# Cropping System Diversity and Tillage Intensity Affects Wheat Productivity in Texas

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Perejitei Bekewe
Texas A&M University


Jamie L Foster
Texas A&M University


Clark B. Neely
Washington State University


Haly L. Neely
Texas A&M University

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# Cropping system diversity and tillage intensity affects wheat productivity in Texas

**Perejitei E. Bekewe**[1] | **Jamie L. Foster**[2] | **Clark B. Neely**[3] | **Haly L. Neely**[3] | **Katie L. Lewis**[4] | **Lauren E. Tomlin**[1] | **Ronnie W. Schnell**[1] | **A. Peyton Smith**[1] | **Thomas W. Boutton**[5] | **Brandon Gerrish**[3]

[1]Soil and Crop Sciences Dep., Texas A&M Univ., College Station, TX 77843, USA

[2]Texas A&M AgriLife Research, Hwy 59 E, Beeville, TX 78102, USA

[3]Dep. of Crop and Soil Sciences, Washington State Univ., Pullman, WA 99164, USA

[4]Texas A&M AgriLife Research and Extension Center, Lubbock, TX 79403, USA

[5]Dep. of Ecology and Conservation Biology, Texas A&M Univ., College Station, TX 77843, USA

**Correspondence**
Jamie L. Foster, Texas A&M AgriLife Research, Hwy 59 E, Beeville, TX 78102, USA.
Email: JLFoster@ag.tamu.edu

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**Abstract**

Wheat (*Triticum aestivum* L.) production in Texas depends heavily on conventional tillage (CT) and a long summer fallow period, which contributes to soil degradation. This study compared the impact of reducing tillage intensity (CT, no-tillage, and strip-tillage) combined with summer cropping to CT–summer fallow on wheat establishment, grain production, and herbage mass from 2016 to 2020 in three Texas ecoregions (Coastal Plains, Southern High Plains, and Blackland Prairie). Tillage and summer cropping resulted in variable impacts on wheat stand establishment, grain yield, and herbage mass across years and locations. At Beeville, in the Coastal Plains, wheat grain and herbage mass yields were not impacted by tillage. Sorghum (*Sorghum bicolor* [L.] Moench) cropping resulted in less wheat grain yield in 2020. In 1 yr at Lubbock in the Southern High Plains, wheat grain yield was greater with CT than reduced tillage. Sorghum summer cropping resulted in lower wheat grain yield than cover crop mixture or cowpea (*Vigna unguiculata* [L.] Walp.) in 2017, but yield was greater in 2020. At Thrall, in the Blackland Prairie, wheat stand establishment and yield with reduced tillage were greater than CT in 2016, whereas CT was greater in 2017 and 2020. Sorghum or cover cropping resulted in reduced wheat grain yield compared with fallow in 2018, but sorghum and sesame (*Sesamum indicum* L.) resulted in increased yield compared with fallow in 2019 and 2020. Summer cropping in wheat production systems rarely had a negative impact on wheat production compared with summer fallow in all three ecoregions.

**Abbreviations:** CT, conventional tillage; NT, no-tillage; ST, strip-tillage.

## 1 | INTRODUCTION

Wheat (*Triticum aestivum* L.) is one of the most sought-after agricultural products in the world and has been identified as one of the major sources of food supply and security due to its high-quality nutrition and health benefits, especially in developing countries (FAO, 2011; Farvid et al., 2016; Slavin, 2004). In 2020, 17.9 million ha was planted in the United States with 1.98 million ha planted in Texas (USDA-NASS, 2020). The majority of wheat production systems in Texas are managed under conventional tillage (CT) and followed by 3–7 mo of fallow, leaving the soil without cover and increasing its susceptibility to erosion and evaporative water loss (Massee and Cary, 1978).

Management practices in agroecosystems, such as tillage, crop rotation, and cover crops, can improve soil structure and physiochemical characteristics of the soil leading to significant impacts on soil organic C, which is the major driver of soil health (Kibblewhite et al., 2008; McClelland et al., 2021). No tillage (NT) has long been considered one of the most important management practices for sustainable cropping intensification to meet future global food demands (Derpsch et al., 2014) while preserving soil quality and security by reducing soil erosion (Lal, 2001). Around the world, adoption of NT has increased from 45 Mha in 1999 to >180 Mha in 2015, equal to approximately 13% of arable land globally (Kassam et al., 2019). In NT systems, residues left on the soil surface after crop harvest are a driving force for promoting microbial activity, accumulating organic C and nutrients near the soil surface, improving aggregate stability, protecting against erosion, and increasing water infiltration rate (Tebrugge & During, 1999). No tillage has been shown to increase yields under water-limited environments (Farooq et al., 2011; Rusinamhodzi et al., 2011). However, studies have also shown NT practices resulted in low productivity because of possible soil water-logging and cooler soil temperatures, which can have negative impacts on crop stands in temperate environments (Anken et al., 2004; Hay et al., 1978; Riley et al., 1994; Soane et al., 2012; Van Ouwerkerk & Perdok, 1994). Other research indicates no difference between crop yield in NT or CT management (Foster et al., 2018). At present, NT is implemented on only 15% of cropland in Texas, placing it among the lowest of all states in the United States (Myers & LaRose, 2019).

Diverse crop rotations, including cover crops and double cropping, have been shown to magnify the beneficial impacts of reduced tillage and prevent soil erosion through ground coverage (Keeling et al., 1989; Magdoff & Van Es, 1993). Double cropping can be defined as planting and harvesting more than one crop from the same land area annually. Studies have shown that residues or ground coverage on the soil's surface creates a physical barrier resulting in less water evaporation and improved protection from wind erosion, which serves as erosion control (Massee & Cary, 1978; Shangning & Unger, 2001). A USDA national survey given between 1999 and 2012 estimated only 2% of all cropland was farmed with double cropping (Borchers et al., 2014). Farmers' skepticism about double cropping systems was attributed to water availability or low precipitation that may affect their primary crop (Borchers et al., 2014; Unger et al., 2006). Researchers also found that the combination of double cropping and reduced tillage intensity helped increase productivity and net returns of cropping systems (Baumhardt et al., 1985; Dhuyvetter et al., 1996; Unger, 1984) and specifically wheat production (Alexandratos & Bruinsma, 2012). In contrast, traditional management practices such as fallow periods and CT over time can lead to soil degradation and decline in productivity, which may decrease long-term sustainability, economic viability, and consequently diminish the ability to produce food for an exponentially increasing world population (Alexandratos & Bruinsma, 2012; Alvarez & Steinbach, 2009; Tebrugge & During, 1999). Despite the benefits of no tillage and cover or double cropping during the fallow period, most wheat is produced under conventional tillage and a long fallow period.

The overall objective of this study was to determine the effects of reduced tillage and summer double cropping on cropping system productivity across Texas. In Texas, winter wheat and fall-planted spring wheat are harvested in May or June; therefore, selecting a summer crop that is adapted to heat and drought stress during Texas summers and will be harvested prior to wheat planting in November or December is key to ensuring wheat–summer double crop rotation functionality. The specific objectives were to quantify the impact of CT, NT, and strip-till (ST) as well as summer double crops on (a) wheat and double crop establishment, (b) wheat and double crop grain yield, and (c) wheat and double crop herbage mass in three agriculturally important ecoregions in Texas.

**Core Ideas**

- Tillage and summer cropping had variable effects on yield and herbage mass across semi-arid environments.
- Conservation tillage practices, no-tillage, or strip-tillage are feasible practices for wheat production systems.
- Wheat–summer crop rotations are potentially feasible systems in the Coastal Plains and Blackland Prairie regions.
- Wheat–summer crop rotations are not feasible in the Southern High Plains due to limited precipitation and timing.

**TABLE 1** Soil characteristics of the three experimental sites (Beeville, Lubbock, and Thrall) in Texas determined at soil depth of 0–15 cm sampled at experiment initiation in 2016

| Soil characteristics | Beeville | Lubbock | Thrall |
|---|---|---|---|
| Soil type | Parrita sandy clay loam | Olton clay loam | Burleson clay |
| Clay, g $kg^{-1}$ | 300 | 190 | 500 |
| Silt, g $kg^{-1}$ | 170 | 300 | 280 |
| Sand, g $kg^{-1}$ | 530 | 510 | 220 |
| pH | 7.1 | 7.7 | 5.4 |
| Soil organic C, %[a] | 1.4 | 0.64 | 0.9 |
| Bulk density, Mg $m^{-3}$[a] | 1.50 | 1.43 | 1.43 |

[a]Soil texture and bulk density reported in USDA-NRCS (2021).

We hypothesized that including summer double crops will not reduce wheat grain or herbage mass when compared with the summer fallow control. We also hypothesized that reduced tillage (NT and ST) will not decrease wheat or double crop grain or herbage mass compared with CT.

