Weed Science

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No-tillage altered weed species dynamics in a long-term (36-year) grain sorghum experiment in southeast Texas

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Research Article

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Abstract

Tillage regimes can influence weed population dynamics and, consequently, the choice of appropriate weed management practices. Studies were conducted in 2016 and 2017 in a long-term (36-yr) grain sorghum [*Sorghum bicolor* (L.) Moench ssp. *bicolor*] experiment at Texas A&M University, College Station, to determine the impact of long-term no-till (NT) and conventional till (CT) systems on weed species dynamics. Higher densities of johnsongrass [*Sorghum halepense* (L.) Pers.], prostrate spurge [*Chamaesyce humistrata* (Engelm. ex A. Gray) Small], waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer], and henbit (*Lamium amplexicaule* L.) were recorded in the NT system compared with the CT system. Further, the NT system showed greater weed diversity (Shannon-Wiener index, $H = 0.8$) and species richness ($S = 6.2$), compared with the CT system ($H = 0.6$, $S = 4.2$). Seedling emergence of some dominant weed species was also delayed in the NT system. In the CT system, 50% emergence of *S. halepense* (8.5 C base temperature) and waterhemp (10 C base temperature) occurred at 59 and 63 growing degree days (GDD), respectively, whereas 68 and 75 GDD, respectively, were required in the NT system. Further, a greater proportion (61%) of the viable seedbank was present at the top 5 cm of the soil in the NT system compared with the CT system (46%). Overall, findings from this 36-yr-long tillage experiment have revealed that the NT system had greater weed densities (especially of the perennial weed *S. halepense*) and a high proportion of weed seeds (particularly small-seeded annuals) on the topsoil layer, corroborating some earlier reports that were based on short-term investigations. Findings indicate that growers transitioning to NT systems should be mindful of potential shifts in weed species dominance and develop appropriate management tactics.

Introduction

Changes in tillage practices from conventional tillage (CT) to no-tillage (NT) or reduced tillage (RT) can improve the sustainability of an agricultural ecosystem (Lal et al. 1999; West and Post 2002). Several advantages of conservation-tillage practices (NT and RT), including timely planting of crops, reduction in soil erosion and nutrient loss, retention of soil moisture, increased stable soil aggregate formation, and improved soil organic matter status, have been documented by researchers (Derpsch et al. 2010; Pimentel et al. 1995; Triplett and Dick 2008). Thus, conservation-tillage practices have been promoted worldwide to improve soil and ecosystem sustainability. Dobberstein (2014) reported that the area under conservation tillage in the United States has increased steadily since 1972 at an annual rate of 2.3%. Estimations made by the U.S. Department of Agriculture in 2012 showed that about 39 million ha of U.S. farmland was under conservation-tillage practices (USDA 2012). Kansas has the largest area under conservation tillage (4.21 million ha), followed by Nebraska, North Dakota, South Dakota, Iowa, and Montana (USDA 2012). In Texas, adoption of conservation tillage is very limited, with only about 0.10 million ha under NT or RT (USDA 2012).

Shifting from CT to conservation tillage can influence weed population dynamics by altering the vertical distribution of weed seeds in soil and impacting weed seedbank persistence and seedling recruitment (Farmer et al. 2017; Young and Thorne 2004). The lack of soil inversion in conservation-tillage systems may lead to the accumulation of weed seeds in the topsoil layer, thus altering their distribution in the soil profile. For instance, Refsell and Hartzler (2009) found a higher (21 seed cm^{-3}) waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer] seedbank density at the 0- to 3-cm soil depth in an NT system compared with chisel plowing (10 seed cm^{-3}). The lack of weed seed burial in the NT system may favor the persistence of small-seeded annual weeds (Moyer et al. 1994; Swanton et al. 1999) that are able to emerge from a shallow soil depth compared with large-seeded weeds. In a study conducted in Iowa by Leon and Owen (2004), greater (>4-fold) *A. tuberculatus* seedling recruitment was observed in the NT system compared with the CT system. Higher seedbank densities in the topsoil layer and a selection toward small-seeded annuals may subsequently lead to higher weed densities in NT compared with CT. Barberi and Lo Cascio (2001) reported a greater emergence (60%) of winter annual weeds in the NT system compared with the CT system (≤ 43%). Further, the absence of tillage can promote greater persistence of perennial weeds (lack of disturbance to perennial underground structures) in the conservation-tillage systems (Barberi and Lo Cascio 2001; Tuesca et al. 2001). In Iowa, Buhler et al. (1994) observed a higher density (215 plants 0.04 ha^{-1}) of field bindweed (*Convolvulus arvensis* L.) in a 14-yr NT system compared with moldboard (105), chisel (148), or ridge (70) plowing in a corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] rotation. Likewise, in a 22-yr-long study in Alaska (Conn et al. 2006), higher seedbank densities of quackgrass [*Elymus repens* (L.) Gould], a perennial grass species, were recorded in NT (19 seeds m^{-2}) compared with treatments with chisel plowing (0), disking once (9), or disking twice (0) at 0-to 15-cm soil depth.

The impact of tillage regimes on weed population dynamics can be altered by specific cropping systems, and such impacts can be better understood using long-term field studies rather than short-term investigations. At Texas A&M University, a long-term grain sorghum [*Sorghum bicolor* (L.) Moench ssp. *bicolor*] experiment was initiated in 1982 to understand the impact of an NT regime on soil properties and health. However, the impact of long-term NT practices on weed population dynamics is yet to be investigated in this experiment. The objective of this study was to compare the effects of long-term NT and CT practices on weed population dynamics and yield characteristics in grain sorghum, an important agronomic crop in Texas.

