Frontiers in Agronomy

TYPE Original Research
PUBLISHED 24 October 2023
DOI 10.3389/fagro.2023.1277054

OPEN ACCESS

EDITED BY
Simerjeet Kaur,
Punjab Agricultural University, India

REVIEWED BY
Navjot Brar,
Guru Angad Dev Veterinary and Animal Sciences University, India
Chandrima Shyam,
Bayer, United States

*CORRESPONDENCE
Scott Nolte
✉ scott.nolte@ag.tamu.edu

RECEIVED 13 August 2023
ACCEPTED 29 September 2023
PUBLISHED 24 October 2023

CITATION
Vulchi R, Nolte S, McGinty J and McKnight B (2023) Herbicide programs, cropping sequences, and tillage-types: a systems approach for managing *Amaranthus palmeri* in dicamba-resistant cotton.
Front. Agron. 5:1277054.
doi: 10.3389/fagro.2023.1277054

Herbicide programs, cropping sequences, and tillage-types: a systems approach for managing *Amaranthus palmeri* in dicamba-resistant cotton

Rohith Vulchi[1], Scott Nolte[1]*, Joshua McGinty[2] and Benjamin McKnight[1]

[1]Soil and Crop Science Department, Texas A&M University, College Station, TX, United States,
[2]Soil and Crop Sciences Department, Texas A&M University, Corpus Christi, TX, United States

Herbicide-resistant *Amaranthus palmeri* poses a significant threat to cotton production in the US. Tillage, cover crops, crop rotations, and dicamba-based herbicide programs can individually provide effective control of *A. palmeri*, but there is a lack of research evaluating the above tactics in a system for its long-term management. Field trials were conducted near College Station and Thrall, TX (2019–2021) to evaluate the efficacy of dicamba-based herbicide programs under multiple cropping sequences and tillage types in a systems approach for *A. palmeri* control in dicamba-resistant cotton. The experimental design used was a split–split plot design. The main plots were no-till cover cropping, strip tillage, and conventional tillage. The subplots were cotton:cotton:cotton (CCC) and cotton:sorghum:cotton (CSC) sequences for 3 years within each tillage type, and sub-subplots were a weedy check (WC), a weed-free check (WF), a low-input program without residual herbicides (LI), and a high-input program with residual herbicides (HI). Using HI under the CSC sequence was the only system that provided >90% control of *A. palmeri* for 3 years across all tillage types and locations. By 2021, *A. palmeri* densities in the CSC sequence at College Station (4,156 plants ha^{-1}) and Thrall (4,006 plants ha^{-1}) are significantly low compared to the CCC sequence (31,364 and 9,867 plants ha^{-1}, respectively) when averaged across other factors. Similarly, *A. palmeri* densities in HI at College Station (9,867 plants ha^{-1}) and Thrall (1,016 plants ha^{-1}) are significantly low compared to LI (25,653 and 13,365 plants ha^{-1}, respectively) when averaged across other factors. We also observed that the CSC sequence reduced *A. palmeri* seed bank by at least 40% compared to the CCC sequence at both College Station and Thrall when averaged across other factors. Over 3 years, we did not observe significant differences between LI and HI for cotton yields at College Station (1,715–3,636 kg ha^{-1}) and Thrall (1,569 –1,989 kg ha^{-1}). However, rotating cotton with sorghum during 2020 improved cotton yields by 39% under no-till cover cropping in 2021 at Thrall. These results indicate that using dicamba-based herbicide programs with residual herbicides and implementing crop rotations can effectively manage *A. palmeri* in terms of seasonal control, densities, and seed bank buildup across tillage types and environments.

KEYWORDS

dicamba-based herbicide programs, crop rotation, no-till cover cropping, strip tillage, conventional tillage, Palmer amaranth, seedbank, densities

Introduction

Cotton (*Gossypium hirsutum*) is an important commercial crop in the United States (US) in terms of both internal revenue and exports valued at more than US$21 billion (USDA ERS, 2023a). Approximately 50% of the US upland cotton was planted in Texas during 2022, of which more than 90% contained herbicide-resistant traits (USDA ERS, 2023b). Dicamba-resistant cotton was introduced into the US market in 2017 and was planted on >50% cotton acres in the southern US by 2020 (USDA Agricultural Marketing Service - Cotton and Tobacco Program Memphis, 2020). It facilitated the growers with the use of over-the-top postemergence (POST) applications of dicamba alone or combined with glyphosate and glufosinate for weed control in cotton (Merchant et al., 2013; Cahoon et al., 2015; Inman et al., 2016). *Amaranthus palmeri* is reported as the most common and troublesome weed in the US cotton production systems (Van Wychen, 2019), affecting yield and quality, especially during the early stage of crop growth. *A. palmeri* densities as low as 0.4 and 0.9 plants m^{-2} can reduce cotton yields by 67% and 92%, respectively (Rowland et al., 1999a; Webster and Grey, 2015). *A. palmeri* densities of 8 plants m^{-1} row can decrease cotton yield by 91% when weed and crop emerge simultaneously (Massinga et al., 2001; Bensch et al., 2003). Furthermore, with each increase of 1 plant 9.1 m^{-1} row at the two-leaf stage of cotton, yield can be reduced by 10.7%–11% (Rowland et al., 1999b). Similarly, yields can be reduced by 0.9% with every *A. palmeri* increase by 1 m^2 at the three- and nine-leaf stages of cotton (MacRae et al., 2013).

The competitive abilities of *A. palmeri* can be attributed to high fecundity, extended germination periods, aggressive growth, and prolific seed production (Keeley et al., 1987; Ward et al., 2013). Outcrossing abilities within and between *Amaranthus* spp. (Franssen et al., 2001), increase the probability of finding a resistant individual under heavy selection pressure. *A. palmeri* can recover up to 78% of initial growth in just 21 days after initial foliage is removed (Browne et al., 2020) and produce up to 28,000 seeds when chopped 3 cm above the ground (Sosnoskie et al., 2014). It has an extended germination period from March to October (Keeley et al., 1987), which covers the entire cotton growing season in the southern US. Furthermore, the C_4 photosynthetic mechanism helps to adapt to lower levels of light (Jha et al., 2008), thereby managing the constraints associated with strategies like cover cropping. *A. palmeri* can tolerate water stress conditions using osmotic adjustment as a drought tolerance mechanism (Ehleringer, 1983). Through these adjustments, stomata can stay open and continue carbon fixation (Ehleringer, 1985) in water-stress environments.