# 2 | MATERIALS AND METHODS

## 2.1 | Study area description

This study was conducted for 5 yr (2016–2020) in three locations (Beeville, Lubbock, and Thrall) that represented important agricultural ecoregions in Texas (Supplemental Figure S1). The Beeville site was located at the Texas A&M AgriLife Research Station (28˚27′ N, 97˚42′ W; 74 m asl) in the Coastal Plains ecoregion, which is a humid subtropical climate. The Beeville site soil was classified as a Parrita sandy clay loam (loamy, mixed, superactive, hyperthermic, shallow Petrocalcic Paleustoll; NRCS, 2021). The Lubbock site was located at the Texas A&M AgriLife Research and Extension Center (33˚41′ N, 101˚49′ W; 1,001 m asl) in the High Plains ecoregion, which is a semi-arid temperate climate. The Lubbock soil was classified as an Olton clay loam (fine, mixed, superactive, thermic Aridic Paleustolls; USDA-NRCS, 2021). The Thrall site was located at the Stiles Farm Foundation (30˚36′ N, 97˚18′ W; 173 m asl) in the Blackland Prairies ecoregion, which is warm and temperate. Thrall soil was classified as a Burleson clay (fine, smectitic, thermic Udic Haplusterts; USDA-NRCS, 2021). Soil characteristics of all three locations are reported in Table 1. The land use history in the three locations prior to this study were perennial peanut (*Arachis glabrata* Benth.) for 25 yr at the Beeville location, and cotton (*Gossypium hirsutum* L.) for over 10 yr (conventionally tilled) at the Lubbock and Thrall sites. Monthly rainfall and average monthly temperature data were collected through National Oceanic and Atmospheric Administration weather sites (https://www.noaa.gov/) and are reported in Figure 1. The weather station was within 200 m of the experiment at the Beeville location, and within 0.6 and 24.1 km of the Lubbock and Thrall experiments, respectively.

## 2.2 | Treatments and experimental design

The experimental design was a randomized complete block split-plot design with three replications. Treatment factors were randomly assigned to experimental units in 2016 (2015 for Thrall) and the same treatments implemented each year. The main plots were tillage system (CT, NT, and ST), and the subplots were the summer crop, including double crop species or cover crop mixture. Summer double crop species included cowpea (*Vigna unguiculata* [L.] Walp.), grain sorghum (*Sorghum bicolor* [L.] Moench), sesame (*Sesamum indicum* L.), or fallow control. The cover crop mixture consisted of ‘Mancan’ buckwheat (*Fagopyrum esculentum* Moench), ‘Iron and Clay’ cowpea, ‘Kinman’ guar (*Cyamopsis tetragonoloba* [L.] Taubert), ‘Rio Verde’ lablab (*Lablab purpureus* [L.] Sweet), short stature sunflower (‘8H668S’, *Helianthus annuus* L.), pearl millet (*Pennisetum glaucum* [L.] R. Br.), sunn hemp (*Crotalaria juncea* L.), ‘Tamrun OL 11′ peanut (*Arachis hypogaea*), and German foxtail millet (*Setaria italica* [L.] P. Beauv.). Peanut and German foxtail millet were removed from the cover crop mixture in Year 3 due to peanut incompatibility with the other cover crop species planting depth and poor stands of German foxtail millet. The experimental unit size at Beeville was 9.1 m long × 3.0 m wide, Lubbock was 12.2 m long × 4.1 m wide, and Thrall was 22.9 m long × 7.6 m wide.

## 2.3 | Cropping system management

The experimental design and treatment factors were consistent at each location; however, management decisions were different because they were based on common practices specific to each region. At Beeville and Thrall, conventional tillage plots were tilled to a depth of 15 cm using a disk (Case IH 370), and ST plots were tilled to a depth of 15 cm with an

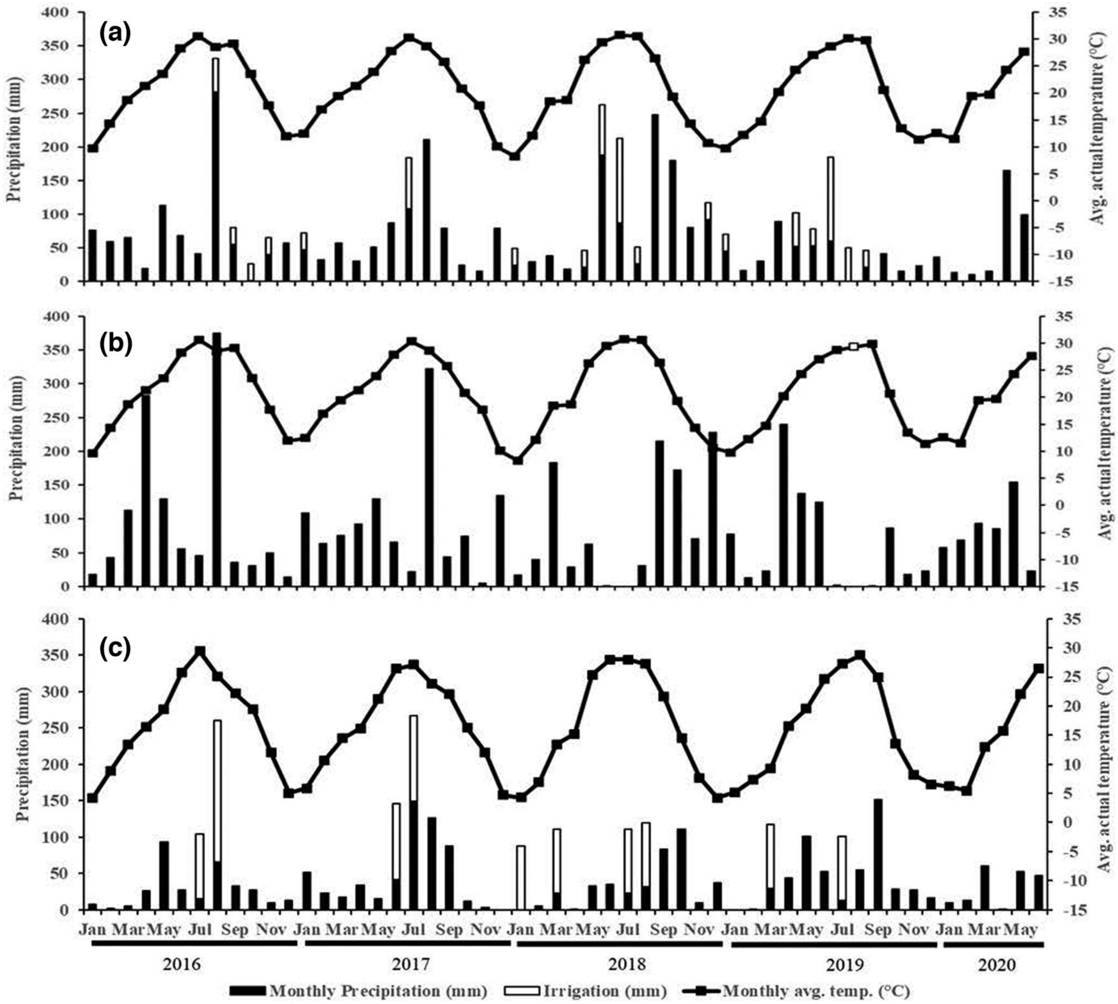


**FIGURE 1** Average monthly temperature (˚C), precipitation (mm), and irrigation (mm) during the experimental period at experimental sites in (a) Beeville, (b) Thrall, and (c) Lubbock, Texas. Data point for Thrall for the month of August 2019 was not available, thus, July and September 2019 average was used.

Orthman 1tRIPr (Lexington) with individual row spacing of 76 cm. At Beeville, a modified 1.5-m Great Plains NT drill was used to plant wheat. At Thrall, a modified 1.5-m Great Plains NT drill was used to plant wheat in 2015, 2016, 2019, and 2020, whereas a 3.7-m John Deere 8200 and Sunflower 9.1-m NT drill 9421 were used to plant wheat in 2017 and 2018, respectively. Summer crops were planted at Beeville and Thrall with John Deere Max Emerge Plus planter unit fitted with Almaco 31-cell cones for seed metering. Conventional tillage received three passes at Thrall and two passes at Beeville, whereas ST received a single pass at both Beeville and Thrall.

At Lubbock, CT plots were tilled with a John Deere tandem disk, model 630 with a 4.3-m width and 15-cm depth. Prior to planting in the CT treatment each season, it made two passes, one from each direction. For ST plots, the implement was an Orthman 1tRIPr that is 4 rows wide on 102-cm row spacing. Each individual strip was 30-cm wide and ran 8-cm deep with one pass made. The drill used for wheat planting was a Great Plains minimum till drill, model 1200, with a 3.7-m width and 19-cm spacing. The planter used for summer crops was a John Deere Max Emerge plus 1700 that is 4 rows wide and equipped with Almaco cones to plant the plots.

