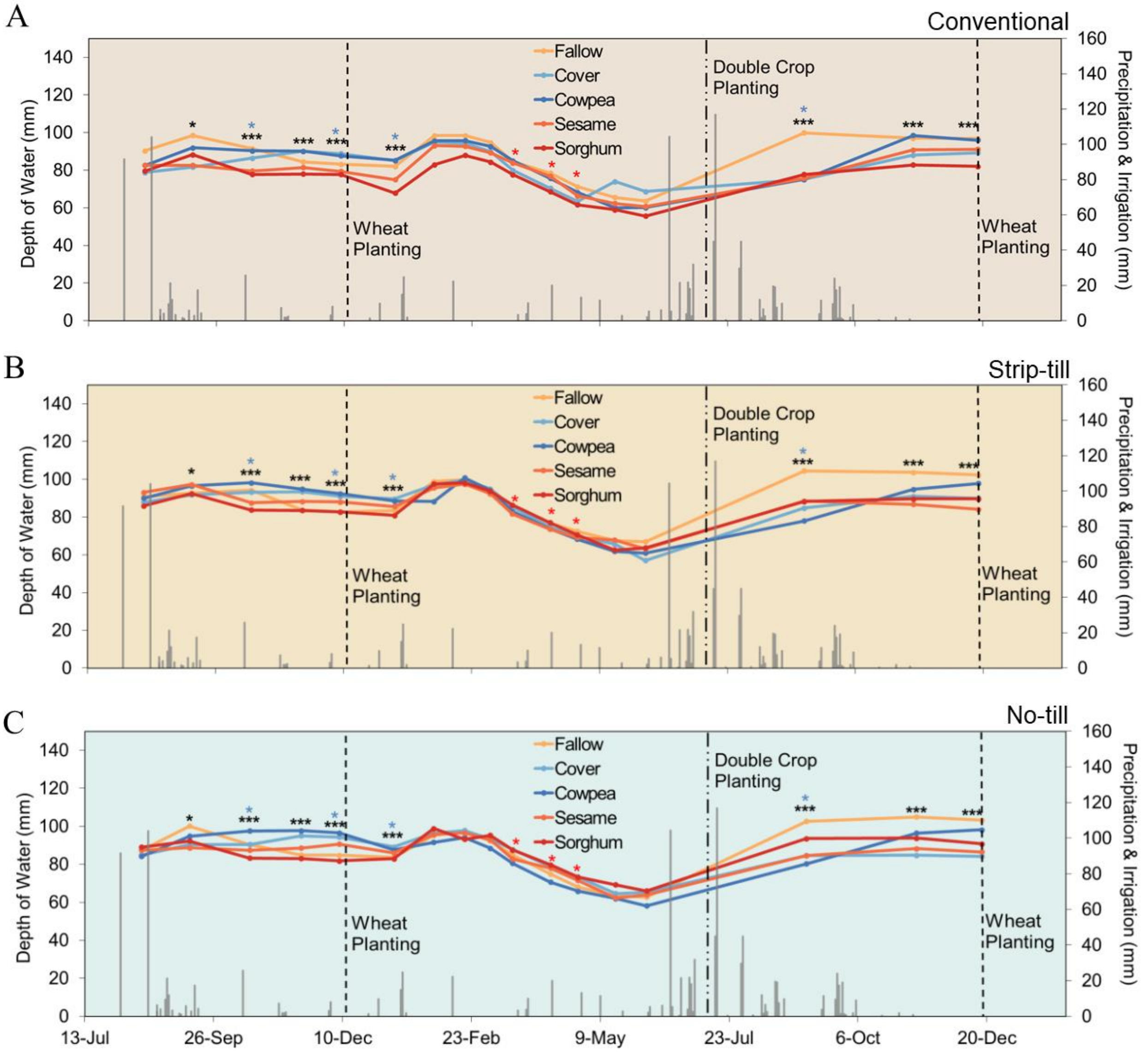

Figure 3. 2 Soil moisture (mm) over time by tillage (a = conventional till, b = strip-till, and c = no-till) as affected by double crop treatments in Lubbock for the 0-60 cm soil layer. * (*P* value < 0.05); ** (*P* value < 0.01); *** (*P* value < 0.001). Red asterisks indicate tillage × crop interaction and blue asterisks indicate significant tillage effects at the same levels of significance. Precipitation and irrigation are displayed as grey bars across the bottom.

The increased water use at day 15 from these two crop treatments could potentially be explained by increased crop productivity and change in cowpea variety (Fig. 3.2). The average total water was significantly lower (84.0 mm soil moisture average) for this soil type and environment compared to Beeville (150.0 mm soil moisture average).

Precipitation throughout the double crop growing season in 2016 (169.0 mm) was 77% lower than in 2017 (299.0 mm). However, when combined with irrigation, the amount of water put on throughout the growing season was greater in 2016, 441.0 mm in 2016 and 403.0 mm in 2017. There were three large irrigation events in 2016 (July 12th, 2016, 89.0 mm and August 3rd, 2016, 91.0 mm, and August 19th, 2016, 10.0 mm), but gradual precipitation events throughout the 2017 growing season resulted in water capture and stored more soil moisture.

Fallow plots in 2016 appeared to experience decreases in soil moisture in all tillage types compared to cover crop and cowpea plots that were harvested/ terminated in late August and late September, respectively. Fallow fields in the Great Plains region of the United States are often subjected to harsh environmental effects of a semi-arid summer. Massee and Cary (1978) attribute fallow soil water evaporation to solar energy exposure, turbulent wind energy and lack of physical separation from these energy sources (lack of residue on soil surface). The less impactful water events (precipitation and irrigation) in combination with fallow plots having increased exposure to high winds (22.8 km h^{-1}, 60-year average) and solar energy could be help explain the trending decrease of soil moisture in the 2016 double crop growing season (National Oceanic and Atmospheric Administration, 1998). In 2017, fallow plots tended to have greater soil moisture than the double crop plots. Absence of soil moisture measurements throughout the 2017 summer double crop growing season cannot explain the possible in-season differences that could have occurred. However, frequent precipitation events in the summer of 2017 and the absence of a growing crop may have contributed to the greater soil moisture levels in fallow plots in 2017.

The soil moisture profile in the cover crop plots gradually increased after termination (August 26th, 2016) until reaching the highest point of moisture in the summer growing season. It appeared that early termination (15 weeks before wheat planting) allowed the soil moisture profile to recover in time for wheat planting on December 12th, 2016. Similar results were seen in Nielsen and Vigil's (2005) study where early termination of a summer legume green manure increased water storage (mm) by 89% compared to late termination which on average was 5 weeks later and about 10 weeks before wheat planting. In 2017, cover crops were harvested on October 12th, which only gave the soil moisture profile 8 weeks to recover in time for wheat planting on December 7th, 2017. The growing season in 2017 was increased by 23 days as compared to the growing season in 2016. The increased moisture use due to a longer growing season could be detrimental to 2018 wheat yields. Cover crops were shredded in 2017, but not chemically terminated as they were in 2016, this could be the reason for the slower soil moisture recovery in the 0-60.0 cm layer of soil. Similarly, Daniel et al. (1999) observed greater volumetric water content (2.4 $m^3 m^{-3}$) in no-till cotton plots that previously contained cover crops terminated using glyphosate herbicide as compared to conventional plots terminated using a mower and disk. We speculate that soil moisture at time of wheat planting could be the key to a successful wheat crop. Based on these findings, chemical termination of cover crops, as well as increasing the time between termination and wheat planting would be recommended to ensure greater soil moisture recovery going forward.