A. palmeri evolved resistance to most of the PRE and POST herbicides used in cotton in the US (Vulchi et al., 2022). A population of *A. palmeri* resistant to six different modes of action has been reported in Kansas (Shyam et al., 2021). In Texas, *A. palmeri* is resistant to glyphosate and atrazine has been reported (Heap, 2021). Gene amplification, a target site resistance mechanism (Chahal et al., 2017; Dominguez-Valenzuela et al., 2017; Singh et al., 2018; Chaudhari et al., 2020), reduced absorption, and impaired translocation, a nontarget site resistance mechanism, were discovered as mechanisms of resistance to glyphosate in *A. palmeri* (Gaines et al., 2010; Nakka et al., 2017; Palma-Bautista et al., 2019; Koo et al., 2021). Enhanced metabolism, a nontarget site resistance mechanism has been discovered as the mechanism of atrazine resistance in *A. palmeri* recently (Nakka et al., 2017; Chahal et al., 2019). Additionally, nontarget site resistance mechanisms were responsible for synthetic auxin resistance in weeds (Shyam et al., 2022; Hwang et al., 2023).

With *A. palmeri* evolving both target and nontarget site resistance mechanisms to the commonly used herbicides in cotton, it is important to diversify the available weed management strategies by combining chemical and nonchemical strategies to achieve sustainable long-term weed control (Norsworthy et al., 2012). Dicamba-based herbicide programs have shown promise in providing long-term weed control in cotton (Oreja et al., 2022). Multiple POST applications of dicamba provide greater *A. palmeri* control compared to a single POST application (Cahoon et al., 2015). Residual herbicides, when applied at PRE and POST timings with dicamba, provide greater *A. palmeri* control than dicamba applications without residual herbicides (Inman et al., 2016). PRE + POST herbicide programs of dicamba, when combined with high cover crop biomass, provide greater *A. palmeri* control (Wiggins et al., 2017; Hand et al., 2021; Grint et al., 2022). However, reduced sensitivity to dicamba has been reported recently in *A. palmeri* populations of the High Plains regions of Texas (Garetson et al., 2019). *A. palmeri* has the ability to evolve resistance to a full dose of dicamba in three generations when exposed to sub-lethal doses (Tehranchian et al., 2017), and, agreeing with that, reduced control of *A. palmeri* was observed in East Texas in a grower field with dicamba-only use history from the past 3 years (S. Nolte, personal communication, January 11, 2023). On the other hand, nonchemical strategies like cover crops (Wiggins et al., 2017; Palhano et al., 2018; Denton et al., 2023), crop rotations (Ball, 1992; Liebman and Dyck, 1993; Martin and Felton, 1993), and tillage practices (Refsell and Hartzler, 2009; Farmer et al., 2017) can influence *A. palmeri* germination and its composition in the weed communities. When combined with herbicide programs, they can be effective in managing GR *A. palmeri* (Aulakh et al., 2012; Aulakh et al., 2013). Therefore, this study was conducted to provide Texas cotton growers with sustainable weed control solutions by evaluating combinations of dicamba based herbicide programs, cropping sequences, and tillage types in a systems approach looking at long-term GR *A. palmeri* management and crop yields.

Materials and methods

Field experiments were conducted from 2019 to 2021 at Texas A&M AgriLife Extension Farm near College Station, TX (30°30′ 40.3″N 96°25′06.7″W) and Stiles Farm near Thrall, TX (30°36′04.4″ N 97°18′06.5″W). The soil texture is belked clay with a pH of 8.1, 18% sand, 29% silt, 53% clay, and 1.5% organic matter at College Station, and Branyon clay with a pH of 6.0 18% sand, 35% silt, 47% clay, and 2.5% organic matter at Thrall (USDA - NRCS, 2022). Both locations share cation exchange capacity values of 30–45 meq 100

g^{-1} of soil, indicating their ability to retain more cations and salinity of 0–2 mmhos cm^{-1} of soil, indicating low electrical conductivity (USDA - NRCS, 2022). The location at College Station had overhead linear irrigation (Valley® Linears, A Valmont Industries Inc, NE 68064 USA), whereas Thrall was a rainfed/dryland environment. The experimental design was a randomized complete block design with a split–split plot arrangement of treatments. The main factors included no-till cover cropping, strip tillage, and conventional tillage blocks, each measuring 24.4 m wide and 36.6 m long. The 'Expresso' spring wheat variety was planted as the cover crop in 2019 and 2021, and the 'LCS Trigger' spring wheat variety was planted in 2020. These varieties were planted at 115 kg ha^{-1} under irrigated conditions and at 65–75 kg ha^{-1} under dryland conditions using a no-till seed drill following the forage seeding rates for wheat in Texas. Glyphosate (Roundup PowerMax, Bayer Crop Sciences, St. Louis, MO, USA) at 1.54 kg ai ha^{-1} rate was used to terminate the cover crop 4 weeks before planting main crops. One strip tillage activity was carried out from 2019 to 2021 near College Station. No strip tillage activity was carried out in 2019 due to earlier wet conditions near Thrall, but one strip tillage activity was carried out during the 2020 and 2021 cropping seasons. Only one disking activity was carried out in a conventional tillage block in 2019 due to earlier wet conditions during spring. However, two disking activities were carried out in 2020 and 2021, one during late fall and another within a week before planting, according to local practices.

The cropping sequence served as the split–plot factor, with half of each tillage type practiced under cotton:cotton:cotton (CCC) sequence and the other half under cotton:sorghum:cotton (CSC) sequence over the 3 years. Each split plot measured 12.2 m wide and 36.6 m long. Dicamba-resistant cotton variety DP 1646 B2XF and grain sorghum variety DK57-07 were planted at a targeted population of 112,000 plants ha^{-1} and 170,000 plants ha^{-1}, respectively. Herbicide programs served as the split–split plot factor. A weedy check (WC), weed-free check (WF), low input herbicide program (LI), and a high input herbicide program (HI) were applied to four rows of cotton or sorghum measuring 3 m wide and 9.1 m long in each cropping sequence and replicated four times. In both cotton and sorghum, HI included a preemergence application (PRE) at planting, a mid-postemergence (MPOST) application, and a lay-by as postdirected (PDIR) application; LI included an early-postemergence (EPOST) application and a late-postemergence (LPOST) application; WF were maintained using herbicide applications and hand weeding; WC did not receive any form of weed management. MPOST, PDIR in HI, and EPOST, LPOST in LI are hereafter referred to as the first (POST 1) and second (POST 2) postemergence applications, respectively. POST applications in both herbicide programs were applied based on the *A. palmeri* densities every year and not by the growth stage of the main crop. All herbicide applications were made using a CO_2-propelled backpack sprayer with a six-nozzle boom delivering 140 L ha^{-1} at 234 kPa. PRE applications were made using Drift Guard (DG)11002 nozzles, POST applications were made using Turbo TeeJet Induction (TTI) 11002 nozzles, and PDIR applications were made using TTI 9504E nozzles (TeeJet Technologies, Springfield, IL, USA).