Wheat varieties for each location were selected based on their adaptability across regions, and over the course of the study were changed to address yield limiting issues such as poor vernalization at Beeville and Thrall, weed control at Thrall, and wheat streak mosaic virus at Lubbock. In Beeville, hard red winter wheat cultivar ‘TAM 304’ (Rudd et al., 2015) was planted in Year 1 and was changed to hard red winter wheat cultivar ‘TAM 305’ (Ibrahim et al., 2015) in Year 2, and hard red spring wheat cultivar ‘LCS Trigger’ (Limagrain) was planted for the final three seasons of the study. In Lubbock, ‘TAM 304’ was planted in the first 2 yr of the study and was changed to hard red winter wheat cultivar ‘TAM 204’ (Rudd et al., 2019) in years 3–5, though overall poor stands in Year 4 required a replant using the spring wheat variety ‘LCS Trigger’. In Thrall, hard red winter wheat cultivar ‘WB Cedar’

(Westbred) was planted in the first 2 yr, changed to hard red winter wheat cultivar 'Gallagher' (Marburger et al., 2021) in Year 3 because of poor vernalization by WB Cedar, and LCS Trigger in Years 4 and 5 to allow for later planting and better fall weed control. The row spacing for wheat planting was 19 cm for all three locations. In the ST treatment, the wheat crop was planted using NT, as tilled strips were wider than the row spacing for wheat.

The summer crops were planted on a row spacing of 76 cm in Beeville and Thrall, and 102-cm row spacing for Lubbock. Cowpea 'Texas Pinkeye Purple Hull' variety was planted in all locations in 2016 and was changed to 'Golden Eye Cream' cultivar in 2017, 'California Black Eye 5' in 2018 and 2019. The cowpea cultivars were changed due to availability. Sesame variety 'S32' was planted at all locations throughout the study. Sorghum variety 'SP7715' (medium–long) was planted at Beeville and Thrall location throughout the study, whereas sorghum variety 'DKW37-07' (medium–early) was planted at Lubbock. All summer double crops, except sesame, were pretreated with Apron XL fungicide (Mefenoxam, Syngenta), Cruiser 5FS insecticide (Thiamethoxam, Syngenta), and Dual safener. The cover crop mixture and the cowpea treatments were treated at the time of planting with a powdered Rhizobium species (N-DURE, Verdesian) inoculant to facilitate seed inoculation (Flynn, 2015). Wheat and summer crop seeding rates in pure live seed, planting dates, and harvest dates are detailed in Supplemental Tables S1 and S2 in supplementary data. Wheat fertilization was based on summer soil sample results and recommendations from the Texas A&M AgriLife Extension Service Soil, Water, and Forage Testing Laboratory (College Station, TX; Supplemental Table S3). At Beeville all fertilizers were broadcast applied, but at Lubbock, UAN was diluted with water (1:1) for side dress application (4 row). At Thrall, wheat was fertilized with liquid fertilizer, N was applied to double crops as side dress application (4 row); whereas $P_2O_5$ and $K_2O$ were broadcast.

Herbicide applications are detailed in Supplemental Table S4 in supplementary data. Irrigation is presented with monthly precipitation totals in Figure 1 for Beeville and Lubbock but was not available at the Thrall site. Cowpea was damaged by insects and wildlife grazing at all three locations in 2018. Sesame grain was not harvested at Lubbock in 2017 because it did not mature prior to the first frost. Sorghum grain was not harvested at Beeville in 2016 due to bird damage. To avoid bird damage, wire mesh crop cages (1.5 × 1.2 m) were installed across two center rows in each sorghum plot at all locations beginning in 2017 and in subsequent years.

## 2.4 | Response variables

The response variables measured were: (a) wheat stand establishment, (b) wheat grain yield, (c) wheat herbage mass, (d) summer crop stand establishment, (e) summer double crop grain yield, and (f) summer crop herbage mass.

## 2.5 | Stand establishment and yield

Wheat stand counts were taken approximately 3 wk after emergence in four (Beeville and Lubbock) or six (Thrall) 1-m length random locations within the center four rows in each plot. Wheat herbage mass subsamples were taken before combine harvest by hand clipping a 1-$m^2$ area to 5-cm stubble height near the center of the plot. Wheat heads were separated from the herbage mass and both samples dried in a forced-air oven at 50 ˚C to a constant weight and heads threshed (Almaco LPR thresher). Following threshing, grain weight was subtracted from the initial head weight and the difference, which represented the head non-grain herbage mass, was added to the herbage mass sample to calculate total aboveground mass. Harvesting of wheat grain was performed using a Wintersteiger (Wintersteiger Ag) classic plot combine (1.5-m header) for all locations.

Summer crop stand counts were taken approximately 3 wk after emergence in two (Beeville and Lubbock) or four (Thrall) 1-m length within center rows in each plot. All summer double crops were harvested by hand in 1-m row length of the two center rows and were dried at 50 ˚C in a forced-air oven until constant weight and then weighed for aboveground herbage mass estimate. The dried and weighed sorghum (heads), sesame (pods), and cowpea (pods) samples were then threshed. Following threshing, the grain weights were subtracted from the head (sorghum) and pod (cowpea and sesame) weights, and the difference, which represented the head and pod chaff weights, were added to the herbage sample to calculate total aboveground mass. Test weight and moisture was performed using a Dickey John Model GAC 2100 (Dickey-John) to standardize sorghum grain yields to 78.9 kg $hL^{-1}$ and 13.5% moisture. Cover crop herbage mass was measured by hand clipping two row lengths (1-m) within the two center rows. Samples were dried in a forced-air oven at 50 ˚C until constant weight and herbage mass per hectare calculated.

## 2.6 | Statistical analysis

Wheat and summer crop stand establishment and all grain and herbage mass were analyzed using PROC GLIMMIX in SAS (SAS Institute, 2010). Location was analyzed separately because each location represented a different ecoregion. Treatments (tillage and summer crop), year, and their interactions were considered fixed effects; block and block × tillage were considered random effects. Tillage × summer crop × year interaction was not significant for any variables.

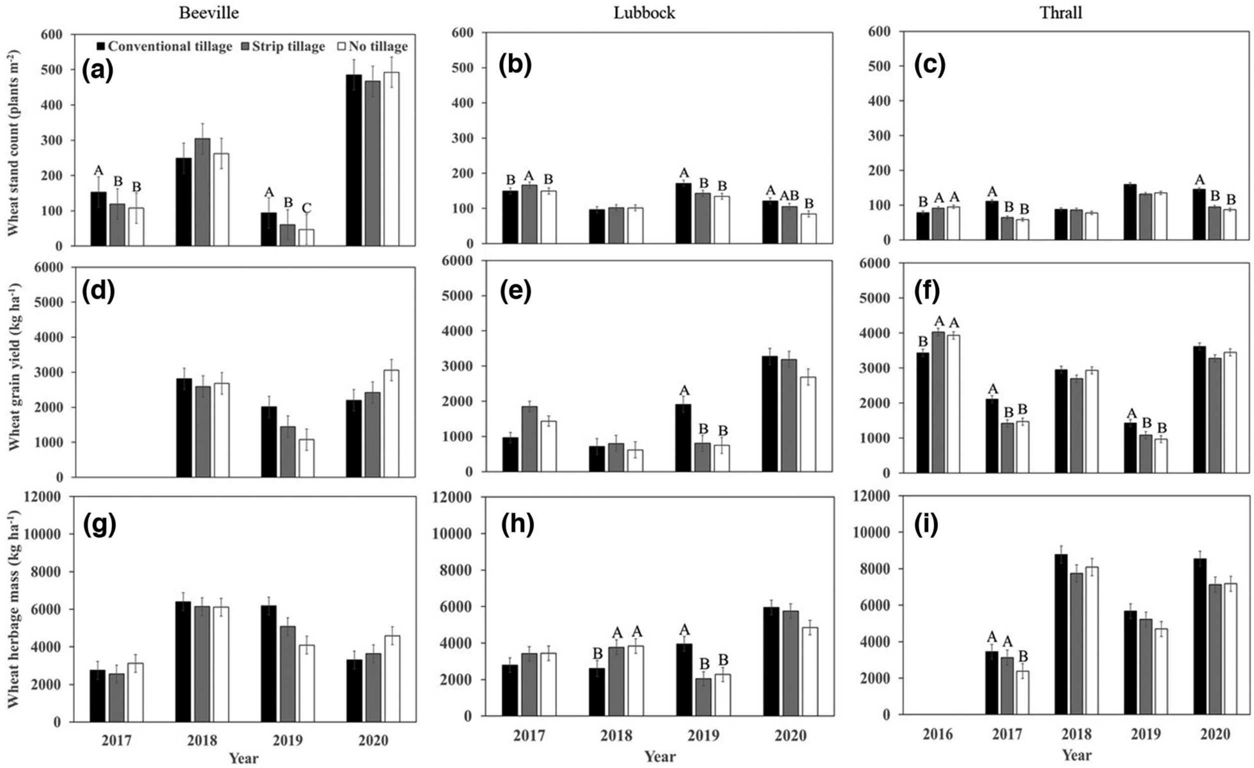


FIGURE 2 Wheat stand count (plants/m$^2$), wheat grain yield (kg ha$^{-1}$), and wheat herbage mass (kg ha$^{-1}$) as affected by tillage at Beeville, Lubbock, and Thrall locations in Texas from 2016–2020. Bars represent SE of mean and different letters within each year at each location indicate significance ($P < .05$).

Year was significant for all dependent variables at all locations, so data were analyzed by year. Regression stability analysis was conducted to determine yield stability of wheat grain and herbage mass across years within location (Finlay and Wilkinson, 1963). Pearson correlation analysis was performed for wheat and summer crop stand establishment and all grain and herbage mass across years for each location. The LSMEANS function with the DIFF option was used to determine mean separation among significant effects. Statistical analysis results were considered significant if $P \leq .05$.