Materials and Methods

Study Site and Experimental Design

A long-term field experiment was initiated in 1982 along the Brazos River floodplain at the Texas A&M field Research Facility near College Station (30.46°N, 96.43°W). The specific field experiments presented here were carried out during the 2016 and 2017 growing seasons. The soil type of the study site was Weswood silty clay loam (fine-silty, mixed, superactive, thermic Udifluventic Haplustepts) with 29% sand, 42% silt, and 29% clay, and a pH of 8.0. Two tillage treatments (CT and NT) were arranged in a randomized complete block design with four replications (plot size: 4 m by 12 m). Grain sorghum was planted in 1-m-wide rows during mid- to late March and harvested during late July to early August. Glyphosate (Roundup WeatherMax®, Bayer Crop Science LP, 2 T.W. Alexander Drive, Research Triangle Park, NC 27709) was applied as a burndown herbicide at 1,000 g ae ha^{-1} before planting grain sorghum in both NT and CT systems, and atrazine (Atrazine 4L, Helena Chemical, 225 Schilling Boulevard, Suite 300, Collierville, TN 38017) was applied at 1,120 g ai ha^{-1} at the time of grain sorghum planting in both NT and CT systems to provide PRE weed control. In the CT system, tillage was performed using a disk harrow (~15-cm depth) after crop harvest, followed by chisel plowing (20- to 25-cm depth) and a second disking before the winter season. The beds were formed subsequently. No land preparation was required at the time of grain sorghum planting in spring, except that the ridge top was knocked off using a cultivator to allow for seed placement in the moisture zone. Interrow cultivation was carried out twice during the early crop growth period for weed control in the CT plots. No soil disturbance was carried out in the NT plots. All plots were fertilized with 135 kg ha^{-1} nitrogen (NH_4NO_3) as a band application before grain sorghum planting. Weather data (maximum and minimum air temperature and precipitation) were obtained from a weather station installed near the research site.

Weed Seedbank Dynamics and Seedling Emergence

In this experiment, we studied both extractable seedbank (ESB) and germinable seedbank (GSB) to account for the weeds present in the soil seedbank as well as the ones emerging from the soil, respectively. Studying both GSB and ESB provides comprehensive information about the persistence and viability of weeds in different tillage systems. To estimate weed seedbank size (GSB) and vertical distribution pattern, soil core samples (5-cm diameter) were collected at depths ranging from 0 to 70 cm using a motorized soil auger (AMS, Main Office, 105 Harrison Street, American Falls, ID 83211) a week before grain sorghum planting. Each soil core was divided into five depths (0 to 5, 5 to 15, 15 to 30, 30 to 50, and 50 to 70 cm). The soil samples were washed under a gentle flow of water, and the weed seeds were separated using appropriate sieves (850, 425, and 90 microns). The seeds were then counted under a microscope (AM Scope, Irvine, CA), and placed into Petri dishes to determine the germination potential, followed by a viability test (1% tetrazolium chloride), as described by Patil and Dadlani (2009), conducted on the nongerminated seeds.

To determine weed seedlings emergence pattern (ESB), four quadrats (0.5 m by 0.5 m) were randomly placed within each plot between two grain sorghum rows. Weed seedling emergence was recorded at weekly intervals starting at crop planting in March through the end of June when the majority of seedling emergence was completed. The newly emerged weed seedlings at each observation timing were identified, counted, and removed from each quadrat. The quadrats were covered with a plastic sheet during herbicide applications to the plots to prevent any impact on weed seedling emergence. Total aboveground weed densities per plot were determined from four additional quadrats (0.5 m by 0.5 m) randomly placed in each plot before grain sorghum harvest.

Data Analysis

Data were subjected to ANOVA using PROC GLIMMIX in SAS (SAS Institute, 100 SAS Campus Drive, Cary, NC 27513-2414), and treatment means were separated using the Fisher's protected Least Significant Difference (LSD) method at $\alpha = 0.05$. Tillage system and year were considered as the fixed effects in the model, whereas blocks (nested within years) were considered as the random effect. Before performing ANOVA, the normality of residuals was tested using the Shapiro-Wilk test (PROC UNIVARIATE).

Weed Diversity Indices

Weed diversity indices were calculated using the emerged seedlings and weed seed density data. Species richness was calculated by counting the number of weed species present in a treatment (Clements et al. 1994). Weed diversity, dominance, and evenness were determined using the Shannon-Wiener index, Simpson's index, and Pielou's measure (Equations 1 to 3), respectively.

Further, similarity values were estimated using the Jaccard index (Equation 4).

Shannon-Wiener index (Krebs 1985):

$$H = -\sum p_i \ln p_i \quad [1]$$

where H is the species diversity index, and p_i is the proportion of the species i in total number of species.

Simpson index (Southwood 1978):

$$D = \sum \frac{(n_i(n_i - 1))}{(N(N-1))} \quad [2]$$

where n_i is the number of individuals of species i, and N is the total number of individuals in a sample.

Pielou's measure of evenness (Pielou 1966):

$$E = H/\ln S \quad [3]$$

where H is species diversity index (i.e., Shannon-Wiener index), and S is the species richness (number of weed species present in a plot).

Jaccard measure (Janson and Vegelius 1981; Southwood 1978):

$$C_j = j/(a + b - j) \quad [4]$$

where j is the number of species found in both the tillage systems, a is the total number of individuals in CT, and b is the total number of individuals in NT.