The timeline of activities from planting cover crops to harvesting main crops is listed in the Supplementary Data. Herbicide programs, active ingredients, application timing, and rates applied are listed in Table 1. Along with the natural seed bank, a known population of at least 1,000 GR *A. palmeri* seeds were broadcast in each herbicide plot prior to planting in 2019 and were allowed to go to seed at the end of each year at both locations. All treatments were applied to the same area for 3 years to evaluate the compounding effect of treatments for seasonal and long-term *A. palmeri* control, densities, seed bank, cotton, and sorghum yields. Visual *A. palmeri* control was rated from 0 to 100, where 0 is no control and 100 is complete control (Frans, 1986). Except during 2019 in College Station, when cotton plots were harvested using a four-row cotton stripper, a sub-sample from 0.004 ha (1/100th acre) area in each cotton plot was hand-harvested at College Station and Thrall from 2019 to 2021. Grain sorghum was harvested from the middle two rows using a Wintersteiger plot combine (Wintersteiger Inc., Salt Lake City, UT, USA) at both locations. When cotton stripper was used, 7.6 m of the middle two rows of each four-row plot were harvested. All the sub-samples in each plot were interpolated to per-hectare yields for statistical analysis. Harvested seed cotton was ginned on a 20-saw table to calculate the lint percentages separately. Cover crop biomass was randomly harvested from the middle of each plot using three 0.25 m^2 quadrats on the day of termination in 2020 and 2021. Biomass samples were oven-dried at 55°C for 24 h before dry weights were collected. Similarly, *A. palmeri* densities were recorded from three randomly selected 0.25 m^2 areas in the middle of two rows of each plot during 2020 and 2021.

A. palmeri seed bank data collection

Ten 5-cm-wide, 15-cm-long soil cores were collected from LI and HI plots within a week after harvest from 2019 to 2021 at both locations. A total of 480 (2 herbicide programs × 2 cropping sequences × 3 tillage types × 4 replications × 10 soil cores) soil cores were collected each year using a probe truck. *A. palmeri* seeds were separated from soil in the cores by running water through the soil using fabric organza bags at the Norman Borlaug Institute for International Agriculture at Texas A&M University, College Station. Later, the seeds were collected, counted under a microscope, and stored at −10°C. Though density and seed bank data were not collected from the WC plots, comparing LI to HI can provide an understanding of the relative effectiveness of these strategies.

Data collection and statistical analysis

Percent *A. palmeri* control, seed bank data, seed cotton, and grain sorghum yields were collected from 2019 to 2021. Additionally, *A. palmeri* densities at 28 DA POST 2 timing in 2020 and 2021 were recorded. Weed control data were collected at 28 DA PRE, POST 1, POST 2, and a week before harvest at both locations. Data were analyzed using a generalized linear mixed

TABLE 1 Herbicides, application timings, active ingredients, and rates in respective herbicide programs used in cotton and sorghum used from 2019 to 2021 in College Station and Thrall, TX.

Crop	Program	Timing	Herbicides	Active ingredient	Rates used (kg a.i. or a.e. ha^{-1})
Cotton	WC	–	–	–	–
	WF	PRE	Dual Magnum®	*S*-Metolachlor	1.4
		EPOST	Roundup® PowerMAX® + Dual Magnum®	Glyphosate + dicamba	1.54 + 1.4
		LPOST	Roundup® PowerMAX® + Dual Magnum®	Glyphosate + dicamba	1.54 + 1.4
	LI	EPOST	XtendiMax® Plus VaporGrip® + Roundup® PowerMAX®	Dicamba + glyphosate	0.56 + 1.54
		LPOST	XtendiMax® Plus VaporGrip® + Roundup® PowerMAX®	Dicamba + glyphosate	0.56 + 1.54
	HI	PRE	Cotoran®	Fluometuron	1.12
		MPOST	XtendiMax® Plus VaporGrip® + Warrant® +Roundup® PowerMAX®	Dicamba + acetochlor + glyphosate	0.56 + 1.26 + 1.54
		LAYBY	Direx®	Diuron	1.12
Sorghum	WC	–	–	–	–
	WF	PRE	Huskie®	Pyrasulfutole and bromoxynil	0.09, 0.5
		EPOST	Aatrex® + Huskie®	Atrazine + pyrasulfutole & bromoxynil	1.12 + 0.09, 0.5
		LPOST	Aatrex® + Huskie®	Atrazine + pyrasulfutole & bromoxynil	1.12 + 0.09, 0.5
	LI	EPOST	Aatrex®	Atrazine	1.12
		LPOST	Aatrex®	Atrazine	1.12
	HI	PRE	Outlook®	Dimethenamid-P	1.7
		MPOST	Aatrex® + Outlook®	Atrazine + dimethenamid-P	1.12 + 1.7
		LAYBY	Aatrex® + Outlook®	Atrazine + dimethenamid-P	1.12 + 1.7

PRE, preemergence; EPOST, early-postemergence; MPOST, mid-postemergence; LPOST, late postemergence; PDIR, postdirected; WC, weedy check; WF, weed-free check; LI, low-input herbicide program; HI, high-input herbicide program.

model, PROC GLIMMIX (Statistical Analysis Systems, version 9.4, SAS Institute, Inc., Cary, NC, USA). Tillage, cropping sequence, herbicide programs, and locations were considered fixed variables. Years and replications nested within a location were considered random variables. Effects and interaction means were separated using Tukey's LSD at $p(\alpha) = 0.05$.

Results

A. palmeri control

Location, rating timing, year, tillage, cropping sequence, herbicide programs, and their two-way, three-way, four-way, and five-way interactions were significant for *A. palmeri* control (Supplementary Data). Therefore, data were separated by location, tillage, year, and rating timing to understand the influence of cropping sequence and herbicide programs on *A. palmeri* control in each tillage type at College Station and Thrall (Supplementary Data).