## 3 | RESULTS AND DISCUSSION

### 3.1 | Wheat

Significant year × tillage and year × summer crop interactions for wheat stand establishment, grain yield, and herbage mass were detected at all three locations, except for wheat stand establishment (year × summer crop) and wheat herbage mass (year × tillage) in Beeville; thus, results are presented by year. The wheat stand establishment at Beeville was approximately 35 and 43% greater for CT in 2017 and 2019, respectively, compared with NT and ST (Supplemental Table S5; Figure 2a). At Lubbock, tillage impact on wheat stand establishment was inconsistent across years. In 2017, ST (166 plants m$^{-2}$) results in greater stand establishment than CT or NT (each 149 plants m$^{-2}$), whereas CT was greater than NT and ST in 2019 and greater than NT in 2020 (Figure 2b). At Thrall, wheat stand establishment with NT (95 plants m$^{-2}$) and ST (91 plants m$^{-2}$) were greater than CT (78 plants m$^{-2}$) in 2016, whereas CT was greater than NT and ST in 2017 and 2020 (Figure 2c).

Summer cropping did not affect wheat stand establishment throughout this study at Beeville (Supplemental Table S5; Figure 3a). Summer cropping at Lubbock affected wheat stand establishment in 1 of 4 yr. In 2020 at Lubbock, wheat stand establishment was greater in cover crop (120 plants m$^{-2}$) and sorghum (113 plants m$^{-2}$) treatments and least in fallow (87 plants m$^{-2}$) and cowpea (90 plants m$^{-2}$) treatments (Figure 3b). Summer cropping affected wheat stand establishment at Thrall in 2017, 2019, and 2020 (Figure 3g). In 2017, wheat stand establishment was greater in the cover crop (89 plants m$^{-2}$) treatment compared with the summer fallow control (68 plants m$^{-2}$) and grain sorghum (70 plants m$^{-2}$) treatments (Figure 3c). For the 2019 wheat crop, cover crop and cowpea treatments resulted in the least wheat stands, whereas in 2020, wheat stand establishment was greatest in the sorghum (119 plants m$^{-2}$) treatment and least in cowpea (103 plants m$^{-2}$) and fallow (107 plants m$^{-2}$) treatments.

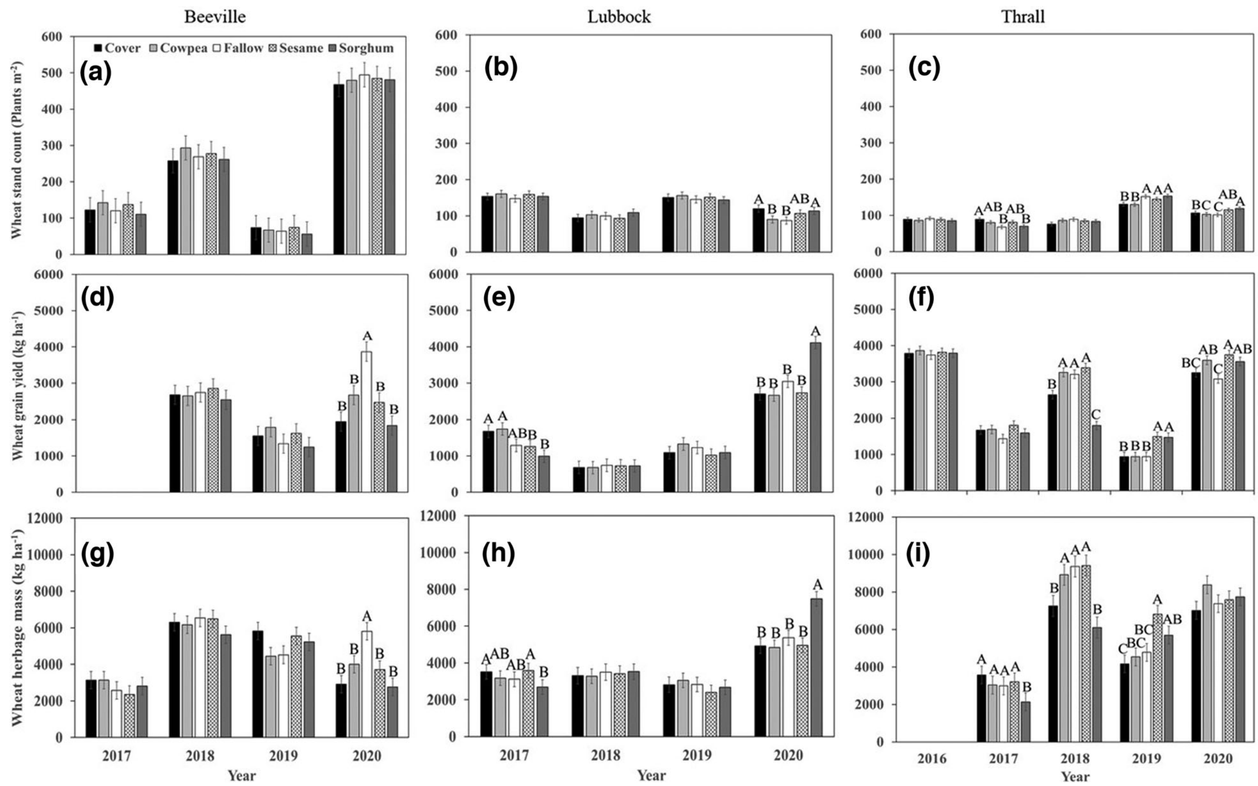


**FIGURE 3** Wheat stand count (plants m$^{-2}$), wheat grain yield (kg ha$^{-1}$), and wheat herbage mass (kg ha$^{-1}$) as affected by summer cropping at Beeville, Lubbock, and Thrall locations in Texas from 2016 to 2020. Bars represent SE of mean and different letters within each year at each location indicate significance ($P < .05$).

Other studies have also shown mixed results of crop rotation on wheat performance (Yadav et al., 2003). Berzsenyi et al (2000) showed positive impacts of crop rotation on wheat when rotated with maize or alfalfa; however, they attributed much of the rotation effect to fertility. Lenssen et al (2014) did see a small (5%) reduction in spring wheat stand following field pea in a 2-yr rotation, but not in a 3- or 4-yr rotation with barley, maize, and field pea in a 6-yr rotation study.

In general, trends in wheat stands across years for each location tended to correlate with seeding rates, though environmental factors also played a role (Supplemental Table S1; Figure 1). For example, below average rainfall occurred in Lubbock from October 2017 to February 2018 (Figure 1c); thus, low soil moisture likely reduced wheat stand establishment. Other studies reported no differences for stand establishment between NT and CT (Ahmad et al., 2008; Lithourgidis et al., 2006; Schillinger, 2001; Wilkins et al., 1989). Hemmat & Eskandari (2006) found greater wheat stand establishment in NT compared with CT or reduced tillage systems, which is consistent with our 2016 Thrall location findings. Residue management at our experimental locations, especially following sorghum, could have impacted seed–soil contact and wheat stand establishment. For instance, shredding sorghum residue in fall 2016 at Thrall created a thick mat of residue when planting wheat that fall and appeared to be the reason for reduced stands that year. In subsequent years, sorghum residue was left standing and no stand reductions were observed.

Wheat grain yield at Beeville was not affected by tillage throughout the study (Supplemental Table S5; Figure 2d). At Lubbock, tillage affected wheat grain yield in 1 of 4 yr, and was greater with CT (1,895 kg ha$^{-1}$) compared with NT (729 kg ha$^{-1}$) and ST (815 kg ha$^{-1}$) in 2019 (Supplemental Table S5; Figure 2e). At Thrall, tillage and summer cropping affected wheat grain yield in 3 of 5 yr. Wheat grain yield under NT (3,931 kg ha$^{-1}$) and ST (4,030 kg ha$^{-1}$) were greater than CT (3,433 kg ha$^{-1}$) in 2016, whereas CT was greater than NT and ST in 2017 and 2019 (Figure 2f). In 2016, NT and ST were advantageous as CT resulted in a less uniform seedbed, poorer seed placement, and ultimately reduced yield. The reverse was true in 2017 as persistent wet weather conditions and equipment failure necessitated the use of a drill ill-equipped to direct seed. Interestingly, tillage differences at Thrall were also apparent in wheat in 2019 even though tillage was not performed prior to wheat planting. In 2019, wheat was planted later than is ideal due to persistent wet conditions in the fall and winter.

Summer cropping negatively affected wheat grain yield in 2020 at Beeville (Supplemental Table S5; Figure 3d). Sorghum treatment produced numerically less wheat grain yield each year, though it was only significantly less than fallow in 2020 (Figure 3d). Summer cropping affected wheat grain yield in 2 of 4 yr at Lubbock (Figure 3e). Sorghum grown in summer before wheat resulted in the lowest wheat grain yield compared with cover crop mixture or cowpea in 2017 (Figure 3e). Yet in 2020, sorghum resulted in the greatest wheat grain yield compared with all other treatments (Figure 3e). At Thrall, summer cropping reduced wheat grain yield compared with fallow in only 1 of 5 yr (Figure 3f). In 2018, sorghum or cover crop grown prior to wheat production resulted in reduced wheat grain yield compared with fallow (Figure 3f). In 2019 and 2020, sorghum and sesame treatment resulted in increased wheat grain yield compared with the fallow control.