Seedling Emergence Data Analysis

Seedling emergence data for each of the dominant weed species were converted into cumulative emergence (%) across the entire duration of emergence. The cumulative seedling emergence data were regressed over the accumulated growing degree days (GDD) (Equation 5) using a three-parameter sigmoidal function (Equation 6). The GDD is a time-based integral of heat accumulation (C) measured daily and is calculated using the following equation (Gilmore and Rogers 1958):

$$\mathrm{GDD} = \left(\frac{T_{\max} + T_{\min}}{2}\right) - T_{\mathrm{b}} \quad [5]$$

where $T_{\max}$ is the maximum air temperature, $T_{\min}$ is the minimum air temperature, and T_{b} is the base temperature for each weed species. Base temperatures of 8.5 C for johnsongrass [*Sorghum halepense* (L.) Pers.] (Arnold et al. 1990), 10 C for *A. tuberculatus* (Uscanga-Mortera et al. 2007), and 15 C for prostrate spurge [*Chamaesyce humistrata* (Engelm. ex A. Gray) Small] (Asgarpour et al. 2015) were used for calculating respective GDD values.

The three-parameter sigmoidal growth function (Equation 6) was fit to the seedling emergence data using SigmaPlot (v. 14.0, Systat Software, 2107 North First Street, San Jose, CA 95131-2026) and took the following form:

$$[Y = a/(1 + exp - [(x - x_0)/b] \quad [6]$$

where Y is cumulative seedling emergence (%) at a given value of x (GDD), a is the upper asymptote (theoretical maximum for Y, normalized to 100%), x_0 is the GDD required for 50% seedling emergence, and b is the slope of the sigmoidal function at x_0.

Model Goodness of Fit

The goodness of fit for the sigmoidal function was tested by estimating the root mean-square error (RMSE) (Equation 7) and the Nash-Sutcliffe model efficiency coefficient (E_f) (Equation 8). The R^2 is an inadequate measure of goodness of fit for nonlinear models (Spiess and Neumeyer 2010), but RMSE and E_f could be better suited for such functions (e.g., Sarangi et al. 2016). RMSE and E_f were calculated as follows (Mayer and Butler 1993; Roman et al. 2000):

$$\mathrm{RMSE} = \left[\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2\right] \quad [7]$$

$$E_f = 1 - \left[\sum_{i=1}^{n}(P_i - O_i)^2 / \sum_{i=1}^{n}\left(O_i - \overline{O_i}\right)^2\right] \quad [8]$$

where P_i is the predicted value, O_i is the observed value, and n is the total number of observations. Smaller RMSE values indicate high degrees of model fit. The E_f values range between $-\infty$ to 1, and a value closer to 1 indicates a better model fit.

Sum of Square Reduction Test (SSRT)

The differences in cumulative weed seedling emergence (%) between NT and CT were examined through an SSRT (two-curve comparison), as shown by Schabenberger et al. (1999) for herbicide dose–response data and used in Bagavathiannan et al. (2012) to compare weed fecundity data. For performing this test, full (considering tillage as a factor) and reduced models (without considering tillage as a factor) were developed. Model significance was tested based on the test statistic, F_{obs}, calculated using Equation 9:

$$F_{\mathrm{obs}} = \frac{[(\mathrm{SS\ Residual})_{\mathrm{Reduced}} - (\mathrm{SS\ Residual})_{\mathrm{Full}}]/[(\mathrm{df\ Residual})_{\mathrm{Reduced}} - (\mathrm{df\ Residual})_{\mathrm{Full}}]}{(\mathrm{MS\ Residual})_{\mathrm{Full}}} \quad [9]$$

where SS is the sum of squares, df is the total degrees of freedom, and MS is the mean squares. The calculated F_{obs} was compared with the cutoffs from an F distribution, considering df $(\mathrm{Residual})_{\mathrm{Reduced}}$ − df $(\mathrm{Residual})_{\mathrm{Full}}$ as the numerator and df $(\mathrm{Residual})_{\mathrm{Full}}$ as the denominator df.

Results and Discussion

To our knowledge, this is the first report comparing weed population dynamics between CT and NT systems in a long-term experiment running for more than 35 yr. The tillage-by-year interaction was nonsignificant ($P \geq 0.05$) for weed density, weed indices, and cumulative seedling emergence; therefore, data from 2016 and 2017 were combined. The monthly maximum and minimum air temperatures were similar during the 2016 and 2017 growing seasons (May to September) (Figure 1). However, cumulative summer rainfall was greater in 2017 (884 mm) than in 2016 (659 mm).

Seedbank Distribution

The vertical distribution of viable weed seeds in the soil varied between the two tillage systems (Figure 2), and in general the NT system had greater seedbank densities (8% greater) in the topsoil layer compared with the CT system (data not shown). In the