College Station

In conventional tillage, significant differences were not detected between herbicide programs, cropping sequences, or their interaction for *A. palmeri* control in 2019 and 2020. Greater than 95% *A. palmeri* control was observed until a week before harvest during the first 2 years, averaged across herbicide programs and cropping sequences. In 2021, HI plots that received residual herbicides at PRE and POST timings for 3 consecutive years resulted in ≥98% *A. palmeri* control until a week before harvest in both cropping sequences (Table 2). In no-till cover cropping, we observed ≥97% *A. palmeri* control in both herbicide programs until a week before harvest in 2019. In 2020, at least 90% *A. palmeri* control was recorded in HI plots in both cropping sequences until 28 DA POST 2. However, POST 1 application in LI failed to provide >75% control in both cropping sequences, which compounded until harvest (Table 3A). Low cover crop biomass content of 1,841 kg ha^{-1} (Supplementary Data), absence of overlapping residuals, and high early season *A. palmeri* densities resulted in a drastic reduction of *A. palmeri* control in LI plots during 2020. Additionally, POST 1 application in LI plots in cotton during 2020, is overall the third

TABLE 2 Percent *A. palmeri* control as influenced by cropping sequence and herbicide programs at different timings in conventional tillage at College Station, TX[a,b].

	Conventional tillage											
	28 DA PRE			28 DA POST 1			28 DA POST 2			WBH		
	2019	2020	2021	2019	2020	2021	2019	2020	2021	2019	2020	2021
CCC	95 aB	100 aA	98 aA	99 aA	96 aA	93 bA	98 aA	100 aA	96 aA	99 aA	99 aA	95 aB
CSC	98 aA	100 aA	98 aA	99 aA	98 aA	100 aA	97 aA	99 aA	98 aA	97 aA	98 aA	96 aA
LI	–	–	–	98 aA	95 aA	94 aA	96 aA	99 aA	95 bB	97 aA	98 aA	93 bA
HI	97 B	100 A	98 A	99 aA	99 aA	99 aA	99 aA	100 aA	99 aA	100 aA	99 aA	98 aA

[a] Values followed by the same letter are statistically similar based on Tukey's least significant difference (α = 0.05): lowercase letters compare means within the same column, whereas uppercase letters compare means within the same row.

[b] DA, days after; PRE, preemergence application, POST 1, first postemergence application; POST 2, second postemergence application; WBH, week before harvest; CCC, cotton: cotton: cotton; CSC, cotton: sorghum: sorghum; LI, low input herbicide program; HI, high input herbicide program.

POST application of dicamba after the research began in 2019. Previous research reported the potential of *A. palmeri* populations evolving resistance to dicamba after three generations (Tehranchian et al., 2017). In 2021, >90% *A. palmeri* control was observed only in HI plots under CSC sequence up to 28 DA POST 2 application. By a week before harvest, only HI plots under the CSC sequence provided >75% *A. palmeri* control while, other herbicide program × cropping sequence combinations provided only ≤60% control. In LI plots under the CCC sequence, control dropped from 100% in 2019 to 36% in 2021 (Table 3A). This dramatic reduction in *A. palmeri* control can be attributed to lower levels of cover crop biomass, the use of only two modes of action for 3 years, and the compounded annual increase in *A. palmeri* densities. Overall, HI under the CSC sequence, the system that used seven different herbicide modes of action over 3 years provided >90% control up to 28 DA POST 2 applications for 3 years (Table 3A). In strip tillage, both herbicide programs provided ≥90% *A. palmeri* control until a week before harvest in 2019. In 2020, PRE-fb two POST applications in HI in both cropping sequences provided >90% control until a week before harvest (Table 3B). Similar to no-till

TABLE 3 Percent *A. palmeri* control as a function of significant interaction between cropping sequence and herbicide program in no-till cover cropping (A) and Strip tillage (B) in College Station, TX[a,b].

	(A) No-till cover crop											
	28 DA PRE			28 DA POST 1			28 DA POST 2			WBH		
	2019	2020	2021	2019	2020	2021	2019	2020	2021	2019	2020	2021
Cotton: cotton: cotton												
Low input	–	–	–	98 aA	50 bB	10 bC	99 aA	68 bB	51 aB	98 bA	58 bB	36 aB
High input	80 B	94 A	66 B	97 aA	91 aA	69 aB	100 aA	90 aA	61 aB	100 aA	76 aB	48 aC
Cotton: sorghum: cotton												
Low input	–	–	–	100 aA	75 bB	50 bC	97 aA	50 bB	68 bB	97 bA	76 bB	60 bC
High input	66 B	95 A	91 A	98 aA	95 aA	97 aA	99 aA	93 aA	91 aA	100 aA	99 aA	78 aB
	(B) Strip tillage											
	28 DA PRE			28 DA POST 1			28 DA POST 2			WBH		
	2019	2020	2021	2019	2020	2021	2019	2020	2021	2019	2020	2021
Cotton: cotton: cotton												
Low input	–	–	–	100 aA	69 aB	65 aB	97 aA	80 bB	88 aB	97 aA	78 bA	74 aB
High input	89 A	90 A	75 B	94 bA	81 aA	88 aA	96 aA	95 aA	55 bB	100 aA	90 aB	60 aB
Cotton: sorghum: cotton												
Low input	–	–	–	98 aA	80 bB	93 aA	96 aA	87 aB	92 aA	96 bA	91 aA	90 aA
High input	91 A	85 A	93 A	93 aA	98 aA	96 aA	94 aA	94 aA	98 aA	100 aA	100 aA	95 aB

[a] Values followed by the same letter are statistically similar based on Tukey's least significant difference (α = 0.05): lowercase letters compare means within the same column, whereas uppercase letters compare means within the same row.

[b] DA, days after; PRE, preemergence application, POST 1, first postemergence application; POST 2, second postemergence application; WBH, week before harvest.

cover cropping, POST applications in LI under the CCC sequence provided ≤80% *A. palmeri* control until a week before harvest. In 2021, both herbicide programs under the CSC sequence provided >90% control until a week before harvest, and two POST applications in LI under the CCC sequence provided 88% control until 28 DA POST 2 (Table 3B). Overall, using HI under the CSC system provided at least 90% control throughout the season from 2019 to 2021, and control in LI plots under the CCC sequence reduced from 97% in 2019 to 74% in 2021 (Table 3B). Poor control was observed in HI plots under the CCC sequence in both no-till cover cropping (48%) and strip tillage (60%), a week before harvest in 2021. In the 4 weeks after the layby application of diuron in 2021, College Station received 15 cm of precipitation (data not shown), which could have accounted for the poor control in these plots. Previous research (Whitaker et al., 2011; Houston et al., 2019) documented reduced *A. palmeri* control of up to 61% when more than a 12-cm precipitation was recorded after diuron application.