At Beeville, there was no wheat grain yield to harvest in 2017 due to incomplete vernalization. The low wheat yield recorded in 2018 at Lubbock was mainly due to low in-season precipitation, (Figure 1c) (Lithourgidis et al., 2005; Matsi et al., 2003). Poor vernalization (due to mild winter temperatures) occurred in 2017 at Thrall, whereas delayed wheat planting in 2019 (due to persistent rains) contributed to the overall lower wheat grain yields in those 2 yr at Thrall (Supplemental Table S1; Figure 1b). In many cases, wheat grain yield followed similar patterns as wheat stand establishment, with the exception of tillage treatments at Beeville. In general, wheat grain yield at Lubbock was comparable between CT and NT in most years, whereas summer cropping did not significantly reduce wheat grain yield in any year compared with the fallow control. At both Lubbock and Thrall, when tillage impacted wheat stand, it often led to a similar trend in wheat grain yield. Hence, good stand establishment is key to ensuring wheat productivity at these sites. Other studies reported no significant impact of tillage on wheat grain yield (De Vita et al., 2007; Izaurralde et al., 1986; Norwood et al., 2013; Schillinger, 2001; Soane et al., 2012). Other researchers have found significant differences between CT and NT in certain environments when greater soil moisture negatively impacts uniformity of crop emergence of NT compared with CT (De Vita et al., 2007; Hemmat & Eskandari, 2006; Norwood et al., 2013; Rothrock, 1987). For crop rotation systems, Rothrock (1987) found no difference in wheat grain yield between wheat–soybean double cropping and wheat monoculture in a temperate environment. In Tribune, KS, Norwood et al. (2013) reported no difference for wheat grain yield between wheat–fallow and wheat–sorghum–fallow crop rotation systems in most of the years of the study.

Wheat herbage mass at Beeville was not affected by tillage (Supplemental Table S5; Figure 2g). At Lubbock, wheat herbage mass response to tillage was inconsistent across years (Figure 2h). In 2018, wheat herbage mass was 44% greater in NT and ST treatments than CT, whereas in 2019, CT wheat herbage mass was 73% greater than NT and ST (Figure 2h). At Thrall, tillage significantly impacted wheat herbage mass in only 1 of 4 yr, which was due to greater wheat herbage mass in CT (3,449 kg $ha^{-1}$) and ST (3,226 kg $ha^{-1}$) treatments compared with NT (2,382 kg $ha^{-1}$) in 2017 (Figure 2i).

In general, wheat herbage mass followed very similar response to tillage and summer crop treatments as wheat grain yield, which was not unexpected (Figure 2). The same vernalization and environmental impacts that were relevant to wheat grain yields impacted wheat herbage mass. Mrabet (2000) found no differences between NT and CT for wheat herbage mass in a 4-yr study. However, other researchers reported contradicting results. Hemmat and Eskandari (2006) reported greater wheat herbage mass for NT than CT and suggested greater yield in NT was due to increased capacity to store soil moisture, which was consistent with our findings in 2018 at Lubbock. Hajabbasi (2003) also reported greater wheat herbage mass during drought years for NT. Summer cropping reduced wheat herbage mass at Beeville in 1 of 4 yr and was greatest in fallow in 2020 (Figure 3g). The grain sorghum treatment had less wheat herbage mass in 2017 but the greatest in 2020, whereas the other double crop treatments were never significantly different from the fallow control in any year at Lubbock (Figure 3h). Grain sorghum (2017 and 2018) and cover crop (2018) were the only double crop treatments that reduced wheat herbage mass in any year at Thrall (Figure 3i). These double crops produced the most summer biomass, which may have reduced nutrient availability that limited wheat herbage production, and, in some cases, reduced wheat stands because of poorer seed–soil contact from abundant residue at planting.

Stability of wheat grain yield was not affected by the three tillage systems as all tillage management practices resulted in stable wheat grain yield at Beeville (Table 2). At Lubbock, yield stability for wheat grain yield was reduced by NT, whereas CT reduced yield stability at Thrall (Table 2). Summer fallow and sorghum summer double cropping reduced yield stability for wheat grain yield at Beeville, whereas sorghum treatment reduced wheat grain yield stability at Lubbock. At Thrall, summer fallow and all summer cropping treatments resulted in stable wheat grain yield. Stability of wheat herbage mass at Beeville, Lubbock, or Thrall were not affected by tillage system because all three tillage management practices resulted in stable herbage mass yield (Table 3). Summer cropping did not affect stability for wheat herbage mass at Beeville. At Lubbock, sorghum treatment reduced stability of wheat herbage mass; whereas, at Thrall, cover crop treatment reduced wheat herbage mass yield stability.

The impacts of implementing reduced or NT practices on wheat grain yield were quite variable across years at each location. In many, but not all cases, impacts on yield could be attributable to tillage impacts on stand establishment. When wheat grain yield stability is considered, ST or NT may result in less management risk at Lubbock, and at Thrall either ST or

**TABLE 2** Yield stability analyses for wheat grain yield as impacted by tillage and summer cropping systems at Beeville, Lubbock, and Thrall, Texas from 2016 to 2020

| | Beeville | | | | Lubbock | | | | Thrall | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Parameter estimate | | | | Parameter estimate | | | | Parameter estimate | | | |
| Treatment | $β_0$ | $β_1$ | $R^2$ | Test of slope = 1 | $β_0$ | $β_1$ | $R^2$ | Test of slope = 1 | $β_0$ | $β_1$ | $R^2$ | Test of slope = 1 |
| Tillage | | | | | | | | | | | | |
| CT | 89.832 | 0.971 | 0.72 | 0.685 | 49.416 | 1.050 | 0.67 | 0.580 | 652.600 | 0.793 | 0.77 | 0.001 |
| ST | 0.215 | 0.955 | 0.81 | 0.278 | −12.566 | 1.056 | 0.77 | 0.426 | −283.454 | 1.082 | 0.88 | 0.105 |
| NT | −90.226 | 1.074 | 0.77 | 0.278 | −30.330 | 0.893 | 0.77 | 0.069 | −342.017 | 1.118 | 0.86 | 0.036 |
| Double crop | | | | | | | | | | | | |
| Fallow | −78.488 | 1.233 | 0.84 | 0.007 | 8.167 | 0.991 | 0.78 | 0.921 | −212.897 | 1.032 | 0.84 | 0.667 |
| Cowpea | 46.614 | 1.017 | 0.80 | 0.829 | 176.737 | 0.875 | 0.77 | 0.092 | −209.584 | 1.108 | 0.88 | 0.102 |
| Sorghum | −10.077 | 0.839 | 0.80 | 0.017 | −313.926 | 1.364 | 0.76 | 0.004 | 182.965 | 0.900 | 0.76 | 0.221 |
| Sesame | 11.714 | 1.019 | 0.80 | 0.810 | 25.753 | 0.886 | 0.69 | 0.224 | 366.885 | 0.955 | 0.86 | 0.464 |
| Cover crop | 29.939 | 0.891 | 0.69 | 0.242 | 105.763 | 0.887 | 0.73 | 0.201 | −150.204 | 1.012 | 0.86 | 0.860 |

*Note*. $β_0$, intercept; $β_2$, slope; CT, conventional tillage; ST, strip tillage; NT, no tillage. Yield stability analyses includes parameter estimates and $R^2$.

**TABLE 3** Yield stability analyses for wheat herbage mass as impacted by tillage and summer cropping systems at Beeville, Lubbock, and Thrall, Texas from 2016 to 2020

| | Beeville | | | | Lubbock | | | | Thrall | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Treatment | Parameter estimate | | | | Parameter estimate | | | | Parameter estimate | | | |
| $β_0$ | $β_1$ | $R^2$ | Test of slope = 1 | $β_0$ | $β_1$ | $R^2$ | Test of slope = 1 | $β_0$ | $β_1$ | $R^2$ | Test of slope = 1 | |
| Tillage | | | | | | | | | | | | |
| CT | −186.821 | 1.088 | 0.75 | 0.232 | 51.529 | 1.025 | 0.65 | 0.789 | 74.589 | 1.089 | 0.84 | 0.132 |
| ST | −98.942 | 0.996 | 0.81 | 0.941 | −190.599 | 1.061 | 0.75 | 0.408 | 168.480 | 0.934 | 0.81 | 0.233 |
| NT | 285.942 | 0.916 | 0.64 | 0.300 | 144.221 | 0.915 | 0.76 | 0.172 | −243.451 | 0.977 | 0.88 | 0.615 |
| Double crop | | | | | | | | | | | | |
| Fallow | 198.684 | 1.027 | 0.75 | 0.771 | 19.137 | 1.000 | 0.76 | 0.995 | −183.292 | 1.045 | 0.82 | 0.560 |
| Cowpea | 174.062 | 0.940 | 0.75 | 0.474 | 247.106 | 0.875 | 0.75 | 0.110 | −255.916 | 1.085 | 0.89 | 0.162 |
| Sorghum | −46.572 | 0.926 | 0.70 | 0.475 | −624.211 | 1.311 | 0.72 | 0.018 | 4.739 | 0.923 | 0.84 | 0.227 |
| Sesame | −239.078 | 1.073 | 0.72 | 0.428 | 139.463 | 0.917 | 0.70 | 0.372 | 172.779 | 1.084 | 0.82 | 0.301 |
| Cover crop | −86.796 | 1.035 | 0.77 | 0.694 | 217.916 | 0.898 | 0.73 | 0.251 | 261.053 | 0.864 | 0.84 | 0.027 |

*Note*. $β_0$, intercept; $β_2$, slope; CT, conventional tillage; NT, no tillage; ST, strip tillage. Yield stability analyses includes parameter estimates and $R^2$.