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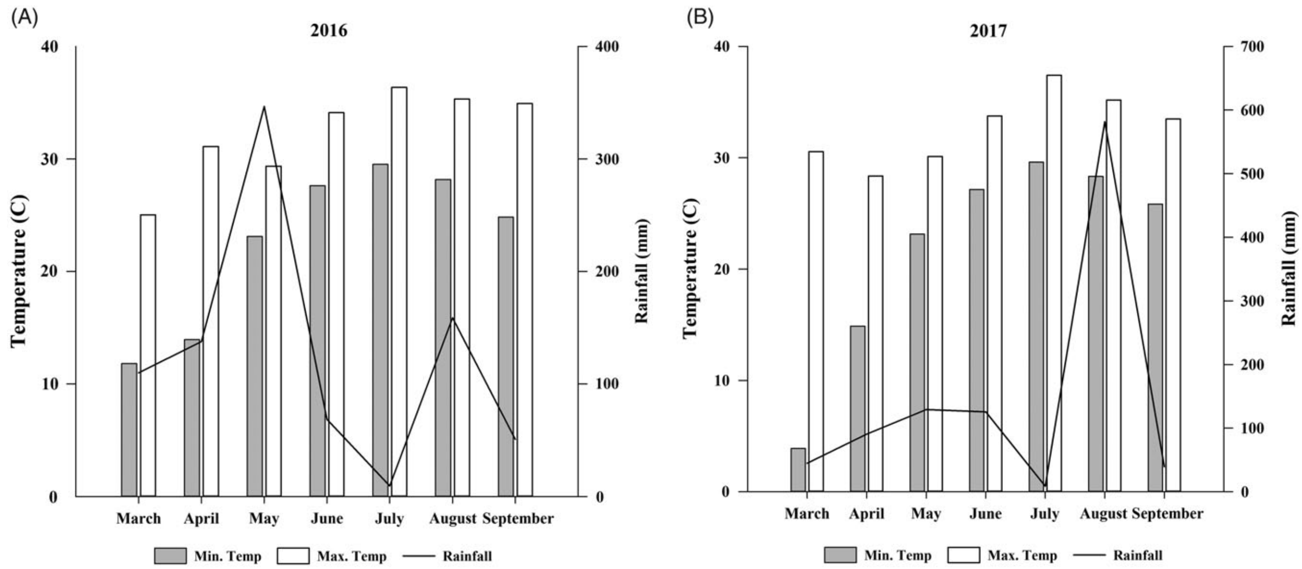

Figure 1. Monthly maximum and minimum temperatures (C) and rainfall (mm) recorded in 2016 and 2017 in the long-term grain sorghum experiment at College Station, TX.

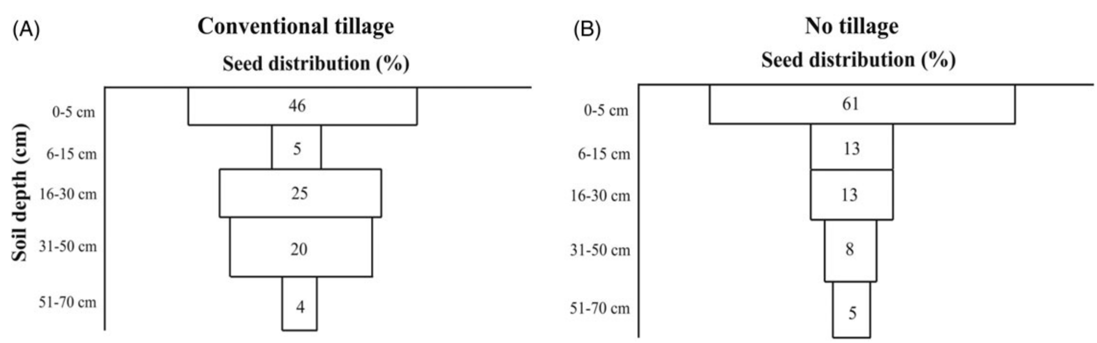

Figure 2. Vertical distribution of viable weed seeds as affected by 36 yr of conventional tillage (A) or no-tillage (B) in a grain sorghum experiment in College Station, TX.

NT system, a greater proportion (61% greater) of viable weed seeds (out of the total weed seeds extracted) were observed at the 0- to 5-cm depth compared with the CT system (Figure 2A and B). This corroborates Clements et al. (1996), who documented 74% of the total viable weed seeds in the top 5-cm soil profile in the NT system but only 37% in the CT system after 11 yr of a tillage experiment. This could be attributed to the minimal seed burial associated with the NT system. Seed viability levels generally declined at increasing depths irrespective of the tillage system (Figure 2), which could be due to higher levels of seed demise caused by futile germination, viability loss, and/or microbial decay (Conn et al. 2006; Darlington and Steinbauer 1961). A relatively higher proportion of viable seeds at greater depths in NT compared with CT could be attributed to seed movement through pronounced soil cracking (PG, personal observation) and root channel formation in NT (Benvenuti 2007; Chambers et al. 1991).

Seedling Emergence Pattern

The RMSE values for the regression models describing cumulative seedling emergence of *S. halepense*, *A. tuberculatus*, and *C. humistrata* were generally low (ranged between 5 and 29) (Table 1), indicating a good model fit (Roman et al. 2000). Further, the E_f values for the cumulative emergence curves of *S. halepense*, *A. tuberculatus*, and *C. humistrata* were 0.9 (Table 1), also indicating a good model fit.

The emergence pattern of *S. halepense* and *A. tuberculatus* varied between the CT and NT systems, though that of *C. humistrata* was comparable between the two systems (Figure 3; Table 1). In CT, model-predicted GDD values based on air temperature to obtain 50% emergence (x_0) of *S. halepense* ($P < 0.05$) and *A. tuberculatus* ($P < 0.05$) were 59 and 63, respectively, whereas they were 68 and 75, respectively, in NT. Thus, there was a significant delay in the emergence of certain weed species in the NT system. Both *S. halepense* and *A. tuberculatus* are C_4 plant species, and soil temperatures were often cooler than air temperatures in NT due to higher water and residue cover (Fabrizzi et al. 2005), especially during the early season. This might have delayed seedling emergence. High residue accumulation in NT reflects solar radiation and alters the albedo of the soil surface, leading to a reduction in surface soil temperature (Cox et al. 1990). Our findings agree with the findings of Refsell and Hartzler (2009), wherein 50% *A. tuberculatus* seedling emergence was achieved at 10 d after planting in CT, whereas it took 35 d in NT. In fact, a considerable level of *S. halepense* and *A. tuberculatus* seedling emergence occurred even during the late season in NT (Figure 3).