Thrall

In conventional tillage, both herbicide programs provided >94% control after POST 2 application until a week before harvest in 2019 (Table 4C). In 2020 and 2021, both herbicide programs in the CSC sequence and HI in the CCC sequence provided ≥97% *A. palmeri* control until a week before harvest (Table 4C). A decline in control was observed from 95% in 2019 to 56% in 2021 a week before harvest in LI plots under the CCC sequence in 3 years (Table 4C). In no-till cover cropping, we observed ≥99% control in both herbicide programs until a week before harvest in 2019 (Table 4A). In 2020, both herbicide programs in the CSC sequence and HI in the CCC sequence provided ≥93% *A. palmeri* control until a week before harvest. However, LI provided only 73% control in CCC a week before harvest in 2020 (Table 4A). In 2021, HI provided ≥93% *A. palmeri* control in both cropping sequences until a week before harvest, while control was reduced to 53% in LI under the CCC sequence a week before harvest (Table 4A). In 3 years, *A. palmeri* control in LI plots under the CCC sequence reduced from 100% to 53% a week before harvest (Table 4A). In strip tillage, >95% *A. palmeri* control was recorded in both herbicide programs after the POST 2 application in 2019 (Table 4B). In 2020, both herbicide programs under the CSC sequence and the HI CCC sequence provided >90% *A. palmeri* control until a week before harvest. In 2021, HI provided ≥93% *A. palmeri* control compared to <50% control by LI in both cropping sequences a week before harvest (Table 4B). Overall, *A. palmeri* control was consistently >90% in HI plots in both cropping sequences, while control reduced from 97% to 36% in LI plots under the CCC sequence and from 99% to 42% in LI plots under the CSC sequence in 3 years (Table 4B).

A. palmeri densities 28 DA POST 2

In 2020 and 2021, the cropping sequence and herbicide program influenced *A. palmeri* densities in all tillage types at both locations (Supplementary Data). Influence of tillage × herbicide program, tillage × cropping sequence, and cropping sequence × herbicide program on *A. palmeri* densities near College Station and Thrall are listed in Tables 5–7, respectively.

College Station

In conventional tillage, *A. palmeri* densities in LI plots were at least 20 times higher compared to HI plots averaged across cropping sequences in 2020 (Table 5). Our results corroborate with Aulakh et al., (2012; 2013) who observed a >90% reduction in *A. palmeri* germination in plots that received a PRE + POST herbicide application in the inversion tillage over 3 years. In 2021, *A. palmeri* densities in the CCC sequence were 2,691 plants ha^{-1} compared to ~0 plants ha^{-1} in the CSC sequence averaged across herbicide programs (Table 6). In no-till cover cropping, *A. palmeri* densities increased significantly only in HI under the CCC sequence in 2 years, and densities were significantly higher in LI plots compared to HI plots during both years. Densities did not increase significantly over time in either herbicide program under the CSC sequence; however, densities of *A. palmeri* in LI plots were at least eight times higher than compared of HI plots under the CCC sequence in 2021 (Table 7). In strip tillage, *A. palmeri* densities in LI plots were at least two times higher than those in HI plots, averaged across cropping sequences in 2020 (Table 5). In 2021, *A. palmeri* densities in the CCC sequence were at least six times higher than those in the CSC sequence averaged across herbicide programs (Table 6). Previous research by Aulakh et al. (2012); Price et al. (2016); Wiggins et al. (2017); Palhano et al. (2018), and Hand et al. (2021) reported that high residue cover crops combined with residual herbicides provide the greatest suppression of *A. palmeri* and corroborate with our results. Failure to produce high biomass content in no-till cover cropping and the absence of soil cover in strip tillage, combined with a lack of residual herbicides, led to the increase in *A. palmeri* densities over time in LI plots. Significantly lower densities in CSC compared to the CCC sequence in 2021 were due to the thick mat of sorghum biomass from the previous year acting like a cover crop, preventing the germination of *A. palmeri*. Negative influences of crop diversification on weed seed germination have been previously reported by Weisberger et al. (2019) and Sharma et al. (2021).

Thrall

In conventional tillage, *A. palmeri* densities in LI plots were 74 times higher than those in HI plots averaged across cropping sequences in 2021. Though statistically insignificant, HI provided at least a 10-fold reduction in densities in 2020, while in 2021 a clear statistical separation was observed between HI and LI for *A. palmeri* densities (Table 5). Also, rotating cotton with sorghum during 2020 resulted in extremely low *A. palmeri* densities (0–100 plants ha^{-1}) in 2020 and 2021 averaged across herbicide programs (Table 6). In no-till cover cropping, HI reduced *A. palmeri* densities by at least 15 times compared to LI under the CCC sequence in 2020 and by at least 10 times averaged across both cropping sequences in 2021 (Table 5). We observed a significant increase in *A. palmeri* densities from 2020 to 2021 in LI in the CSC sequence (Table 7). In strip tillage, *A. palmeri* densities in the CCC sequence were at least 15 times higher than those in the CSC sequence averaged across herbicide programs in 2020 (Table 6). During 2021, *A. palmeri* densities in LI plots were at least 74 times higher than those in HI plots averaged over cropping

TABLE 4 Percent *A. palmeri* control as a function of significant interaction between cropping sequence and herbicide program in no-till cover cropping (A) and strip tillage (B) and conventional tillage (C) in Thrall, TX[a,b].