Soil moisture in the cowpea plots varied between 2016 and 2017 growing seasons. In 2016, cowpea plots were harvested on September 26th just after the day 2 measurement

(September 12th, 2016). An increase in soil moisture from lack of growing crops can be observed on day 3 which continues until wheat planting. Similar results for soil moisture recovery post cowpea harvest were observed at Beeville in 2016. Same as the cover crops, early harvest and termination lead to soil moisture profile recovery in time for wheat planting. In 2017, cowpeas were harvested on October 12th, 2017, and were chemically terminated the following day. An increase in soil moisture post-harvest/termination was observed for day 15 (November 10th, 2017), and continued until wheat planting. Although harvest was much later in 2017 than 2016, chemical termination in combination with gradual precipitation events appeared to allow soil moisture profile recovery in time for wheat planting. Although soil moisture was not statistically different on day 15 (August 15th, 2016) for cowpea and cover crop (data not shown), herbicide termination of cowpea plots appeared to be effective in aiding soil moisture profile recovery (days 16-17) in time for wheat planting. Another possible reason for the successful moisture recovery is total water use. Cowpea plots tended to have less soil moisture at the 15.0 cm measurement depth than at lower depths in the profile (data not shown) and water from lower in the profile could have moved upward via capillary rise, contributing to increased soil moisture which was observed in days 16-17.

Plots containing sesame appeared to contain less soil moisture compared to other double crop plots likely due to sesame's long growing season and late harvests. Sesame plots were harvested on measurement day 4 (November 16th, 2016). The soil moisture profile appeared to not regain sufficient total water in time for planting due to the late harvest. Soil moisture at the time of wheat planting was significantly lower in fallow, sesame, and sorghum plots. Schlegel et al. (2017) found that winter wheat yields were positively correlated with soil water at the time of planting as well as growing season precipitation. Nielsen et al. (2002) also found the same relationship between soil water at planting and wheat grain yields. Lower soil moisture in sesame plots continued to be observed well into the wheat growing season (day 6, January 10th, 2017) and differences greater in plots under conventional tillage. as seen on measurement. In 2017, sesame was likely terminated by an early freeze on October 28th, 2017, so growth and water use likely declined prior to harvest (November 10th, 2017, day 16). Sorghum and sesame plot's soil moisture appeared to not recover in time for wheat planting. This could possibly be explained by the minimal precipitation this location received post freeze on October 31st (2.0 mm) and November 8th, 2017 (1.0 mm; Weather Underground, 2018). Wheat growing in previous sesame plots are likely to be affected in 2018.

Sorghum plots often contained less soil moisture compared to the other plots in the summer double crop growing season of 2016. Similar trends were seen in Beeville for water use by sorghum. Sorghum plots were harvested on October 24th, 2016, which was between measurement days 3 and 4. After day 4, soil moisture began to plateau in the sorghum plots and the soil profile did not regain sufficient moisture in time for planting wheat. Soil moisture at time of wheat planting was significantly lower in fallow, sesame, and sorghum plots compared to fallow, cover and cowpea, which likely affected wheat yields. Lower soil moisture in sorghum plots continued to be observed well into the wheat growing season (day 6, January 10th, 2017), but persisted for a longer period of time in the plots under conventional tillage. Sorghum as well as sesame were likely terminated by an early freeze on October 28th, 2017. Growth and water use likely declined prior to harvest (day 16, November 10th, 2017). In 2017, sorghum, sesame, and cover crop plots' soil moisture did not recover in time for wheat planting. This could possibly be explained by the minimal precipitation this location received post freeze on October 31st (2.0 mm) and November 8th, 2017 (0.8 mm). Wheat yields are likely to be affected for 2018 based on previous findings and observations already made from year 1 of this study (Nielsen and Vigil, 2005; Nielsen, 2006; Schlegal et al., 2017).

Statistical differences in soil moisture for Lubbock plots (Fig. 3.2) as affected by tillage treatments were observed at two points in time, October 17th, and December 8th for the 2016 double crop growing season. Differences remained until day 6 (January 10th, 2017), post winter wheat planting (December 12th, 2016). Double crops were planted on July 14th, and on day 15 (September 7th, 2017), differences were observed with plots under conventional tillage containing less soil moisture than no-till and strip-till. Summer irrigation was applied on June 20th, 2017 (pre-double crop planting), and again on July 17th, 2017 for a total of 221.0 mm (Section 2, Table 2.1). Seasonal rains supplied greater than average precipitation (299.0 mm), enough to carry the crops until termination and/or harvest (October 13th, 2017 for cowpea and cover crop, November 10th for sesame and sorghum). Comparatively, 2017 summer precipitation was 77% greater than the 2016 summer growing season.

Plots under conventional tillage contained less soil moisture than strip-till and no-till plots based off of the majority of statistical differences throughout the 2016 double crop growing season. Dao (1993) found that no-till in silt loam soils consistently had greater volumetric water content than plots subjected to moldboard plowing and stubble-mulch tillage. The soil moisture in the conventionally tilled plots was predictably lower during the time of winter wheat planting, based off day 5 and day 6 differences. Stone and Schlegel (2006) concluded that no-till, because of its minimal disturbance to surface residue, is better equipped than conventional till in capturing and retaining precipitation in the Great Plains. It was also concluded that wheat and sorghum yields were related to available soil water at time of emergence as well as in-season precipitation (Stone and Schlegel, 2006).

Overall, Lubbock appeared to have many instances of soil moisture variance between tillage and double crop treatments. Soil moisture was statistically lower in 2016 at the time of wheat planting in fallow, sesame, and sorghum plots compared to the cowpea and cover plots. These moisture differences in the 0-60.0 cm portion of the soil could have been the cause of decreased wheat yields in those previous double cropped plots (sesame and sorghum; Section 2, Fig. 2.2). These results resemble what was observed in in Nielson and Vigil's (2005) cover crop-wheat rotation in the Great Plains, where subsequent wheat yields were contingent on soil moisture at the time of planting. Soil moisture at the time of wheat planting in 2017 (day 17, December 8th, 2017, $P<0.001$) had significantly lower soil moisture in the cover, sesame, and sorghum plots (fallow > cowpea > sesame > cover > sorghum), and based off of our previous year's data and findings by Nielson and Vigil (2005), decreased wheat yields are expected. Tillage impacted soil moisture at several points in the growing season, with conventional tillage generally having the least amount of soil moisture. In water-limited regions such as Lubbock (489.0 mm $year^{-1}$ mean annual precipitation), there may be fewer double cropping options and other management practices, such as tillage technique, which will have a greater impact on potential yields than areas with greater precipitation (National Oceanic and Atmospheric Administration, 2018).

3.3.1.3 Soil Moisture in Thrall, Texas

Soil moisture was measured 22 times between July of 2016 and January of 2018 (Fig. 3.3). At day 17, August, 11th 2017, a tillage × crop interaction was observed, and again at readings 19 (October, 26th 2017), 20 (November 14th, 2017) and 21 (December 14th, 2017; Fig. 3.3). The delayed double crop harvests in 2016 were not corrected for in the statistics. For day 4, August, 24th, 2016, measurements were taken after several large rain events; we presume the soil moisture at this point in time to be at field capacity. Calculated probabilities or differences among treatments are presented in Appendix B.