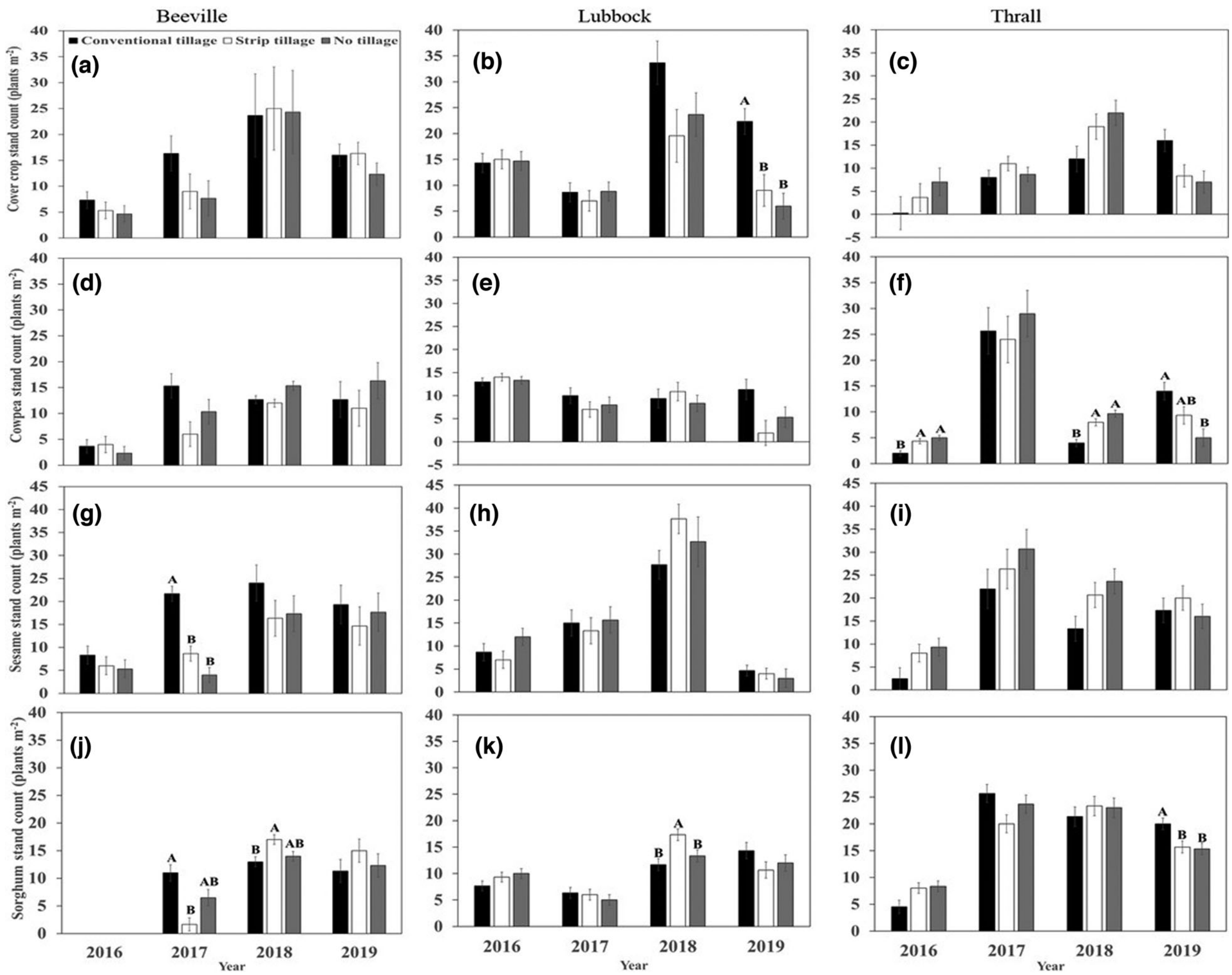


**FIGURE 4** Cover crop, cowpea, sesame, and sorghum stand count (plants $m^{-2}$) as affected by tillage at Beeville, Lubbock, and Thrall locations in Texas from 2016 to 2019. Bars represent SE of mean, and different letters in individual crop within each year at each location indicate significance ($P < .05$).

NT would be the ideal choice of tillage. Ultimately, summer cropping in wheat production systems rarely had a negative impact on wheat production compared with the summer fallow check at all three sites. Sorghum decreased wheat grain yield in 1 yr at Lubbock and Thrall but resulted in increased yield in a different year at each location. Overall wheat grain yield is stable following sorghum at Lubbock and Thrall.

## 3.2 | Summer crops

Tillage did not affect cover crop stand establishment at Beeville or Thrall; however, cover crop stand establishment was greater for CT than NT and ST treatments at Lubbock in 2019 (Supplemental Table S6; Figure 4a–c). Cowpea stand establishment at Beeville and Lubbock were not affected by tillage (Supplemental Table S6; Figure 4d,e). At Thrall, cowpea stand establishment was least in CT in 2016 and 2019 but greater for CT treatment than NT in 2019 (Supplemental Table S7; Figure 4f). Sesame stand establishment was impacted by tillage at Beeville in 2017 with it being greater in CT than NT or ST, but was not different at Lubbock or Thrall (Supplemental Table S6; Figure 4g–i). At Beeville, sorghum stand establishment was greater in CT than ST in 2017, but in 2018 sorghum stand establishment in CT was less than in ST (Figure 4j). At Lubbock, ST resulted in greater sorghum stand establishment compared with CT and NT in 2018 (Figure 4k). At Thrall, sorghum stand establishment was greater in CT than NT and ST in 2019 (Figure 4l).

At Thrall, in 2017, cowpea grain yield was over two times greater in NT than CT or ST treatments (Supplemental Table S7; Figure 5c), which was the only location and time with differences in cowpea grain yield. Overall, cowpea grain yields were very low at both Beeville and Thrall. Tillage did not impact sesame seed yield at Lubbock (Figure 5e). At Beeville, sesame seed yield was least in NT in 2016 and 2017 (Figure 5d), though ST was not significantly different from CT in either year. At Thrall, sesame seed yield was

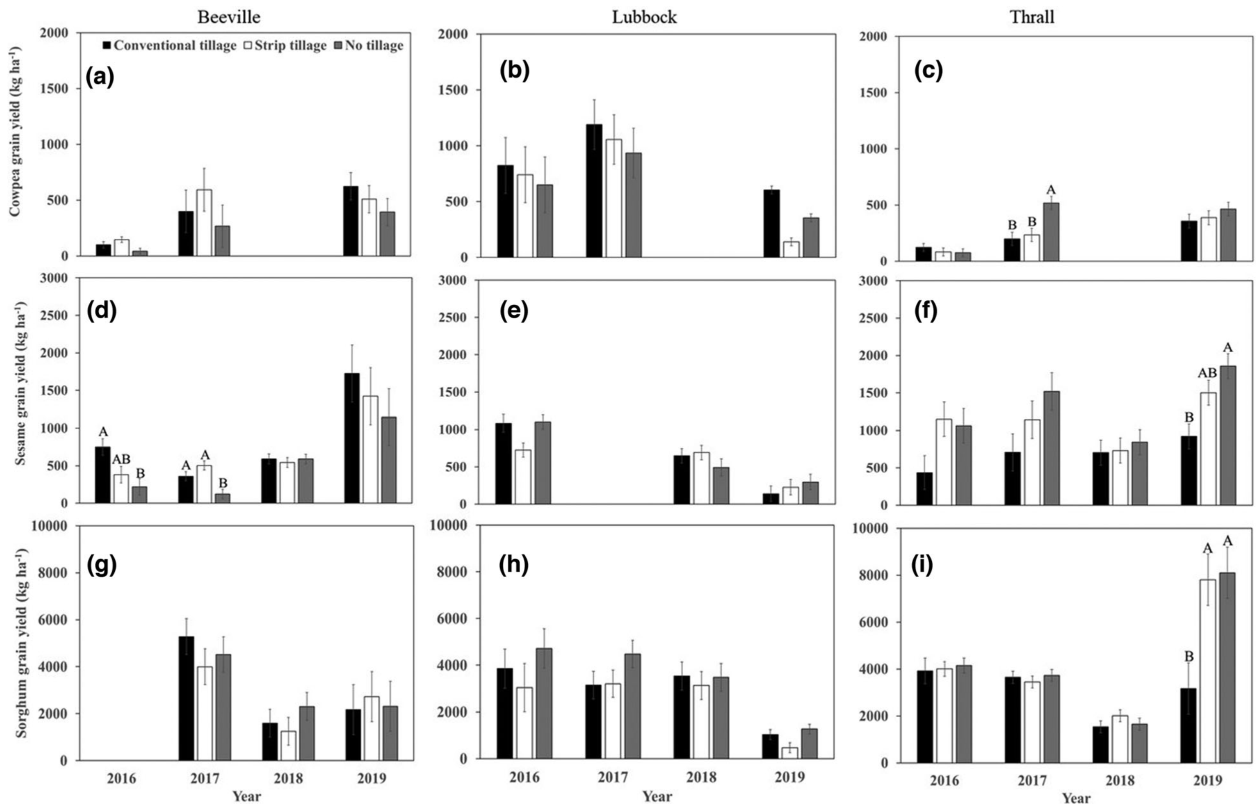


**FIGURE 5** Cowpea pulse, sesame seed, and sorghum grain yield (kg ha$^{-1}$) as affected by tillage at Beeville, Lubbock, and Thrall locations in Texas from 2016 to 2019. Bars represent SE of mean, and different letters within each year at each location indicate significance ($P < .05$).