(A) No-till cover crop												
	28 DA PRE			28 DA POST 1			28 DA POST 2			WBH		
	2019	2020	2021	2019	2020	2021	2019	2020	2021	2019	2020	2021
Cotton: cotton: cotton												
Low input	–	–	–	90 aA	80 bA	68 bB	96 aA	86 bA	88 aA	100 aA	73 bB	53 bB
High input	89 A	93 A	98 A	96 aA	100 aA	99 aA	98 aA	99 aA	94 aB	100 aA	98 aA	93 aB
Cotton: sorghum: cotton												
Low input	–	–	–	91 aA	94 aA	84 bA	100 aA	99 aA	96 aA	99 aA	93 aA	80 aB
High input	89 A	94 A	100 A	98 aB	100 aA	100 aA	98 aA	100 aA	100 aA	100 aA	93 aB	98 aA
(B) Strip tillage												
	28 DA PRE			28 DA POST 1			28 DA POST 2			WBH		
	2019	2020	2021	2019	2020	2021	2019	2020	2021	2019	2020	2021
Cotton: cotton: cotton												
Low input	–	–	–	85 aA	81 bA	48 bB	97 aA	86 aB	80 aB	97 aA	71 bB	36 bB
High input	86 A	76 A	91 A	95 aB	94 aB	100 aA	96 aA	92 aA	98 aA	100 aA	90 aA	96 aA
Cotton: sorghum: cotton												
Low input	–	–	–	85 bA	91 bA	83 bA	97 aA	91 aA	85 bA	99 aA	90 aA	42 bB
High input	85 B	69 C	100 A	98 aA	98 aA	100 aA	96 aA	98 aA	100 aA	99 aA	93 aA	93 aA
(C) Conventional tillage												
	28 DA PRE			28 DA POST 1			28 DA POST 2			WBH		
	2019	2020	2021	2019	2020	2021	2019	2020	2021	2019	2020	2021
Cotton: cotton: cotton												
Low input	–	–	–	83 bA	84 bA	71 bA	94 aA	92 aA	83 bB	95 aA	86 aA	56 bB
High input	83 B	86 B	100 A	94 aB	98 aA	100 aA	97 aA	99 aA	100 aA	99 aA	99 aA	97 aA
Cotton: sorghum: cotton												
Low input	–	–	–	91 bB	100 aA	95 bA	98 aA	99 aA	100 aA	100 aA	100 aA	99 aA
High input	81 B	85 B	100 A	99 aA	100 aA	100 aA	96 aA	100 aA	100 aA	100 aA	100 aA	99 aA

[a] Values followed by the same letter are statistically similar based on Tukey's least significant difference ($\alpha = 0.05$): lowercase letters compare means within the same column, whereas uppercase letters compare means within the same row.

[b] DA, days after; PRE, preemergence application, POST 1, first postemergence application; POST 2, second postemergence application; WBH, week before harvest.

sequences (Table 5). We observed a significant increase in *A. palmeri* densities in LI plots (Table 5) and CSC sequence (Table 6) from 2020 to 2021.

A. palmeri seed bank

College Station

None of the factors influenced *A. palmeri* seed bank during 2019. Tillage, cropping sequence, herbicide programs, and their interactions influenced *A. palmeri* seed bank in 2020 and 2021 (Supplementary Data). In 3 years, *A. palmeri* seedbanks in no-till cover cropping and strip tillage were at least 1.5 times higher than conventional tillage when averaged over other factors (Table 8). CSC sequence had only 33% of the seed bank CCC sequence in 3 years when averaged over other factors. Surprisingly, we observed a 50% higher seed bank in HI plots compared to LI plots, averaged over other factors (Table 8). Therefore, we evaluated tillage × herbicide program interaction in 2021 to understand this pattern more accurately (Table 9). In 3 years, HI plots accumulated at least two times the seed bank in LI plots under no-till cover cropping and in strip tillage. However, under conventional tillage, LI plots accumulated approximately two times the seed bank of HI plots (Table 9). Though the densities in HI plots were significantly lower than those in LI plots in no-till cover cropping and strip tillage, escapes were relatively large in size with numerous seed heads,

TABLE 5 *A. palmeri* densities as a function of significant interaction between tillage and herbicide program in 2020, 2021 at College Station and Thrall, TX[a].

	College Station		Thrall	
	2020	2021	2020	2021
	plants ha^{-1}			
No-till cover crop				
Low input herbicide program	44041 aA	61981 aA	6010 aA	13365 aA
High input herbicide program	4305 bA	22604 aA	807 aA	1166 bA
Strip tillage				
Low input herbicide program	12558 aA	12737 aA	4574 aB	19913 aA
High input herbicide program	3767 bA	6548 aA	1794 aA	269 bA
Conventional tillage				
Low input herbicide program	1884 aA	2242 aA	4844 aA	6817 aA
High input herbicide program	90 bA	449 aA	449 aA	90 bA

[a] Values followed by the same letter are statistically similar based on Tukey's least significant difference (α = 0.05): lowercase letters compare means within the same column, whereas uppercase letters compare means within the same row.

which could explain the anomalously higher seed bank numbers. Also, no significant differences in seed banks were observed between cropping sequences in strip tillage and conventional tillage (Table 10). However, in no-till cover cropping, the CCC sequence accumulated three times more seed banks compared to the seed bank in the CSC sequence (Table 10). Also, using HI under the CSC sequence reduced the seed bank by three times compared to using it under the CCC sequence in all tillage types (Table 11). Increased *A. palmeri* densities along with reduced weed control at the end of each year could have possibly led to seed bank accumulation in no-till cover cropping and strip tillage.

Thrall

A. palmeri seed bank at Thrall was not influenced by tillage types, cropping sequences, or herbicide programs during 2019 and 2020. During 2021, only the cropping sequence influenced the *A. palmeri* seed bank (Supplementary Data). The CSC sequence reduced the seed bank by more than two million seeds per hectare (40% less) compared to the CCC sequence in 3 years. We also observed a 100% increase in *A. palmeri* seed bank in the CCC sequence from 2019 to 2021. Similarly, there was at least a 50% increase in *A. palmeri* seed bank in no-till cover cropping and strip tillage in 3 years (Table 8).

TABLE 6 *A. palmeri* densities as a function of significant interaction between tillage and cropping sequence in 2020, 2021 at College Station and Thrall, TX[a].

	College Station		Thrall	
	2020	2021	2020	2021
	plants ha^{-1}			
No-till cover crop				
Cotton: Cotton: Cotton	40274 aB	74359 aA	6279 aA	10315 aA
Cotton: Sorghum: Cotton	8073 bA	10225 bA	538 bB	4216 aA
Strip tillage				
Cotton: Cotton: Cotton	10315 aA	17042 aA	6010 aA	12468 aA
Cotton: Sorghum: Cotton	6010 aA	2242 bA	359 bB	7714 aA
Conventional tillage				
Cotton: Cotton: Cotton	1166 aA	2691 aA	5292 aA	6917 aA
Cotton: Sorghum: Cotton	807 aA	0 bB	0 bA	90 bA

[a] Values followed by the same letter are statistically similar based on Tukey's least significant difference (α = 0.05): lowercase letters compare means within the same column, whereas uppercase letters compare means within the same row.