Weed Species Composition

A total of 12 summer and 6 winter weed species were documented in the GSB (i.e., based on seedling establishment aboveground) in the 36-yr-long NT grain sorghum plots; however, only 9 were

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Table 1. Parameter estimates and measures of goodness-of-fit (RMSE and E_f) for the three-parameter sigmoidal function fit to cumulative weed seedling emergence as influenced by different tillage systems in a 36-yr-long grain sorghum experiment in College Station, TX.[a,b]

Weed species	Tillage regime	X_0 (±SE)	B (±SE)	RMSE	E_f	SSRT[c]
		—GDD—				
Sorghum halepense	CT	59 ± 2	−20 ± 1	5	0.9	$P \leq 0.05$
	NT	68 ± 2	−22 ± 2	7	0.9	
Chamaesyce humistrata	CT	87 ± 2	−17 ± 2	13	0.9	NS
	NT	85 ± 2	−19 ± 2	21	0.9	
Amaranthus tuberculatus	CT	63 ± 3	−15 ± 3	29	0.9	$P \leq 0.05$
	NT	75 ± 7	−30 ± 7	6	0.9	

[a]Abbreviations: E_f, modeling efficiency coefficient; GDD, growing degree days (C); NS, nonsignificant; RMSE, root mean square error; SE, standard error of the mean; SSRT, the sum of square reduction test.

[b]Three-parameter sigmoidal function: $Y = a/(1 + \exp - [(x - x_0)/b)]$, where, Y is cumulative seedling emergence (%); A is the upper limit (theoretical maximum for Y normalized to 100%); X_0 is the GDD required for 50% seedling emergence; and B is the slope of the sigmoidal function at X_0.

[c]$F_{obs} = \frac{(\text{SS Residual})_{\text{Reduced}} - (\text{SS Residual})_{\text{Full}} / (\text{df Residual})_{\text{Reduced}} - (\text{df Residual})_{\text{Full}}}{(\text{MS Residual})_{\text{Full}}}$, Where SS is the sum of squares, df is degrees of freedom, and MS is the mean square. The calculated F_{obs} was compared with the cutoffs from an F distribution considering df $(\text{Residual})_{\text{Reduced}}$ − df $(\text{Residual})_{\text{Full}}$ as the numerator and df $(\text{Residual})_{\text{Full}}$ as the denominator.

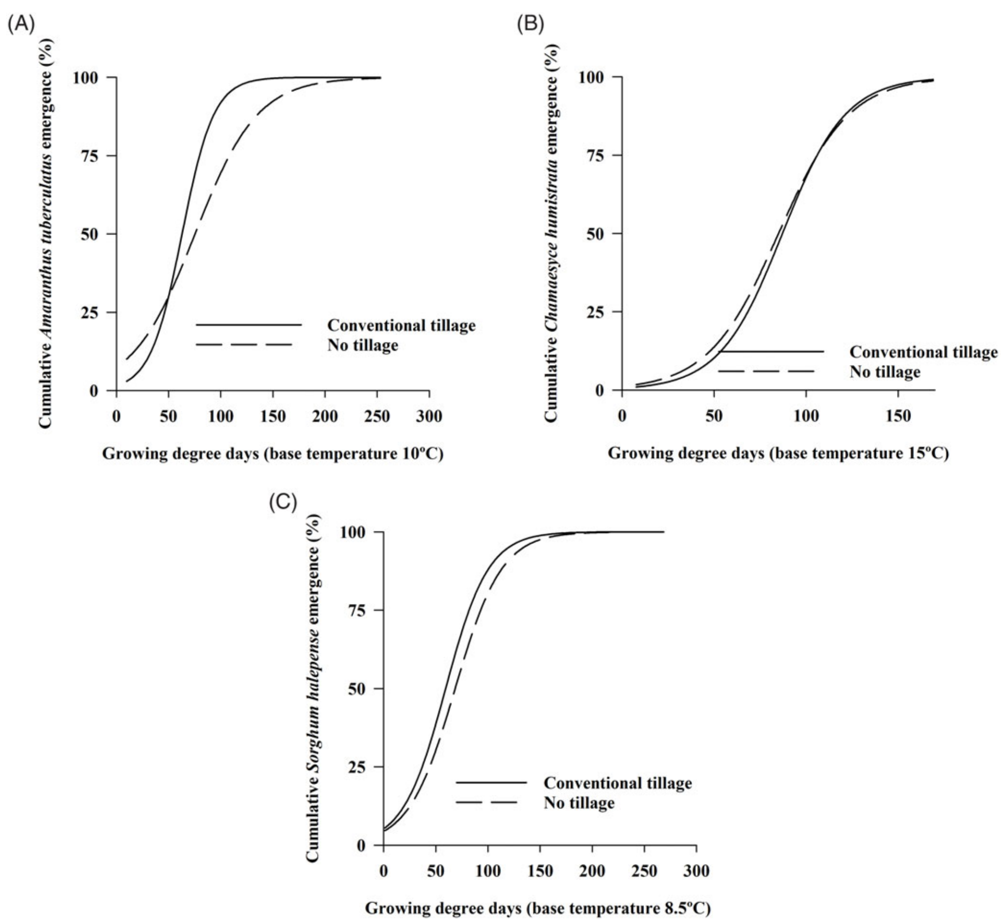

Figure 3. The impact of long-term conventional tillage and no-tillage on cumulative emergence of (A) *Amaranthus tuberculatus*, (B) *Chamaesyce humistrata*, and (C) *Sorghum halepense* in a 36-yr-long grain sorghum experiment in College Station, TX. The growing degree days were calculated based on average air temperatures.