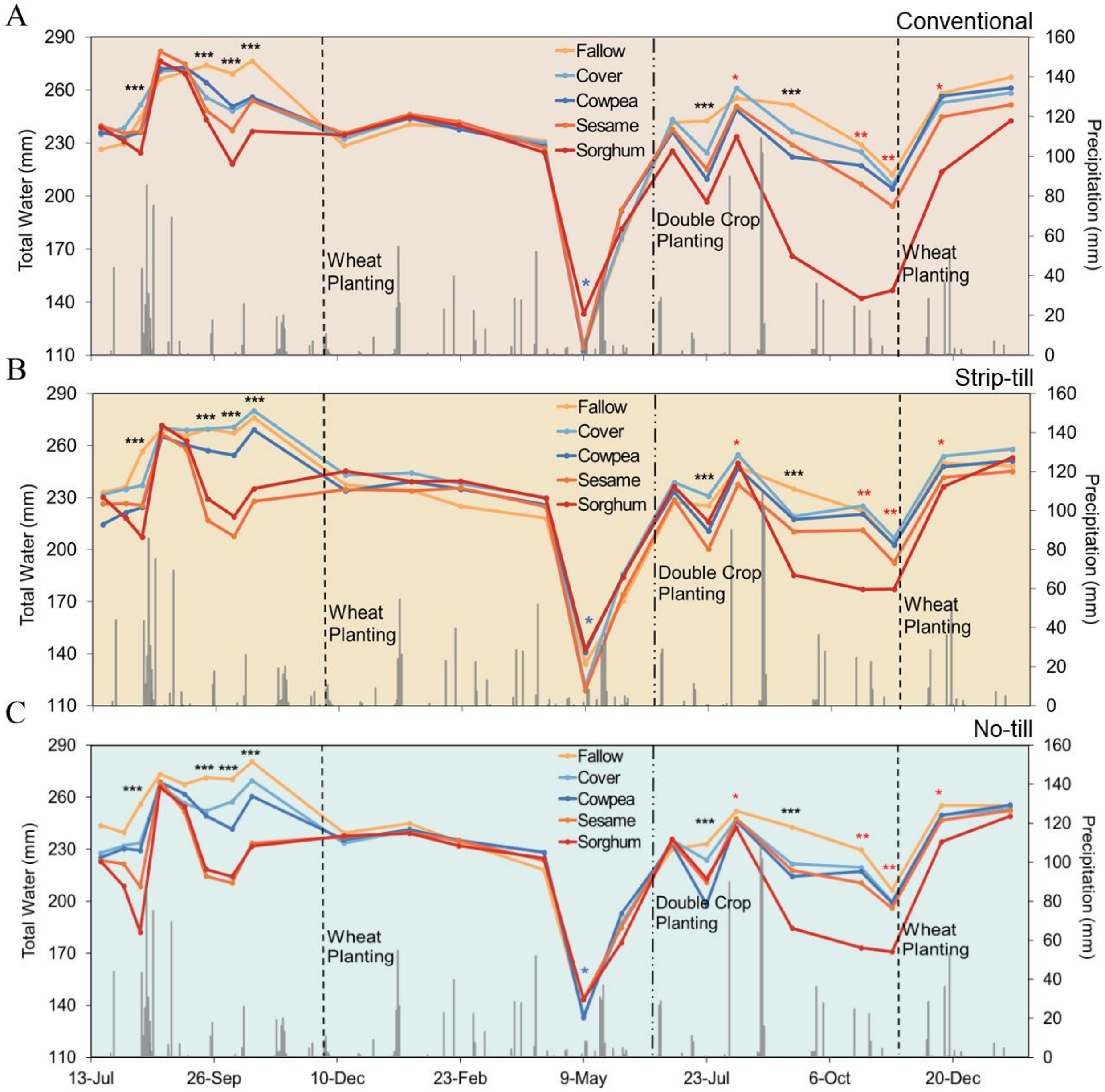

Figure 3. 3 Soil moisture (mm) over time by tillage (a = conventional till, b = strip-till, and c = no-till) as affected by double crop treatments in Thrall for the 0-60 cm soil layer. * (*P* value < 0.05); ** (*P* value < 0.01); *** (*P* value < 0.001). Red asterisks indicate tillage × crop interaction and blue asterisks indicate significant tillage effects at the same levels of significance. Precipitation and irrigation are displayed as grey bars across the bottom.

For 2016 double crop growing season, fallow plots (control) often contained the most soil moisture in the 0-60.0 cm profile (Fig. 3.3). These results differ from what was seen at Lubbock in 2016 where soil moisture in fallow plots trended lower later in the season compared to cover crop and cowpea plots (Fig 3.2). Greater soil moisture that was observed in the fallow plots throughout both double crop growing seasons could be attributed to Burleson clay's high clay content which is relative to the soil's water holding capacity (Brady and Weil, 1996). During the 2017 double crop growing season, fallow plots on average contained the most amount of soil moisture. This goes along with the research done by Osenburg and Mathews (1951) in South Dakota on clay soils where the greatest moisture conservation was observed for summer fallow. Greater soil moisture in the fallow plots was also credited to producing greater subsequent crop yields (Osenburg and Mathews, 1951).

After cover crop harvest on day 7 (October 7th, 2016), an increase in soil moisture is observed, verifying senescence of the cover crop and soil moisture recharge from precipitation events. Cover crops in conventional till plots were harvested a month later than cover crops in the minimally tilled plots (no-till and strip-till) and perceived water use can been seen by cover crops in the plots under conventional tillage. Delayed seedling emergence is often observed in no-till plots due to decreased soil temperatures (Unger, 1978). However, the opposite was observed for this study—emergence in the conventionally tilled plots was delayed by a month compared to the no-till and strip-till plots. This could possibly be due to decreased soil moisture from pre-plant tillage in the conventional plots that took place the same day as planting. McMaster et al. (2002) found that pre-plant tillage in three of the four study years significantly reduced winter wheat seedling emergence in a dryland setting. In their research, they also noted that no-till plots had a faster, more uniform seedling emergence in four out of the six years that were observed in the Central Great Plains on a Nunn clay loam (McMaster et al., 2002). Research plots containing cowpeas in 2016 generally had the second most moisture compared to the other double crops aside from day 1 (July 19th, 2016) which was midseason and 35 days after planting (DAP). Cowpeas in all plots were harvested on September 9th and 15th (2016), soil moisture on day 7, October 7th, 2016, displays minimal soil moisture indicating senescence of the crop. An increase in soil moisture is observed after this date, indicating soil moisture recharge, but less so in plots under conventional tillage. In 2017, cowpeas were harvested on September 22nd, 2017. The next measurement on day 19 (October 26th, 2017) reflects a slight increase in soil moisture indicating lack of a growing crop.

Sesame appears to use the second most water comparatively, which again, goes along with the information we know about the crop water requirement (Langham et al., 2010). Sesame plots appear to have similar moisture trends to the sorghum plots in the 2016 growing season, and especially later in the season. Sesame has a greater water requirement compared to cover crop and cowpea, the plots containing sesame appeared to recover in time for the 2016 wheat planting. Wheat yields were not affected by double crop treatments in 2016. Sesame was harvested on October 19th, 2017. Soil moisture in all plots besides sorghum appear to decline just before wheat planting in 2017. Soil moisture at the time of planting 2017 winter wheat was significantly lower in sesame plots. From this information, we could speculate that soil moisture may have a greater chance of reclaiming adequate soil moisture in time for wheat planting if precipitation events are coupled with earlier crop harvests. The plots that previously contained sesame did not fully recover until day 22 (January 25th, 2017), similar to the soil moisture at day 10 (January 24th, 2016).

Throughout the 2016 growing season, plots with grain sorghum often had less soil moisture than the other double crop plots. Sorghum was harvested on multiple occasions (Section 2, Table 2.2) not only because of late conventional till emergence, but also to avoid yields decimation from birds. In the 2017 the sorghum variety was switched to a variety called SP 7715. It is a longer season variety (medium-full) that is better adapted to a dryland setting and has greater yield potential because of the longer season. The variety switch could be the reason for the increase in presumed water use in 2017. Sorghum was harvested on October 26th, 2017, day 19 in the measurements. A plateau in soil moisture is observed after harvest. Sorghum plots did not appear to fully recover in time for wheat planting in 2017 until day 22 (January 25th, 2017).

Soil moisture at the time of wheat planting (December 2nd, 2016) was predicted to be similar in all plots based on the measurement taken soon after planting (day 10, January 4th, 2017) and the lack of drastic precipitation events pre-planting. There were no observed differences for the 2016 winter wheat growing season, similar to what we have witnessed at our other locations. Statistical differences averaged out during the winter wheat season for 2016-2017. Wheat yields in the sorghum and sesame plots for 2018 harvest are predicted to be lower than the other crop plots based what we know about soil moisture at the time of planting (Nielsen et al. 2002; Nielsen et al., 2005; Stone and Schlegel, 2006). Differences in soil moisture as affected by tillage treatments were observed for only one point in time, measurement 13, May 5th, 2017, when soil moisture was at its lowest point in the wheat growing season, right before wheat harvest (Fig. 3.3). At that point in time, conventional tillage had the least of amount of soil moisture compared to no-till and strip-till possibly due to greater numbers of wheat plants growing in conventional tillage treatments.