TABLE 7 *A. palmeri* densities as a function of significant interaction between cropping sequence and herbicide program in no-till cover cropping in 2020, 2021 at College Station and Thrall, TX[a].

	College Station		Thrall	
	2020	2021	2020	2021
	plants ha^{-1}			
Cotton: Cotton: Cotton				
Low input herbicide program	73552 aA	106022 aA	11840 aA	18836 aA
High input herbicide program	6996 bB	42696 bA	718 bA	1794 bA
Cotton: Sorghum: Cotton				
Low input herbicide program	14531 aA	17939 aA	897 aB	7893 aA
High input herbicide program	1615 aA	2511 bA	179 aA	538 aA

[a] Values followed by the same letter are statistically similar based on Tukey's least significant difference (α = 0.05): lowercase letters compare means within the same column, whereas uppercase letters compare means within the same row.

Cotton and sorghum yields

College Station

Tillage and herbicide programs influenced crop yields from 2019 to 2021. Tillage × herbicide program interaction was significant in 2021. The cropping sequence did not influence cotton yield in 2021 (Supplementary Data). Annual cotton yield from 2019 to 2021 and sorghum yield during 2020 were influenced by tillage type. In 2019, cotton yield in no-till cover cropping was 125% higher than strip tillage and 45% higher than conventional tillage averaged across herbicide programs (Table 12). In 2020, cotton yield in conventional tillage was 30% higher than no-till cover cropping and 23% higher than strip tillage averaged across herbicide programs (Table 12). Similarly, conventional tillage provided 34% higher sorghum yield than no-till cover cropping and 77% higher than strip tillage (Table 12). In 2021, strip tillage provided 11% higher cotton yield than conventional tillage and 14% higher than no-till cover cropping, averaged across cropping sequences and herbicide programs (Table 12). No significant differences were identified between LI plots and HI plots for cotton and sorghum yields from 2019 to 2021. Only in 2021, WF plots provided 40% and 26% higher cotton yields than HI plots and LI plots, respectively, in no-till cover cropping (Table 13).

Thrall

In 2019 and 2020, tillage and herbicide programs influenced cotton yield, while only tillage level differences were observed for sorghum yield in 2020. In 2021, tillage, cropping sequence, herbicide programs, and their two-way interactions were significant (Supplementary Data). In 2019, conventional tillage provided cotton yields 15% higher than no-till cover cropping and 14% higher than strip tillage when averaged over herbicide programs (Table 12). No significant differences were observed in cotton yields between LI, HI, and WF plots averaged across tillage types (Table 12). In 2020, no significant differences were observed between strip tillage and conventional tillage for cotton and sorghum yields when averaged over herbicide programs (Table 12). Each of them provided at least 80% higher cotton yields and 110% higher sorghum yields compared to no-till cover cropping (Table 12). Sorghum yields did not vary significantly between herbicide programs averaged across tillage types (Table 12). In 2021, conventional tillage provided at least 40%

TABLE 8 *A. palmeri* seedbank (ha^{-1}) affected by tillage, cropping sequence and herbicide program in College Station and Thrall from 2019-21.

	College Station			Thrall		
	2019	2020	2021	2019	2020	2021
	Seeds ha^{-1}					
No-till cover crop	884149 aB	2403987 aB	4317455 aA	3102909 aB	3239185 aB	4746940 aA
Strip tillage	1821893 aAB	916420 bB	3539905 aA	3455076 aB	2382341 aB	6268556 aA
Conventional tillage	733319 aB	662994 bB	1245384 bA	3837611 aA	2657412 aA	5767314 aA
Cotton: Cotton: Cotton	758424 aB	1548699 aB	4682545 aA	3506003 aB	2888896 aB	7093277 aA
Cotton: Sorghum: Cotton	1534491 aA	1106909 aA	1385959 bA	3424386 aA	2630379 aA	4095262 bA
Low input herbicide program	1513018 aA	1315091 aA	1907242 bA	4042655 aAB	2914223 aB	5951922 aA
High input herbicide program	779922 aB	1340518 aB	4161263 aA	2887734 aB	2605052 aB	5236642 aA

[a] Values followed by the same letter are statistically similar based on Tukey's least significant difference (a = 0.05): lowercase letters compare means within the same column, whereas uppercase letters compare means within the same row.

TABLE 9 *A. palmeri* seedbank (ha^{-1}) as a function of significant interaction between tillage and herbicide program from 2019-21 at College Station, TX[a].

	2019	2020	2021
	Seeds ha^{-1}		
No-till cover crop			
Low input herbicide program	1132039 aA	2662503 aA	2619878 bA
High input herbicide program	636283 aB	2145446 aB	6015032 aA
Strip tillage			
Low input herbicide program	2597935 aA	690027 aA	1495375 bA
High input herbicide program	10457890 aB	1142838 aB	5584460 aA
Conventional tillage			
Low input herbicide program	809055 aB	592719 aB	1606471 aA
High input herbicide program	657583 aA	733269 aA	884322 bA

[a] Values followed by the same letter are statistically similar based on Tukey's least significant difference (α = 0.05): lowercase letters compare means within the same column, whereas uppercase letters compare means within the same row.

higher cotton yield compared to strip tillage and no-till cover cropping, which averaged across other factors (Table 12). No significant differences were identified between LI plots and HI plots in strip tillage and conventional tillage, but they produced at least 11% higher cotton yields compared to WF plots in no-till cover cropping (Table 13). CSC provided 39% higher cotton yields compared to the CCC sequence under no-till cover cropping, while the yields were comparable under strip tillage and conventional tillage (Table 14). No significant differences were observed between LI plots and HI plots for cotton yield under the CSC sequence, but HI provided at least 43% higher yield compared to WF plots under the CCC sequence (Table 15).

TABLE 10 *A. palmeri* seedbank as a function of significant interaction between tillage and cropping sequence from 2019-21 at College Station, TX[a].

	2019	2020	2021
	Seeds ha^{-1}		
No-till cover crop			
Cotton: Cotton: Cotton	884000 aB	2694947 aAB	6791544 aA
Cotton: Sorghum: Cotton	884322 aA	2113002 aA	1843366 bA
Strip tillage			
Cotton: Cotton: Cotton	679229 aB	1175257 aB	5735512 aA
Cotton: Sorghum: Cotton	2964582 aA	657607 bA	1344323 aA
Conventional tillage			
Cotton: Cotton: Cotton	677629 aB	775894 aB	1520604 aA
Cotton: Sorghum: Cotton	754594 aA	550094 aA	970189 aA

[a] Values followed by the same letter are statistically similar based on Tukey's least significant difference (α = 0.05): lowercase letters compare means within the same column, whereas uppercase letters compare means within the same row.