present in the CT system (Table 2). The eight not observed in CT include annual sowthistle (*Sonchus oleraceus* L.), bull thistle [*Cirsium vulgare* (Savi) Ten.], common sunflower (*Helianthus annuus* L.), hoary bowlesia (*Bowlesia incana* Ruiz & Pav.), cutleaf evening primrose (*Oenothera laciniata* Hill), ivyleaf morningglory (*Ipomoea hederacea* Jacq.), pitted morningglory (*Ipomoea lacunosa* L.), and sicklepod [*Senna obtusifolia* (L.) Irwin & Barneby]. Most of the weeds absent in the CT system are small seeded, except common sunflower, *I. lacunosa*, and *I. hederacea*, which have difficulty germinating below the 15-cm burial depth typical of a CT system (Burton et al. 2004; Chauhan et al. 2006; Oliveira and Norsworthy 2006). For example, Chauhan et al. (2006) reported that *S. oleraceus* seedling emergence was 77% at the soil surface and drastically declined with increased soil depth and stopped at 5-cm depth. For *I. lacunosa*, Oliveira and Norsworthy (2006) found that germination was greater (100%)

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Table 2. Effect of tillage regimes on weed species composition in a long-term grain sorghum experiment in College Station, TX.[a]

Weed species	Growth habit[b]	Conventional tillage[c]	No-tillage[c]
Summer weed species			
Cirsium vulgare (Savi) Ten.	Biennial	×	✓
Portulaca oleracea L.	Annual	✓	✓
Helianthus annuus L.	Annual	×	✓
Oenothera laciniata Hill.	Biennial	×	✓
Ipomoea hederacea Jacq.	Annual	×	✓
Sorghum halepense (L.). Pers.]	Perennial	✓	✓
Ipomoea lacunosa L.	Annual	×	✓
Chamaesyce humistrata (Engelm. ex A. Gray) Small	Annual	✓	✓
Senna obtusifolia (L.) Irwin & Barneby	Annual	×	✓
Cucumis melo L.	Annual	✓	✓
Amaranthus tuberculatus (Moq.) Sauer	Annual	✓	✓
Urochloa texana (Buckley) R.Webster	Annual	✓	✓
Winter weed species			
Sonchus oleraceus L.	Annual	×	✓
Bowlesia incana Ruiz & Pav.	Annual	×	✓
Oenothera laciniata Hill	Biennial	×	✓
Lamium amplexicaule L.	Annual	✓	✓
Lolium perenne ssp. *multiflorum* (Lam.) Husnot	Annual	✓	✓
Capsella bursa-pastoris (L.) Medik.	Annual	✓	✓

[a]Weed species data based on 2016 and 2017 observations.
[b]Growth habit in southeast Texas.
[c]✓ = present; × = not present.

Table 3. Impact of conventional tillage (CT) or no-tillage (NT) systems on population densities of *Sorghum halepense*, *Chamaesyce humistrata*, *Amaranthus tuberculatus*, and *Lamium amplexicaule* in a 36-yr-long grain sorghum experiment in College Station, TX.[a]

Tillage	*S. halepense*	*C. humistrata*	*A. tuberculatus*	*L. amplexicaule*
	no. plants m^{-2}			
CT	11 (± 1.30) b*	2 (± 1.01) a	5 (± 4.59) b	45 (±9.23) b
NT	28 (± 6.44) a	4 (± 1.21) a	19 (± 4.59) a	117 (±9.23) a
P value	0.001	0.26	0.04	<0.001

[a]Data were pooled between 2016 and 2017. The values with different letters are statistically different at P-value < 0.05.

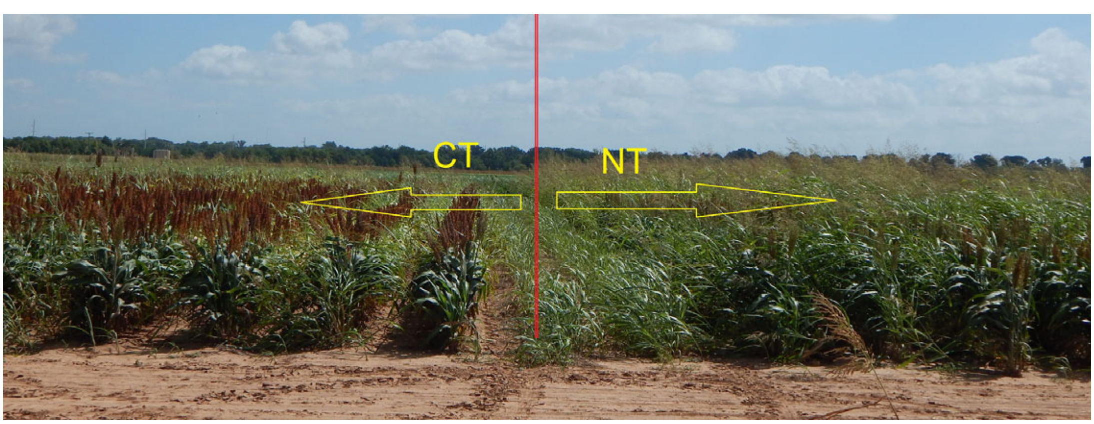

Figure 4. Impact of long-term conventional-tillage (left) and no-tillage (right) on *Sorghum halepense* density in a 36-yr-long grain sorghum experiment in College Station, TX.