Despite no supplemental irrigation, double cropping appears to be possible from a soil moisture perspective. The plots that contained the cover crops generally had the second most soil moisture profile after fallow. Which affirms what we know about summer fallowing in clays soils to store moisture for the subsequent cash crop (Osenburg and Mathews, 1951). Sesame and sorghum crops appeared to use the greatest amount of soil moisture throughout the growing season. The sorghum variety selected for year 2 appears to use a greater amount of soil moisture. Increased moisture use by the SP 7115 variety of sorghum in combination with low precipitation before wheat planting could affect wheat yields. Wheat yields could be lower in plots that previously contained sesame and sorghum for the 2018 wheat harvest. The soil profile appears to recover quickly in Thrall and hold soil moisture by a great capacity. In a double cropping system, precipitation events prior to wheat planting could be crucial to the success of wheat. Tillage at this location appeared to have less impact on soil moisture.

3.3.2 Time-to-Runoff

Time-to-Runoff results differed by location and by tillage treatment for Lubbock and Thrall (Figs. 3.4 and 3.5). There were no significant differences between tillage treatments for the percentage of stable aggregates from the 0-2.0 cm portion of the soil surface in Lubbock after two years of the experiment (Fig. 3.4). Crop type, made no significant impact on wet aggregate stability at either location.

3.3.2.1 Time-to-Runoff in Lubbock

At Lubbock, there was no tillage × crop interaction for T_{ro} at Lubbock. Neither tillage nor double crop treatments effected time-to-runoff (Fig. 3.4). These results may reflect those of a newly implemented soil health study (Hobbs, 2007).

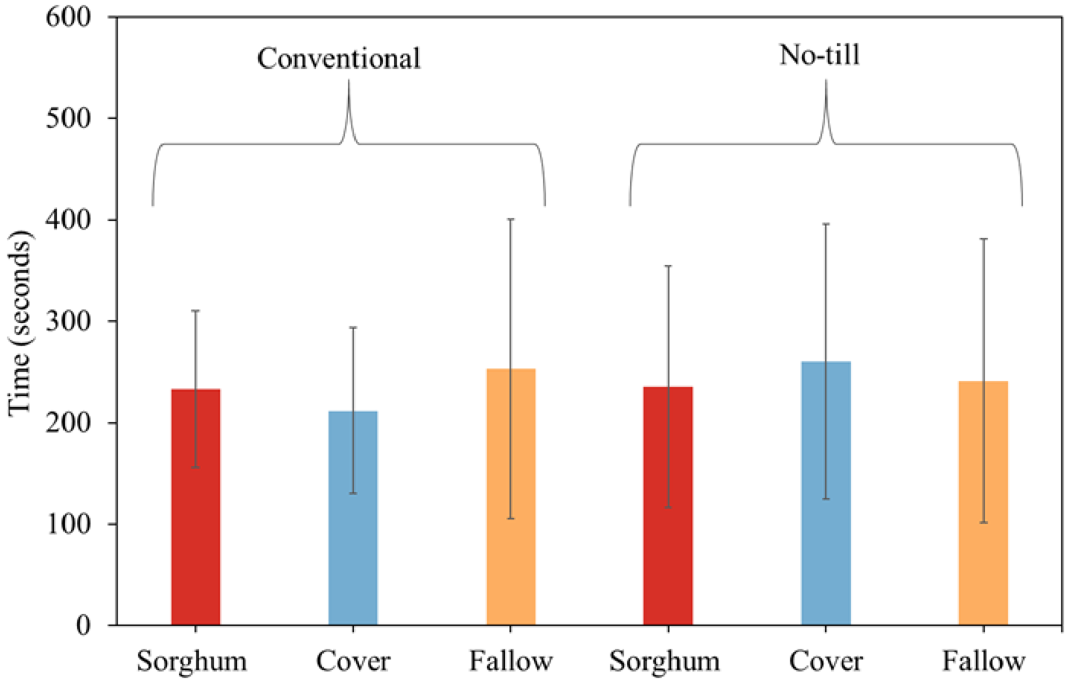

Figure 3. 4 Time-to-runoff (T_{ro}) at Lubbock in 2017, presented as double crops within each tillage system, conventional and no-till, n=54.

Additionally, infiltration rates in clay loam soil can be quite high (Soil Survey Staff, 2014). The percentage of clay in 0-5.0 cm portion of the Olton clay loam soil at Lubbock is said to be 31% according to Soil Web Survey (Soil Survey Staff, 2018). For trends to be observed, it may take years of no-till practices to increase soil OM and for differences to be observed in T_{ro}. Soils from semi-arid landscapes are slow to acculuate OM, this is most notebably due to climate in the region (Jenny, 1980).

3.3.2.2 Time-to-Runoff in Thrall

For Thrall, there was a tillage × crop interaction for T_{ro}. Tillage effected T_{ro}, but crop did not (Fig. 3.5).

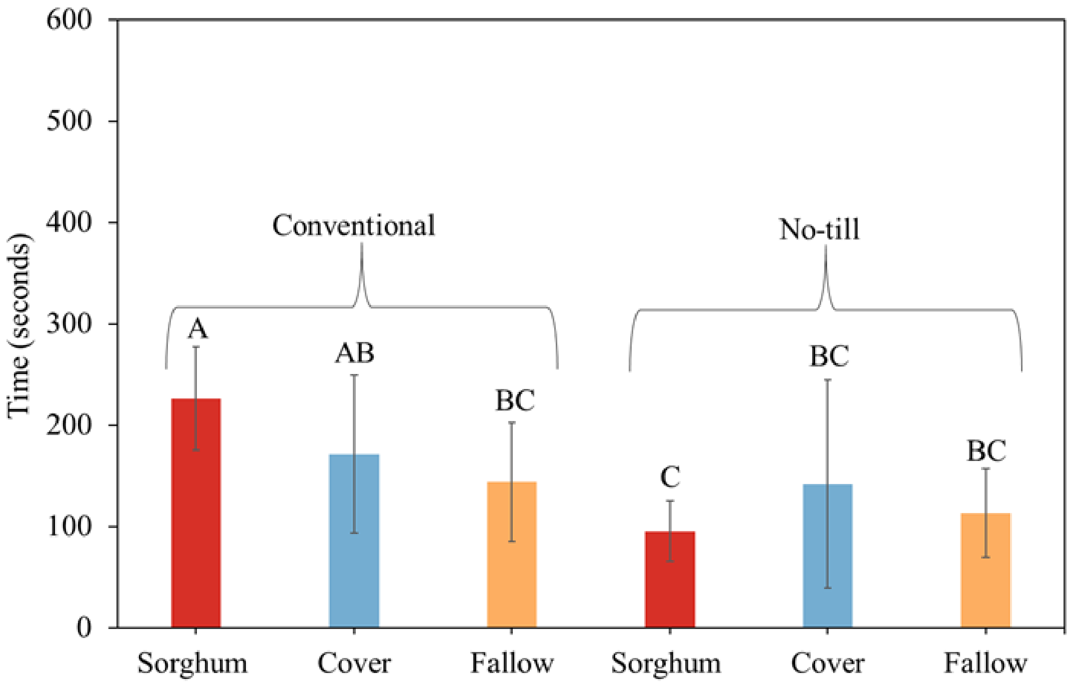

Figure 3. 5 Time-to-runoff (T_{ro}) at Thrall in 2017, presented as double crops within each tillage system. Different letters are significant at *P value* < *0*.05, n = 54.