greater in NT (1,157 kg ha$^{-1}$) than CT (920 kg ha$^{-1}$) in 2019 only (Figure 5f), though a similar trend appeared in all 4 yr. Sorghum grain yield was not different among tillage treatments at Beeville or Lubbock (Supplemental Table S7; Figure 5g,h) throughout this study, though there was a trend of greater yields in the NT than ST treatment at Lubbock. The NT and ST treatments produced 1.5 times greater sorghum grain yield than CT in 1 of 4 yr at Thrall (Figure 5i).

Akinyemi et al. (2003) found no significant difference between CT and NT for cowpea grain yield, which was consistent with our results at Beeville and Lubbock. In contrast, other researchers reported greater cowpea grain yield for CT compared with NT (Adekalu & Okunade, 2006; Aikins & Afuakwa, 2010). Adekalu & Okunade (2006) observed an increase in cowpea grain yield for reduced tillage and CT compared with NT. Weed control was particularly challenging for sesame and may have resulted in lower grain yields in some years; however, Thrall yields, in particular, were similar to or exceeded commonly achieved yields in the Blackland Prairie ecoregion for earlier plantings. In addition, late summer precipitation events may have contributed to the low sesame grain yields experienced in 2017 at Beeville (328 kg ha$^{-1}$; Figure 5d) and 2018 at Thrall (758 kg ha$^{-1}$; Figure 5f). In 2017, Hurricane Harvey played a significant role in reduction of sesame grain yield with heavy precipitation (142 mm) resulting in prolonged soil saturation and observed plant death at the Beeville location. Late season precipitation has been suggested to negatively affect sesame plants after the late bloom development stage (Langham et al., 2010; Sheahan, 2014).

Researchers reported no differences between CT and NT for sorghum grain yield (Foster et al., 2018; Franzluebbers et al., 1995; Sow et al., 1997), which was consistent with our study at Beeville and Lubbock. Studies have demonstrated crop residues under NT systems increased water storage capacity in the soil compared with CT system and may have improved yields in the NT system at Thrall (Baumhardt et al., 1985; Foster et al., 2018; Shaver et al., 2002; Sow et al., 1997). Crabtree et al. (1990) also found they could produce similar grain sorghum grain yield under no-till double cropping systems following wheat compared with typical planting dates for grain sorghum in Eastern Oklahoma. Low sorghum grain yield at Beeville (1,714 kg ha$^{-1}$) in 2018 was mainly due to bird damage. The low sorghum grain yield in 2019 at Lubbock (921 kg ha$^{-1}$) was mainly due to delayed planting because the previous wheat crop was replanted, which delayed wheat harvest. The sorghum variety had been changed to an earlier maturing cultivar to compensate for a shorter growing season and ensure maturation before the first killing frost, but yield still suffered. Thrall had low in-season rainfall (31 mm)

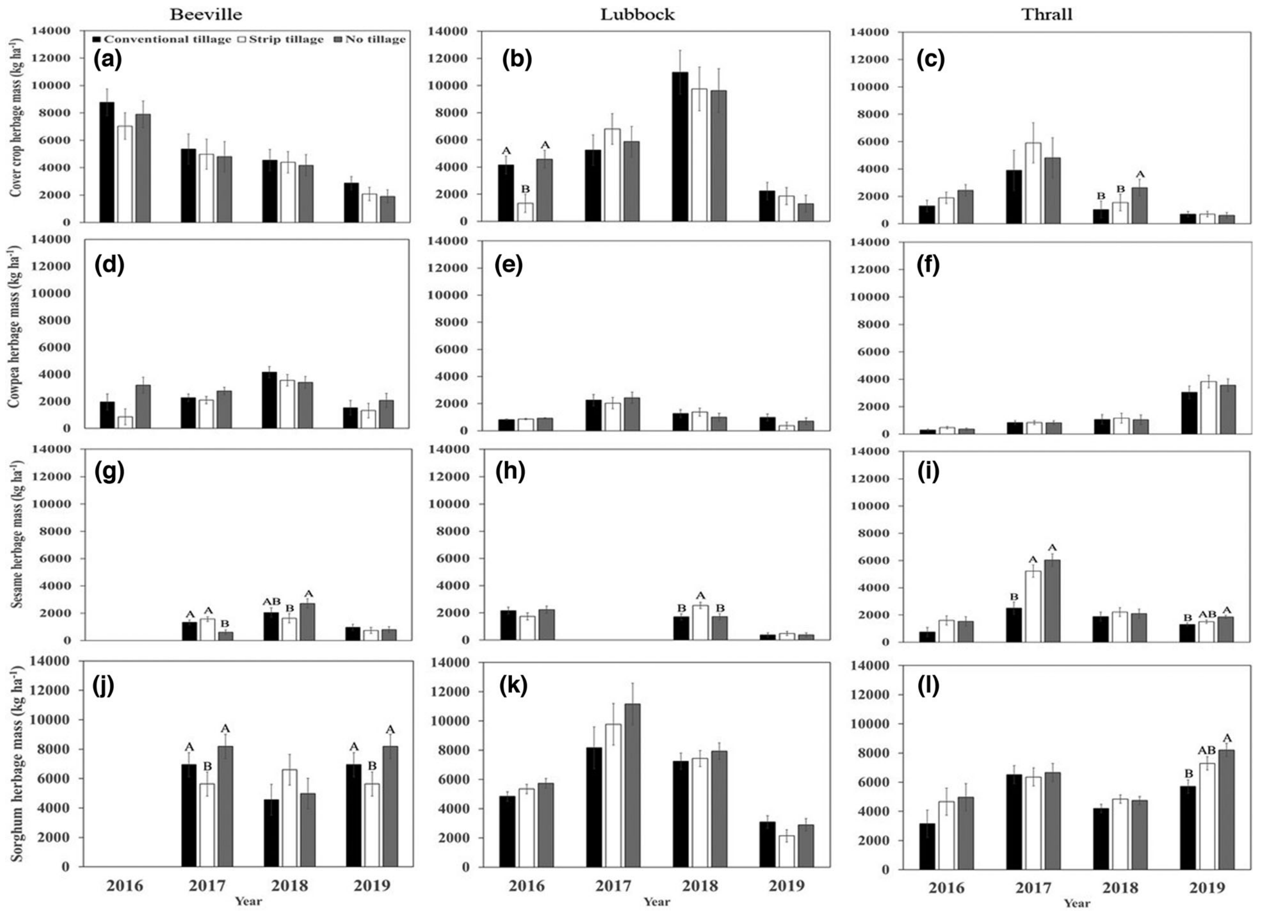


**FIGURE 6** Cover crop, cowpea, sesame, and sorghum herbage mass (kg ha$^{-1}$) as affected by tillage at Beeville, Lubbock, and Thrall locations in Texas from 2016 to 2019. Bars represent SE of mean and different letters in individual crop within each year at each location indicate significance ($P < .05$).

from June of 2018 through August of 2018, resulting in lower sorghum grain production (1,733 kg ha$^{-1}$) in 2018. Whereas timely planting is critical to ensure maturation of grain crops before the first frost at Lubbock, this was not a concern at Thrall or Beeville, which have much longer growing seasons.

Cover crop herbage mass was affected by tillage at Lubbock and Thrall in 2016 and 2018, respectively (Supplemental Table S7; Figure 6b,c). At Lubbock, cover crop herbage mass was 68% less in ST than in the NT and CT treatments in 2016. At Thrall, cover crop herbage mass was greater in NT (2,637 kg ha$^{-1}$) than ST (1,554 kg ha$^{-1}$) or CT (1,041 kg ha$^{-1}$) in 2018. Cowpea herbage mass was not affected by tillage at any of the three locations throughout this study (Supplemental Table S7; Figure 6d–f). In the cover crop mixture, pearl millet and 'Iron and Clay' cowpea were the most reliable species across all three locations, both in terms of establishment and herbage mass (data not shown). Sunflower had the next highest herbage mass. Buckwheat, guar, and sunn hemp established stands well at Lubbock. Lablab also did well at producing herbage mass each year at Thrall, though not as much as cowpea or pearl millet. Based on these results, pearl millet and 'Iron and Clay' cowpea are likely to be good additions to cover crop mixtures in the environments studied. Pearl millet and cowpea performed better than the rest of the cover crop mixture species at Beeville and Thrall; however, pearl millet, cowpea, sunflower, guar, lablab, sunn hemp, and buckwheat all emerged and were productive in Lubbock.