at soil surface, 50% at 4-cm depth, and approximately 10% at 10-cm soil depth. In general, a lack of soil incorporation and higher soil fertility (especially higher organic carbon content; PG, unpublished data) in the NT system facilitates the germination of small-seeded weeds compared with the CT system. *Sorghum halepense* was the only perennial weed species observed in this study. This is perhaps due to genetic similarities between grain sorghum and *S. halepense* and the lack of selective herbicide options for *S. halepense* in grain sorghum. Further, *S. halepense*, *C. humistrata*, *H. annuus*, and *A. tuberculatus* were the dominant weed species present in both tillage systems.

Weed Density

Perennial Weed Density

Though *S. halepense*, the only perennial weed found in the experimental site, occurred in both tillage systems, average *S. halepense* densities were higher (28 plants m^{-2}) in NT compared with CT

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Table 4. Average seed size (length and width) of major weeds extracted from the soil seedbank in a 36-yr-long grain sorghum experiment in College Station, TX.[a]

Weed species	Length	Width
	——mm——	
Common sunflower (*Helianthus annuus* L.)	5.0	2.3
Cutleaf evening primrose (*Oenothera laciniata* Hill)	1.5	1.0
Henbit (*Lamium amplexicaule* L.)	2.1	0.6
Johnsongrass [*Sorghum halepense* (L.). Pers.]	6.8	1.8
Common waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer]	1.0	0.85

[a]Measurements were made using an AM Scope 40×–800× student microscope-LED.

Table 5. Comparison of weed community dynamics indices in conventional-tillage (CT) and no-tillage (NT) systems in a 36-yr-long grain sorghum experiment in College Station, TX.

		Weed community dynamics index[a]			
	Tillage	*H*	*S*	*D*	*E*
Germinable seedbank[b]	CT	0.6 b	4.2 b	0.7 a	0.4 a
	NT	0.8 a	6.2 a	0.6 a	0.4 a
	P-value[b]	0.03***	<0.01**	0.39	0.54
Extractable seedbank[b]	CT	0.2 b	3.0 b	0.5 a	0.3 a
	NT	0.4 a	4.0 a	0.5 a	0.2 b
	P-value[b]	<0.01**	0.01**	0.52	0.02***

[a]*H*, Shannon-Wiener diversity index; *S*, species richness; *D*, Simpson dominance index; and *E*, Pielou's measure of evenness. The mean values followed by different letters are statistically different ($\alpha = 0.05$).
[b]Germinable seedbank represents emerged seedlings (aboveground); extractable seedbank represents weed seedbank in the soil (belowground).
** $P < 0.01$.
*** $P < 0.05$.

(11 plants m^{-2}) (Figure 4; Table 3). Higher densities of *S. halepense* in the NT system can be attributed to the lack of tillage and improved availability of soil moisture. Tillage can be an effective strategy for controlling *S. halepense* by exposing rhizomes to sunlight and desiccation (McWhorter and Hartwing 1965). Conversely, an absence of tillage can allow the proliferation of perennial vegetative structures. Studies have reported higher densities of perennial weeds (spread via vegetative propagules) in NT compared with CT, and attributed this to the absence of tillage (Barberi and Lo Casio 2001; Hume et al. 1991). Other perennial weeds did not dominate the system, likely because the herbicide program was effective in managing them.

Annual Weed Density

Chamaesyce humistrata and *A. tuberculatus* were the most commonly found summer annual weeds at the study site, whereas henbit (*Lamium amplexicaule* L.) was the predominant winter annual weed species. Higher densities of *L. amplexicaule*, *C. humistrata*, and *A. tuberculatus* (117, 4, and 19 plants m^{-2}, respectively) were observed in the NT system compared with the CT system (45, 2, and 5 plants m^{-2}, respectively) (Table 3). *Chamaescyce humistrata*, *A. tuberculatus*, and *L. amplexicaule* all are small-seeded annual weeds that have high levels of fecundity, and the seeds typically remain on the soil surface in the NT system (Table 4). Because of small seed sizes, they have a better ability to germinate and establish from shallow depths. Buhler et al. (1996) and Steckel et al. (2007) have reported that small-seeded annual weeds such as *A. tuberculatus* and redroot pigweed (*Amaranthus retroflexus* L.) can be predominant in an NT system. Likewise, Hill et al. (2014) found high densities (10 to 65 plants m^{-2}) of *L. amplexicaule* in an NT system due to this weed's ability to germinate readily from the soil surface, supporting the findings of our research.