The reason for quick T_{ro} at Thrall could be partly attributed to a greater clay percentage, ~44% (Bouyoucos, 1962). The likelihood of compaction in heavy clay soils is more likely occurs using no-till practices (Potter et al., 1995). In Thrall, T_{ro} tended to occur more slowly in the conventionally tilled plots compared to the no-till plots where sorghum had previously grown. Similar results were reported by Guzha's (2004), where infiltration rates were found to be significantly greater in tilled soils than un-tilled loam soils in Dodoma, Tanzania that had sandy clay surface soil and loam subsoil. The presence of double crops, as compared to fallow also appeared to have an impact on T_{ro} in conventionally tilled plots. This could potentially indicate that cropping intensity effects rate of infiltration via presence of OM on aggregation or presence of decaying roots channels below the plow zone. However, the impact of crops in the no-till treatments had no effect on T_{ro}. The T_{ro} was much quicker in the no-till plots, likely due to compaction issues commonly experienced in heavy clay soils. Additionally, there was longer T_{ro} at Lubbock than at Thrall, but trends have yet to be observed over a longer period of time to validate the results.

3.3.3 Wet Aggregate Stability

3.3.3.1 Wet Aggregate Stability in Lubbock

At Lubbock, low overall percent aggregate stability was observed (Fig.3.6). Soils from semi-arid climates are known to have difficulty procuring OM (Jenny, 1980) which is a primary constituent in aggregate formation and stabilization (Amézketa, 1999) among other natural cohesive materials. Surface aggregates in landscapes such as these will generally exhibit lower aggregate stability because of less OM.

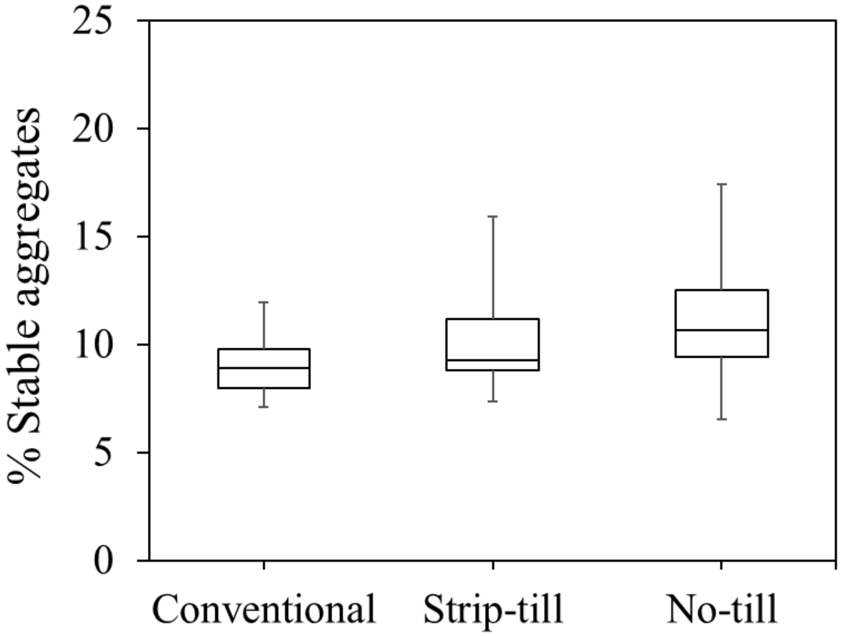

Figure 3. 6 Percentage of stable aggregates from conventional, strip-till, and no-till plots in Lubbock, n = 90.

The percentage of clay in 0-5.0 cm portion of the Olton clay loam soil at Lubbock is said to be 31% according to the Soil Web Survey website (Soil Survey Staff, 2018). Clay type can be an even greater component in determining the stability of aggregates (Kemper and Koch, 1966). It is thought that generally, a greater percentage of smectitic clay minerals than kaolinite and illite clay minerals, yields greater aggregate stability due to increased surface area and cation exchange capacity (CEC), respectively (Amézketa, 1999). In addition, the swelling quality of smectitic clays are also less likely to slake than kaolinite and illite clays (Amézketa, 1999). However, the relationships between clay types and aggregate stability are more complex than direct, and so their behavior is often dependent on other minerals within the soil (Amézketa, 1999).

3.3.3.2 Wet Aggregate Stability in Thrall

The percentage of stable aggregates from the 0-2.0 cm portion of the soil surface that were 0.25 mm to 2.0 mm in size was significantly affected by tillage treatments in Thrall after two years of the experiment (Fig. 3.7). Crop type made no significant impact on wet aggregate stability.

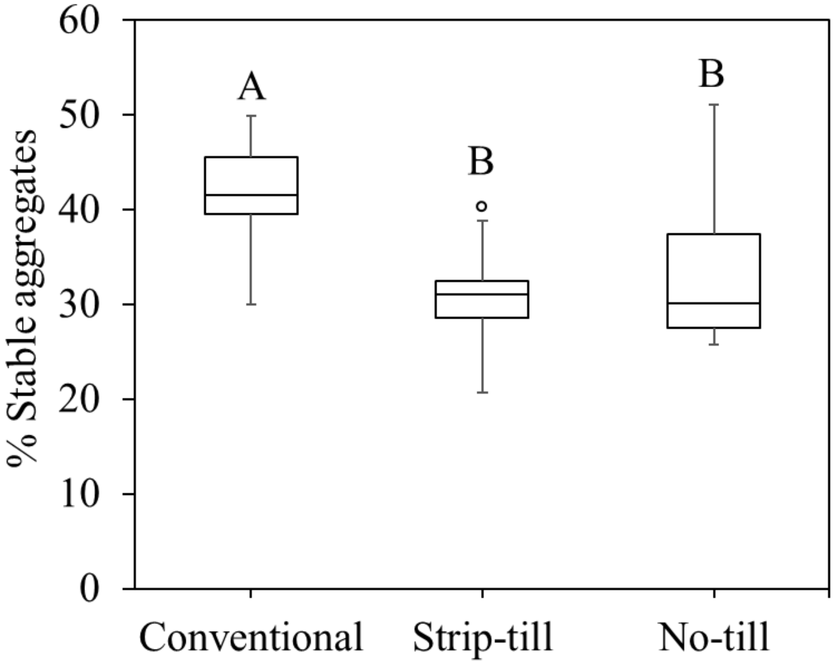

Figure 3. 7 Percentage of stable aggregates from conventional, strip-till, and no-till plots in Thrall. Different letters are significant at *P* value < *0*.05, n = 90.

At Thrall, there were a greater percentage of stable aggregates in the conventionally tilled plots (41.7%) as compared to the strip-till (30.8%) and no-till (33.2%) plots. These results contrast with what is commonly known, that the relative amount of stable aggregates influences the rate and amount of water that infiltrates into and through the soil profile (Brady and Weil, 1996). Kasper et al. (2009) found that increasing tillage on fine sandy loam soil in Austria destabilized aggregates. Similar results were also found by Bartlova et al. (2015) on varying soil types under differing intensive crop rotations in the Czech Republic. However, Bartlova et al. (2015) used surface soil samples taken from greater depths (0-30.0 cm), as are many other surface samples in wet aggregate stability studies (Roth and Eggert, 1994; Idowu et al., 2009).

Results are likely to differ in our study because of the sampling depth. The 0-2.0 cm portion of the soil surface was sampled in our study, which would potentially limit the likelihood of better structure at this location. This sampling depth is continuously subjected to soil slaking from rainfall impact energy. Moldenhauer and Kemper (1969) found that soils with a higher clay content have an increased potential for surface crusting. Le Bissonnais (1996) found that soil crusting is dependent on aggregate stability. Considering these parameters, the no-till plots likely have less stable structure due to continuous impacts from crusting and slaking events. One method farmers can use to protect the structure of their surface soil is to increase residue (Laflen et al., 1978). By double cropping with conservation tillage, residue accumulation will likely increase, which can physically protect as well as contribute to the surface soil structure through OM additions (Laflen et al., 1978; Hatfield, and Karlen and Stott, 1994).