Sesame herbage mass was affected by tillage at all three locations (Supplemental Table S7). At Beeville, tillage impact on sesame herbage mass was inconsistent. In 2017, ST and CT treatments had sesame herbage mass 54% greater than NT treatment, whereas in 2018, NT had the greatest sesame herbage mass (Figure 6g). At Lubbock, sesame herbage mass was 39% greater in ST than CT and NT (Figure 6h). At Thrall, sesame herbage mass was greatest in NT and least in CT in 2017 and 2019 (Figure 6i). At Beeville, sorghum herbage mass was greater with NT and CT treatments than ST in 2017 and 2019 (Supplemental Table S7; Figure 6j). At Thrall, sorghum herbage mass was greatest in NT (8,211 kg ha$^{-1}$) and least in CT (5,707 kg ha$^{-1}$; Figure 6l). Tillage did not affect sorghum herbage mass at Lubbock throughout this study (Supplemental Table S7; Figure 6k).

**TABLE 4** Pearson correlation across years for wheat and summer crop stand count, grain yield, and herbage mass at Beeville, Lubbock, and Thrall locations in Texas from 2016 to 2020

| Response variables | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| **Beeville** | | | | | | |
| 1 Wheat stand count | – | .53** | NS† | −.35** | −.29** | −.36** |
| 2 Wheat grain yield | | – | .69** | NS | −.25** | −.26** |
| 3 Wheat herbage mass | | | – | .30** | NS | NS |
| 4 Summer crop stand count | | | | – | NS | .39** |
| 5 Summer crop grain yield | | | | | – | .70** |
| 6 Summer crop herbage mass | | | | | | – |
| **Lubbock** | | | | | | |
| 1 Wheat stand count | – | NS | −.19** | NS | NS | NS |
| 2 Wheat grain yield | | – | .84** | −.39** | −.24** | −.35** |
| 3 Wheat herbage mass | | | – | −.29** | −.17* | −.26** |
| 4 Summer crop stand count | | | | – | .15* | .45** |
| 5 Summer crop grain yield | | | | | – | .66** |
| 6 Summer crop herbage mass | | | | | | – |
| **Thrall** | | | | | | |
| 1 Wheat stand count | – | NS | .36** | NS | NS | NS |
| 2 Wheat grain yield | | – | .15* | −.20** | −.14* | −.33** |
| 3 Wheat herbage mass | | | – | .14* | NS | −.20** |
| 4 Summer crop stand count | | | | – | .31** | .46** |
| 5 Summer crop grain yield | | | | | – | .73* |
| 6 Summer crop herbage mass | | | | | | – |

*Note*. $n = 180$.
*Significant at the .05 probability level.
**Significant at the .01 probability level.
†NS, nonsignificant.

Overall, summer crops were successfully established in most years and locations throughout the study. Documenting weed control issues was beyond the scope of the trial, but intensifying cropping systems does limit herbicide options available for use without impacting subsequent crops and should be considered. Economic analysis will determine whether these double crop yields will offset the cost of production; however, even some return on investment may make these crops more profitable than a cover crop that does not produce any immediate returns on investment unless grazing is implemented. Double crops, and in particular grain sorghum, produced as much, or in many cases, more aboveground biomass than the multispecies cover crop mixture, and therefore is likely to improve soil health as greater herbage mass can enhance soil C storage, increase water retention, ground coverage, and microbial activity, and protect against erosion (Lal, 2004).

Correlation among response variables were obtained to evaluate the relationship among variables measured in this study across years and locations (Table 4). At Beeville, wheat stand establishment showed significant positive correlation with all response variables except wheat herbage mass. Wheat grain yield had a strong positive correlation with all response variables, with the exception of summer crop stand establishment at Beeville. Also, summer crop grain yield and herbage mass did not result in a significant correlation with wheat herbage mass. Interestingly, there was a strong positive correlation among summer crop stand establishment and wheat herbage mass, but not wheat grain yield at Beeville (Table 4). One confounding factor at Beeville that helps explain this was Hurricane Harvey, which resulted in reduced sesame grain yields with no impact on stands or herbage mass in the 2017 season. At Lubbock, all response variables had a significant positive correlation with each other, except wheat stand establishment that only had a significant positive correlation with wheat herbage mass (Table 4). At Thrall, correlation significance across variables was nearly identical to Lubbock except that wheat herbage mass was not correlated with summer crop grain yield (Table 4). Interestingly, wheat herbage mass was positively correlated with summer crop stand count at Beeville and Thrall, but not Lubbock. Negative correlations existed between wheat grain yield and summer crop grain yield or herbage mass at all sites. This likely indicates that there was adequate soil moisture following wheat harvest to facilitate germination and establishment of summer crops only at Beeville or Thrall. Additionally, production of both wheat and summer crops in this system is possible but maximizing productivity of both wheat and a summer crop is not likely feasible.

Positive correlations at all three locations indicate that achieving good stand establishment of summer crops was important for increasing summer crop grain yield and herbage mass. Not surprisingly, grain yield and herbage mass were positively correlated with each other at all three sites for both wheat and summer crops (Naharudin et al., 2021; Zhuanyun et al., 2020). Whereas wheat stand count was correlated with wheat grain yield at Beeville, it was not correlated at Lubbock or Thrall. Stand establishment is considered important for wheat grain yield in many cases; wheat is considered quite plastic and can compensate for low plant populations by producing additional tillers if environmental conditions are favorable (Dahlke et al., 1993; Tilley et al., 2019). Being the most southern location, Beeville was generally planted last and harvested first out of the three locations. Perhaps the shorter growing season reduced tillering time resulting in fewer tillers per plant and less time for the wheat to compensate for lower plant populations.

## 4 | CONCLUSIONS AND IMPLICATIONS

The 5 yr of experimentation in three Texas locations indicate that reduced tillage systems (NT and ST) and summer cropping may be feasible practices in the Coastal Plains and Blackland Prairie ecoregions of Texas. Both tillage and summer cropping treatment impacts on wheat establishment, wheat grain yield, and wheat herbage mass were inconsistent across years in all the three ecoregions. Under normal conditions, tillage did not impact wheat grain yield at Beeville, and at Thrall, wheat grain yield for NT and ST was greater or not different than CT in 3 of 5 yr. Summer cropping generally did not have a deleterious effect on wheat grain production at any site, with the exception of reduced wheat grain yield compared with the fallow control in two of twelve site-years. Yields of wheat, when rotated with any of the summer crops, were generally stable at all sites over the course of this project, except for grain sorghum at Beeville and Lubbock.

Double cropping in the High Plains region of Texas should be carefully considered based on access to irrigation. Whereas double cropping did not decrease wheat grain yield in any year compared with fallow control, it should be noted that the winter wheat was planted approximately 1 mo later than is typical for the region to allow for summer crop maturation and harvest, and this likely lowered the wheat grain yield. The shorter growing season requires a very quick turnaround between harvest of one crop and planting of the subsequent crop. As noted in 2019, a late wheat harvest delayed double crop planting and sorghum and sesame yields were affected by an early killing frost before reaching full maturity. Double crop species or cultivars that have short growing cycles should be considered at Lubbock to ensure timely maturation before wheat planting; however, limited growing degree days are not a concern at the southern locations at Thrall and Beeville. These results indicate limitations to the northern bounds of double cropping in the southern United States and may be somewhat dependent on the speed of wheat maturation in any given year.

Summer double cropping of grain sorghum and sesame has the potential to improve farmers' annual net return over cover crop as well as enhance soil health and long-term productivity and sustainability goals. Overall, this study demonstrates the possibilities for intensifying and diversifying cropping systems as well as implementing conservation tillage systems (no tillage or strip till) across multiple ecoregions in Texas.

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## AUTHOR CONTRIBUTIONS

Perejitei E. Bekewe: Data curation; Formal analysis; Investigation; Writing – original draft. Jamie L. Foster: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Supervision; Writing – review & editing. Clark B. Neely: Conceptualization; Funding acquisition; Investigation; Methodology; Validation; Writing – review & editing. Haly L. Neely: Funding acquisition; Investigation; Methodology; Project administration; Writing – review & editing. Katie L. Lewis: Conceptualization; Formal analysis; Investigation; Methodology; Supervision; Writing – review & editing. Lauren E. Tomlin: Investigation; Methodology. Ronnie W. Schnell: Investigation; Resources; Writing - review & editing. A. Peyton Smith: Resources; Witing - review & editing. Thomas W. Boutton: Conceptualization; Methodology; Resources; Writing - reveiw & editing. Brandon Gerrish: Investigation.

## CONFLICT OF INTEREST

Authors declare no conflicts of interest.

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