Weed Diversity Indices

In both GSB (aboveground weed densities) and ESB evaluations (belowground seedbank densities), the Shannon-Wiener index (*H*) and the species richness (*S*) values were relatively greater in the NT system compared with the CT system (Table 5), showing that tillage had an impact on weed diversity and composition in the 36-yr-long grain sorghum experiment. The *H* values for the CT and NT systems, respectively, were 0.6 and 0.8 for GSB and 0.2 and 0.4 for ESB, indicating a higher number of weed species in NT than in CT (Table 5). Our findings agree with the trend observed by Legere et al. (2011), who reported *H* values of 1.8 and 2.1 in CT and NT, respectively, in an 18-yr rye (*Secale cereale* L.) experiment in Canada. Further, the larger *S* values of 6.2 and 4.0 for GSB and ESB, respectively, in NT (vs. 4.2 and 3.0 in CT) in the current study indicate the generally greater weed densities in the NT system. The greater weed species diversity (*H*) and species richness (*S*) in the NT system are probably due to a relatively stable environment, longer persistence of weed seeds owing to lack of incorporation, and higher soil moisture levels compared with the CT system (Govindasamy et al. 2020). In corroboration of this, several studies have found higher *H* and *S* values in NT than in CT systems (Dorado et al. 1999; Sosnoskie et al. 2006). Further, repeated tillage in the CT system affects the vertical distribution of weed seeds in the soil profile, which reduces the emergence of several weed species in CT compared with NT (Cardina et al. 2002; Clements et al. 1996).

Both GSB and ESB evaluations revealed that there were no differences in weed species dominance (Simpson index, *D*) between the NT and CT systems; however, the measure of evenness (Pielou's measure, *E*) differed for ESB, with a greater *E* value (0.3, $P = 0.02$) in CT compared with NT (0.2). Redistribution of weed seeds through continuous plowing in CT could have led to a higher *E* value compared with NT in ESB. Our findings support Pardo

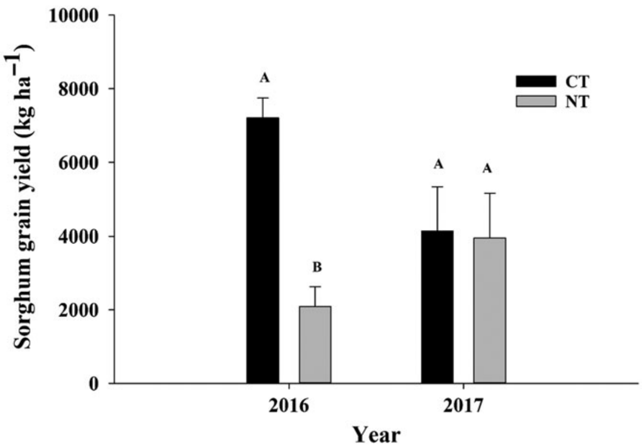

Figure 5. Sorghum grain yield as influenced by long-term tillage practices in College Station, TX. Bars topped with different letters are statistically different at $\alpha = 0.05$.

et al. (2019), who found a higher E value in CT (0.93) compared with NT (0.81) in a long-term (36-yr) tillage experiment in Spain. In general, the lower E values ($\leq$0.4) in both the systems indicated the presence of few dominant weed species in this experiment, which could be attributed to the broad spectrum of activity of the herbicide program followed. Additionally, the Jaccard measure (Cj) showed that 77% of weed species were common in both tillage systems in GSB, whereas it was 82% in ESB evaluations (data not shown).

Grain Sorghum Yield

The impact of tillage systems on grain sorghum yield was weather and weed density dependent. In 2016, higher grain yield was obtained in CT (7,210 kg ha^{-1}) than in NT (2,090 kg ha^{-1}) (Figure 5). Due to the harder soil surface (Govindasamy et al. 2020) and higher weed densities, the establishment and growth of grain sorghum was poor in NT in 2016, while better crop establishment and lower weed densities were observed in CT. In a modeling study conducted in Texas, Ribera et al. (2004) reported greater grain sorghum yields in a CT system (4,600 kg ha^{-1}) compared with NT system (3,940 kg ha^{-1}). However, sorghum grain yields were comparable between the two systems in 2017, highlighting the importance of good crop establishment and growth conditions for preventing any yield reduction in NT. Findings from this 36-yr-long experiment have clearly demonstrated that tillage regime can influence weed population dynamics, with the NT system favoring greater weed densities and diversity compared with the CT system.

The findings from this study are helpful for comprehending the response of different groups of weeds (annual, perennial, small seeded, large seeded, etc.) to the change in the level of soil disturbance. Further, an understanding of the increase or decrease in emergence and density of a particular weed species in response to crop and weed management practices will be helpful for growers to design strategic weed management programs. In particular, the NT system selected for small-seeded annual broadleaf weeds and perennials compared with the CT system (Buhler et al. 1994; Conn et al. 2006). Long-term tillage regimes also influence the distribution of weed seeds in the soil, with the majority of weed seedlings recruiting from shallow soil depths in NT. The dominance of small-seeded annual weeds and perennials in the NT system owing to the absence of soil inversion can lead to greater competition with crops for soil moisture, space, and nutrients and eventually decrease crop yield. Therefore, growers need to alter weed management programs that effectively prevent the dominance of small-seeded annuals and perennials; a strategic deep tillage once every 5 to 10 yr will be helpful in burying weed seeds below germinable depths (Blanco-Canqui and Wortmann 2020; Dang et al. 2015; McGillion and Storrie 2006).

The presence of viable weed seeds beyond 30-cm depth in NT even after 36 yr highlights prolonged viability of certain weed species in the soil seedbank and potential movement of weed seeds through soil cracks. Changes to weed seedling emergence periodicity mean that growers must adjust their weed management practices accordingly. The late-emerging cohorts are less likely to receive any POST application, and such escapes can add a substantial amount of seeds to the soil seedbank. Further, the lack of tillage in NT systems challenges weed control, warranting the development and implementation of robust weed management programs.

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