The results from the aggregate stability test corroborate the results from T_{ro}; they were sampled at the same time in the study and their physical soil properties are often observed in a direct correlation (Brady and Weil, 1996). Based off the infiltration and wet aggregate stability data, we could speculate that the surface soil in the no-till plots had poorer structure which could be influenced by crusting from high clay content, but more importantly, by continuous slaking from precipitation events and low aggregate stability. With the continuation of reduced tillage and residue accumulation from cropping intensification, these physical soil properties are likely to improve with time.

3.4 Conclusions

It may be concluded that after two years of double cropping and winter wheat rotation in combination with reduced tillage, that overall soil moisture around time of planting may impact wheat grain yields. It may also be concluded that double crops have the largest impact on total water, and tillage the least. The dryland research that was performed in heavier clay soils under a greater precipitation zone, encountered runoff quicker in no-till plots than in conventional till plots which was in direct relation to the stability of the surface soil aggregates. Despite these findings, total water seemed not to be affected. It is too soon to claim sustainability of double cropping and reduced tillage in all tested environments; additional years of research are recommended to accurately evaluate the system on soil health and crop productivity parameters.

4. CONCLUSIONS

The results from this study indicate that the integration of double cropping and reduced tillage in a winter wheat cropping system can be sustained if soil moisture is adequate. Soil water deficits created by water intensive crops, sesame and sorghum, at the time of wheat planting were shown to decrease double subsequent wheat yields in Lubbock by 12% and 45%, respectively. Less water requiring crops such as cowpea or a cover crop mix would be best suited for regions experiencing drought or when supplemental irrigation is not available. Water use trends of double crops were similar at all locations—sorghum > sesame > cowpea > cover crop > fallow, fallow plots often containing the greatest amount of soil moisture. Soil water differences between crop treatments averaged out throughout the course of the wheat growing season, and Thrall's subsoil (0-60 cm) was much sooner to recover than Lubbock where total water was inherently lower due to environment and soil type.

Tillage made less impact on crop yields and biomass production in Thrall and Beeville in relation to soil moisture, but it is evident that reduced tillage is imperative in semi-arid or water scarce regions such as Lubbock if double cropping with winter wheat were to be considered. Residue management is another key aspect to water conservation, as decline in soil water were observed in the fallow treatments in Lubbock in 2016. We believe this was attributed to soil water evaporation and increases runoff, and likely was greater in 2016 due to minimal residue accumulation in year one of the study. Similarly in Beeville, soil water increased post-harvest in greater herbage mass plots possibly due to residue cover benefits such as increased infiltration and decreased evaporation. We expect soil moisture in conventional and minimally tilled plots to further diversify with the progression of this project, as the total water in the profiles may gradually decrease as was shown in 2017. Overall, tillage did not greatly affect crop productivity in regions where total water and precipitation was inherently greater—Beeville and Thrall.

Adverse to what we know about soil physical properties, increased tillage promoted greater infiltration and longer time-to-runoff in Thrall; differences were not observed in Lubbock. In regions where soil was more clayey and finer textured, compaction was likely greater and aggregates in the 0-2.0 cm layer of the soil were potentially less structured due to continuous defense against precipitation events. As this experiment continues, we expect wet aggregate stability to increase in no-till plots that are double cropped due to OM accumulation and residue shielding of the soil's surface. Time-to-runoff will likely lengthen in the no-till plots that are under double crops, as crop roots have potential to break up compaction. Differences will likely be seen in Lubbock between tillage types and crop treatments with the continuation of the study, as time is often a key factor for greater observation of differences with conservation research. Plots with greater herbage mass contributions and no-tillage will likely procure longer time-to-runoff and greater proportions of stable aggregates.

We reserved soil health conclusions for future publications, as more years are needed before justifications can be made. Likewise, soil respiration results were left out because they did not fit in with the sections' objectives. The data will be used for future publications as an indicator to assess the progress of soil health at all three locations under different double cropping regimes and tillage types. Soil fertility, crop nutrient analysis and nutrient cycling in the soil will also be reserved for future publications focusing more on soil health. Another future objective would be to assess double cropping effects on soil health to that of cover cropping.

Some limitations that were encountered in this project were difficulties involving labor, time. Processing soil and crop samples in a timely manner was difficult with the amount of labor and time given, as well as having sufficient labor support at all locations. The distance between the research sites put a lot of strain on the project timeline, especially when crops were coming off (ready to harvest) around the same time. Time sensitive soil measurements pushed back planting dates and stretched labor very thin when it occurred in rapid secession as did the infiltration measurements at Thrall and Lubbock.

For the future of this study, expansion and optimization are key to increasing research validations, practice adoption by farmers, and promotion of global sustainability. It is suspected that double cropping could not only minimize fallow periods, provide similar soil health benefits to that of cover cropping, but could also contribute to an increase in farm revenue. Thus, potential expansion of the project might include aspects such as, economic risk and return assessments. Other areas for project expansion and investigation include, cropping systems modeling, additional locations with both dryland and minimal irrigation, additional summer double crops and differing cover crop mixtures, evaluation of ecosystem services, and implementation of grazing for dual purposing winter wheat and cover crops to further incentivize farmers. Adding additional soil health parameters is also desired, as well as implementing infiltration at the Beeville location. Soil health research will contribute to the validity of the system stability in the interest of soil security and longevity of a farmer’s field. The broader implications of conservation agriculture through soil security have potential to defer climate change and abate the more dire implications—food and water security.

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APPENDIX A

SAS code for wheat stand counts in 2017 across location

```
Data Stands;
input loc$ plot$ rep crop$ till$ stands;
cards;
;
proc glimmix data=Stands;
class loc rep crop till;
model stands = loc|crop|till;
random rep(loc) rep*till;
lsmeans loc | till | crop/pdiff lines;
run;
```

SAS code for wheat stand counts in 2017 by location

```
Data Stands;
input loc$ plot$ rep crop$ till$ stands;
cards;
;
proc sort;
by loc;
run;
proc glimmix data=stands;
by loc;
class rep crop till;
model biomass = crop|till;
random rep rep*till;
lsmeans till | crop/pdiff lines;
run;
```

SAS code for wheat yields across locations

```
Data Yields;
input loc$ plot$ rep crop$ till$ yield;
cards;
;
proc glimmix data=Yields;
class loc rep crop till;
model yield = loc|crop|till;
random rep(loc) rep*till;
lsmeans loc | till | crop/pdiff lines;
run;
```

SAS code for wheat yields by location

```
Data Yields;
```

```
input loc$ plot$ rep crop$ till$ yield;
cards;
;
proc sort;
by loc;
run;
proc glimmix data=Yields;
by loc;
class rep crop till;
model yield = crop|till;
random rep rep*till;
lsmeans till | crop/pdiff lines;
run;
```

SAS code for wheat herbage mass across locations

```
Data herbage;
input loc$ plot$ rep crop$ till$ herbage;
cards;
;
proc glimmix data=herbage;
class loc rep crop till;
model herbage = loc|crop|till;
random rep(loc) rep*till;
lsmeans loc | till | crop/pdiff lines;
run;
```

SAS code for wheat herbage mass by location

```
Data herbage;
input loc$ plot$ rep crop$ till$ herbage;
cards;
;
proc sort;
by loc;
run;
proc glimmix data=herbage
by loc;
class rep crop till;
model herbage = crop|till;
random rep rep*till;
lsmeans till | crop/pdiff lines;
run;
```

SAS code for double crop stand counts by crops across locations

```
Data stands;
input year loc$ plot$ rep crop$ till$ stands;
cards;
;
proc glimmix data=stands;
class loc year rep till;
model stands = loc|till;
```

```
random rep(loc) rep*till year year*loc year*loc*till;
lsmeans loc | till /pdiff lines;
run;
```

SAS code for double crop stand counts by crops by location

```
Data stands;
input year loc$ plot$ rep till$ stands;
cards;
;
proc sort;
by loc;
run;
proc glimmix data=stands;
by loc;
class year rep till;
model stands = till;
random rep rep*till year year*till;
lsmeans till /pdiff lines;
run;
```

SAS code for cowpea grain yield across locations

```
Data cowpea;
input year loc$ plot$ rep till$ yields;
cards;
;
 proc glimmix data=cowpea;
class loc year rep till;
model yields = loc|till;
random rep(loc) rep*till year year*loc year*loc*till;
lsmeans loc | till /pdiff lines;
run;
```

SAS code for cowpea grain yield by location

```
Data cowpea;
input year loc$ plot$ rep till$ yields;
cards;
;
proc sort;
by loc;
run;
proc glimmix data=cowpea;
by loc;
class year rep till;
model yields = till;
random rep rep*till year year*till;
lsmeans till /pdiff lines;
run;
```

SAS code for sesame grain yield across locations

```
Data sesame;
input year loc$ plot$ rep till$ yields;
cards;
;
 proc glimmix data=sesame;
class loc year rep till;
model yields = loc|till;
random rep(loc) rep*till year year*loc year*loc*till;
lsmeans loc | till /pdiff lines;
run;
```

SAS code for sesame grain yield by location

```
Data sesame;
input year loc$ plot$ rep till$ yields;
cards;
;
proc sort;
by loc;
run;
proc glimmix data=sesame;
by loc;
class year rep till;
model yields = till;
random rep rep*till year year*till;
lsmeans till /pdiff lines;
run;
```

SAS code for sorghum grain yield across locations (Lubbock and Thrall only)

```
Data sorghum;
input year loc$ plot$ rep till$ yields;
cards;
;
 proc glimmix data=sorghum;
class loc year rep till;
model yields = loc|till;
random rep(loc) rep*till year year*loc year*loc*till;
lsmeans loc | till /pdiff lines;
run;
```

SAS code for sorghum grain yield by location (Lubbock and Thrall)

```
Data sorghum;
input year loc$ plot$ rep till$ yields;
cards;
;
proc sort;
by loc;
run;
```

```
proc glimmix data=sorghum;
by loc;
class year rep till;
model yields = till;
random rep rep*till year year*till;
lsmeans till /pdiff lines;
run;
```

SAS code for sorghum grain yield by location (Beeville)

```
Data sorghum;
input plot$ rep till$ yields;
cards;
;
run;
proc glimmix data=sorghum;
class rep till;
model yields = till;
random rep rep*till;
lsmeans till /pdiff lines;
run;
```

SAS code for double crop herbage mass across locations

```
Data herbage;
input year loc$ plot$ rep crop$ till$ herbage;
cards;
;
proc glimmix data=herbage;
class loc year rep crop till;
model herbage = loc|crop|till;
random rep(loc) rep*till year year*loc year*crop year*till year*loc*crop year*loc*till year*crop*till
year*loc*crop*till;
lsmeans loc | till | crop/pdiff lines;
run;
```

SAS code for double crop herbage mass by location

```
Data herbage;
input year loc$ plot$ rep crop$ till$ herbage;
cards;
;
proc sort;
by loc;
run;
proc glimmix data=herbage;
by loc;
class year rep crop till;
model herbage = crop|till;
random rep rep*till year year*crop year*till year*crop*till;
lsmeans till | crop/pdiff lines;
run;
```

SAS code for cover crop species stands by location

```
Data stands;
input year loc$ plot$ rep crop$ till$ stands;
cards;
;
proc sort;
by loc;
run;
proc glimmix data=stands;
by loc;
class year rep crop till;
model herbage = crop|till;
random rep rep*till year year*crop year*till year*crop*till;
lsmeans till | crop/pdiff lines;
run;
```

SAS code for cover crop herbage mass production by species and by location

```
Data herbage;
input year loc$ plot$ rep crop$ till$ herbage;
cards;
;
proc sort;
by loc;
run;
proc glimmix data=herbage;
by loc;
class year rep crop till;
model herbage = crop|till;
random rep rep*till year year*crop year*till year*crop*till;
lsmeans till | crop/pdiff lines;
run;
```

SAS code for temporal soil moisture at Beeville

```
Data NMM;
input rep tillage$ crop$ date1 date2 date3 date4 date5 date6 date7 date8 date9 date10 date11 date12 date13;

cards;
;
proc print data=NMM;
title 'Beeville NMM' ;
proc glm;
class rep tillage crop;
MODEL date1-date13 = Rep Rep*tillage tillage |crop/ ss3;
test h=tillage e=rep*tillage;
REPEATED moisture 13 (216 252 294 321 377      414 496  537 561 600 645 677 741) / printe ;
LSMEANS tillage |crop / lines ;
run;
```

SAS code for temporal soil moisture at Lubbock (days1-14)

```
Data NMM;
input rep tillage$ crop$ date1 date2 date3 date4 date5 date6 date7 date8 date9 date10 date11 date12 date13 date14;

cards;

;
proc print data=NMM;
title 'Lubbock NMM' ;
proc glm;
class rep tillage crop;
MODEL date1-date14 = Rep Rep*tillage tillage |crop/ ss3;
test h=tillage e=rep*tillage;
REPEATED moisture 14 (228	256	291	321	343	375	398	416	431	444
	466	482	504	522) / printe ;
  LSMEANS tillage |crop / lines ;
run;
```

SAS code for temporal soil moisture at Lubbock (days15-17)

```
Data NMM;
input rep tillage$ crop$ date1 date2 date3;
cards;
;
proc print data=NMM;
title 'Lubbock NMM' ;
proc glm;
class rep tillage crop;
MODEL date1-date3= Rep Rep*tillage tillage |crop/ ss3;
test h=tillage e=rep*tillage;
REPEATED moisture 3 (615	679	717) / printe ;
  LSMEANS tillage |crop / lines ;
run;
```

SAS code for temporal soil moisture at Thrall

```
Data NMM;
input tillage$ rep crop$ date1 date2 date3 date4 date5 date6 date7 date8 date9 date10 date11 date12 date13 date14
date15 date16 date17 date18 date19 date20 date21;
	cards;
proc print data=NMM;
title 'Thrall NMM' ;
proc glm;
class rep tillage crop;
MODEL date1-date21 = Rep Rep*tillage tillage |crop/ ss3;
test h=tillage e=rep*tillage;
REPEATED moisture 21 (201	215	225	237	252	265	281	293	24	54
	106	130	153	184	205	223	257	299	318	348	25
```

```
) / printe ;
LSMEANS tillage |crop / lines ;
run;
```

SAS code for Time-to-runoff across location

```
data Runoff;
input plot$ rep till$ crop$ runoff;
cards;
;
run;
proc glimmix data=runoff;
class loc rep crop till;
model runoff = loc|crop|till;
random rep(loc) rep*till;
lsmeans loc| till | crop/pdiff lines;
run;
```

SAS code for Time-to-runoff by location

```
data Runoff;
input plot$ rep till$ crop$ runoff;
cards;
;
run;
proc glimmix data=runoff;
by loc;
class rep crop till;
model runoff = crop|till;
random rep rep*till;
lsmeans till | crop/pdiff lines;
run;
```

SAS code for Wet Aggregate Stability across locations

```
Data WetAgg;
input plot$ rep crop$ till$ Agg;
cards;
;
run;
proc glimmix data=WetAgg;
class loc rep crop till;
model Agg = loc|crop|till;
random rep(loc) rep*till;
lsmeans loc| till | crop/pdiff lines;
run;
```

SAS code for Wet Aggregate Stability by location

```
Data WetAgg;
input plot$ rep crop$ till$ Agg;
cards;
;
run;
proc glimmix data=WetAgg;
class rep crop till;
model Agg = crop|till;
random rep rep*till;
lsmeans till | crop/pdiff lines;
run;
```

APPENDIX B

Wheat stand counts by location as affected by tillage treatments in 2017.

Location	Tillage	Plants m^{-2}
Beeville	Conventional	153.1 a†
	Strip-Till	119.3 ab
	No-Till	107.6 b
Lubbock	Conventional	149.2
	Strip-Till	166.1
	No-Till	149.2
Thrall	Conventional	110.9 a
	Strip-Till	64.1 b
	No-Till	58.2 b

†Different letters indicate significance (*P* < 0.05) within Beeville and Thrall locations as affected by tillage treatments

Wheat stand counts by location as affected by double crops treatments in 2017.

	Double Crops				
	Cover	Cowpea	Sesame	Sorghum	Fallow
Location	--------- Plants m^{-2}---------				
Beeville	122.8	142.6	137.3	110.5	120.1
Lubbock	153.4	160.3	159.4	153.4	147.8
Thrall	88.7 a†	80.6 ab	81.4 ab	69.8 b	68.1 b

†Different letters indicate significance (*P* < 0.05) within location as affected by double crop treatments

Treatment and interaction significance for wheat grain yield in 2017 by location.

Treatment	F Value	*P* value
	Beeville	
Till†	0.32	0.74
Crops	2.12	0.11
Till x Crop	1.14	0.37
	Lubbock	
Till	10.22	0.02
Crops	5.31	< 0.01
Till x Crop	1.72	0.15
	Thrall	
Till	7.10	< 0.05
Crops	1.52	0.23
Till x Crop	0.79	0.62

†Till = Tillage, Crop = Summer Double Crops

Treatment and interaction significance for wheat herbage mass by location.

Treatment	F Value	*P* value
	Beeville	
Till†	0.74	0.53
Crops	0.74	0.53
Till x Crop	1.08	0.41
	Lubbock	
Till	3.58	0.13
Crops	2.87	0.04
Till x Crop	1.10	0.40
	Thrall	
Till	3.29	0.14
Crops	5.53	< 0.01
Till x Crop	0.73	0.66

†Till = Tillage, Crop = Summer Double Crops

Treatment and interaction significance cowpea yields by location as affected by tillage.

Location	F Value	*P* value
Beeville	1.35	0.43
Lubbock	0.56	0.64
Thrall	0.24	0.81

Treatment and interaction significance sesame yields as affected by tillage.

Location	F Value	*P* value
Beeville	2.66	0.27
Lubbock	0.19	0.84
Thrall	5.19	0.16

Treatment and interaction significance for sorghum yields as affected by tillage.

Location	F Value	*P* value
Beeville	0.72	0.54
Lubbock	3.46	0.22
Thrall	0.91	0.53

Treatment and interaction significance for double crop dry herbage mass at each location averaged across years.

Treatment	F Value	*P* value
	Beeville	
Crop	11.15	0.04
Till†	0.51	0.66
Till x Crop	0.96	0.52
	Lubbock	
Crop	8.47	0.06
Till	1.01	0.50
Till x Crop	1.44	0.33
	Thrall	
Crop	6.10	0.09
Till	2.69	0.27
Till x Crop	0.91	0.54

†Till = Tillage, Crop = Summer Double Crops

Treatment and interaction significance for cover crop species stands at each location averaged across years.

Treatment	F Value	*P* value
	Beeville	
Crop	4.97	0.03
Till†	0.35	0.74
Till x Crop	0.31	0.98
	Lubbock	
Crop	2.96	0.09
Till	1.97	0.34
Till x Crop	1.19	0.37
	Thrall	
Crop	2.11	0.17
Till	0.75	0.57
Till x Crop	1.07	0.45

†Till = Tillage, Crop = Species within cover crop mix

Treatment and interaction significance for cover crop species stands at each location averaged across years.

Treatment	F Value	*P* value
	Beeville	
Crop	42	<0.0001
Till†	0.05	0.95
Till x Crop	0.15	0.1
	Lubbock	
Crop	5.88	0.01
Till	0.13	0.93
Till x Crop	0.56	0.90
	Thrall	
Crop	7.38	0.01
Till	2.55	0.28
Till x Crop	1.00	0.50

†Till = Tillage, Crop = Summer Double Crop

Neutron moisture meter measurement dates in Beeville from 2016-2018.

Location	Year	Measurement Day	Date	Tillage (Till)	Crop	Till x Crop
Beeville				Significance Level		
	2016	1	03 Aug	ns†	ns	ns
		2	08 Sept	ns	ns	ns
		3	20 Oct	ns	**	*
		4	16 Nov	ns	***	**
	2017	5	11 Jan	*	ns	ns
		6	17 Feb	ns	ns	ns
		7	10 May	ns	ns	ns
		8	20 June	ns	ns	ns
		9	14 Jul	ns	ns	ns
		10	22 Aug	ns	ns	ns
		11	06 Oct	ns	ns	ns
		12	07 Nov	ns	**	ns
	2018	13	10 Jan	ns	ns	ns

† ns (not significant); * (*P value < 0.05*); ** (*P value < 0.01*); *** (*P* value < 0.001)

Neutron moisture meter measurement dates in Lubbock from 2016-2017.

Location	Year	Measurement Day	Date	Tillage (Till)	Crop	Till x Crop
Lubbock				Significance Level		
	2016	1	15 Aug	ns†	ns	ns
		2	12 Sept	ns	*	ns
		3	17 Oct	*	***	ns
		4	16 Nov	ns	***	ns
		5	08 Dec	*	***	ns
	2017	6	10 Jan	*	***	ns
		7	02 Feb	ns	ns	ns
		8	20 Feb	ns	ns	ns
		9	07 Mar	ns	ns	ns
		10	20 Mar	ns	ns	*
		11	11 Apr	ns	ns	*
		12	27 Apr	ns	ns	*
		13	19 May	ns	ns	ns
		14	06 June	ns	ns	ns
		15	07 Sept	*	***	ns
		16	10 Nov	ns	***	ns
		17	08 Dec	ns	***	ns

† ns (not significant); * (*P value < 0.05*); ** (*P value < 0.01*); *** (*P* value < 0.001)

Neutron moisture meter measurement dates in Thrall from 2016-2018.

Location	Year	Measurement Day	Date	Tillage (Till)	Crop	Till x Crop
Thrall		Significance Level				
	2016	1	19 July	ns†	ns	ns
		2	02 Aug	ns	ns	ns
		3	12 Aug	ns	***	ns
		4	24 Aug	ns	ns	ns
		5	08 Sept	ns	ns	ns
		6	21 Sept	ns	***	ns
		7	07 Oct	ns	***	ns
		8	19 Oct	ns	***	ns
		9	14 Dec	- ‡	-	-
	2017	10	24 Jan	ns	ns	ns
		11	23 Feb	ns	ns	ns
		12	16 Apr	ns	ns	ns
		13	10 May	*	ns	ns
		14	02 June	ns	ns	ns
		15	03 July	ns	ns	ns
		16	24 July	ns	***	ns
		17	11 Aug	ns	**	*
		18	14 Sept	ns	***	ns
		19	26 Oct	ns	**	**
		20	14 Nov	ns	**	**
		21	14 Dec	ns	**	*
	2018	22	25 Jan	ns	ns	ns

† ns (not significant); * (*P value < 0.05*); ** (*P value < 0.01*); *** (*P* value < 0.001)
‡ Day 9 not analyzed with ANOVA for repeated measures issues experienced in rep 3 with neutron moisture meter and too many values missing from data set. Day 9 was included on Fig. 3.3.

Treatment and interaction significance for time-to-runoff by location.

Treatment	F Value	*P* value
	Lubbock	
Till†	0.39	0.72
Crops	0.05	0.95
Till x Crop	0.29	0.75
	Thrall	
Till	5.53	0.02
Crops	1.19	0.31
Till x Crop	3.29	< 0.05

†Till = Tillage, Crop = Summer Double Crops

Treatment and interaction significance for wet aggregate stability by location.

Treatment	F Value	*P* value
Lubbock		
Till†	0.73	0.49
Crops	0.61	0.66
Till x Crop	0.60	0.99
Thrall		
Till	20.91	< 0.0001
Crops	0.16	0.96
Till x Crop	0.40	0.40

†Till = Tillage, Crop = Summer Double Crops