TABLE 11 *A. palmeri* seedbank as a function of significant interaction between cropping sequence and herbicide program from 2019-21 at College Station, TX[a].

	2019	2020	2021
Cotton: Cotton: Cotton			
Low input herbicide program	1013802 aA	1710352 aA	2221009 bA
High input herbicide program	503046 bB	1387046 bB	7144081 aA
Cotton: Sorghum: Cotton			
Low input herbicide program	2012209 aA	919830 aA	1593449 aA
High input herbicide program	1056773 aA	1293989 aA	1178469 aA

[a] Values followed by the same letter are statistically similar based on Tukey's least significant difference (α = 0.05): lowercase letters compare means within the same column, whereas uppercase letters compare means within the same row.

Summary

In this study, we observed long-term *A. palmeri* control as a function of multiple factors, including the number of MOAs used over time. HI under the CSC sequence, which used seven different herbicide MOAs over 3 years, provided ≥90% *A. palmeri* control consistently across all tillage types and environments. On the contrary, *A. palmeri* control in LI under the CCC sequence, which used only two different herbicide MOAs over 3 years, reduced up to 36% by the end of the third year depending on the tillage type at both locations. These results indicate that the combination of overlapping residual herbicides applied PRE and POST, foliar applications with multiple MOAs over time, and introducing a higher biomass rotational grass crop can together prevent seasonal *A. palmeri* densities, and consequently reduce the soil seed bank. However, >90% control for HI under the CSC sequence provided a different understanding of each tillage type from *A. palmeri* densities point of view. At the end of the third year, *A. palmeri* densities were <1,000 plants ha^{-1} under conventional tillage compared to >8,000 plants ha^{-1} under strip tillage and no-till cover cropping. These findings not only indicate tillage as an effective tool for seasonal and long-term *A. palmeri* management, but also the potential for increased herbicide use in no-till systems, especially during times when cover crop establishment can be challenging. We believe continuing this research into the future could provide additional data and variability to observe separation in yields at the sub-sub-plot level. Especially with increasing densities and seed banks in LI plots under CCC cropping sequence in all tillage types, crop yields could be further reduced in subsequent cropping seasons. Alternatively, future research could address the longevity of best-performing weed control systems in this research by increasing the scale to a grower field level. Also, understanding how time-consuming and expensive long-term multi-location field experiments are, weed control data from this research can be used to build herbicide resistance prediction models similar to those developed by Neve et al. (2003). With the multitude of factors involved in this study that could have influenced weed control, developing economic models looking at net returns instead of only yields can give a better understanding of these weed control

TABLE 12 Seed cotton and grain sorghum yields as affected by tillage, cropping sequences and herbicide programs in College Station, Thrall TX[a,b].

	College Station				Thrall			
	2019	2020		2021	2019	2020		2021
	Cotton	Cotton	Sorghum	Cotton	Cotton	Cotton	Sorghum	Cotton
NTCC	3977 a	1339 b	608 ab	1304 b	1650 b	395 b	757 b	1032 b
ST	1748 b	1420 b	462 b	1717 a	1672 b	740 a	1646 a	1052 b
CT	2753 b	1742 a	815 a	1548 ab	1901 a	722 a	1872 a	1471 a
CCC	–	–	–	1431 a	–	–	–	1118 b
CSC	–	–	–	1615 a	–	–	–	1252 a
WC	762 b	5 b	456 b	81 c	1163 b	5 c	1583 a	144 c
WF	3324 a	2119 a	702 ab	2395 a	1922 a	688 b	1158 a	1353 b
LI	3636 a	1943 a	746 a	1900 b	1989 a	834 ab	1494 a	1673 a
HI	3583 a	1935 a	610 ab	1715 b	1889 a	950 a	1465 a	1569 ab

[a]Values followed by the same letter are statistically similar based on Tukey's least significant difference (α = 0.05): lowercase letters compare means within the same column.
[b]NTCC, no-till cover crop; ST, strip tillage; CT, conventional tillage; CCC, cotton: cotton: cotton; CSC, cotton: sorghum: cotton; WC, weedy check; WF, weed-free check; LI, low input herbicide program; HI, high input herbicide program.

systems and their grower adoption potential. Combining the herbicide resistance prediction models with economic models can provide insights into which systems can be more sustainable for weed control from an economic point of view. Overall, crop rotations and herbicide programs with multiple MOAs provide

TABLE 13 Cotton yields (kg ha^{-1}) in 2021 as a function of significant interaction between tillage and herbicide program at College Station and Thrall[a].

	College Station	Thrall
No-till cover crop		
Weedy check	40 c	360 c
Weed-free check	2393 a	1026 b
Low input herbicide program	1566 b	1597 a
High input herbicide program	1216 b	1144 ab
Strip tillage		
Weedy check	162 c	16 b
Weed-free check	2506 a	1193 a
Low input herbicide program	2375 ab	1377 a
High input herbicide program	1826 b	1621 a
Conventional tillage		
Weedy check	42 b	54 b
Weed-free check	2286 a	1841 a
Low input herbicide program	1760 a	2046 a
High input herbicide program	2102 a	1943 a

[a]Values followed by the same letter are statistically similar based on Tukey's least significant difference (α = 0.05): lowercase letters compare means within the same column.

TABLE 14 Cotton yields (kg ha^{-1}) in 2021 as a function of significant interaction between tillage and cropping sequence at Thrall[a].

	Thrall
No-till cover crop	
Cotton: cotton: cotton	863 b
Cotton: sorghum: cotton	1200 a
Strip tillage	
Cotton: cotton: cotton	1094 a
Cotton: sorghum: cotton	1009 a
Conventional tillage	
Cotton: cotton: cotton	1396 a
Cotton: sorghum: cotton	1546 a

[a]Values followed by the same letter are statistically similar based on Tukey's least significant difference (α = 0.05): lowercase letters compare means within the same column.

TABLE 15 Cotton yields (kg ha^{-1}) in 2021 as a function of significant interaction between cropping sequence and herbicide program at Thrall[a].

	Cotton: cotton: cotton	Cotton: sorghum: cotton
Weedy check	59 c	228 b
Weed-free check	1152 b	1555 a
Low input herbicide program	1607 ab	1740 a
High input herbicide program	1655 a	1483 a

[a]Values followed by the same letter are statistically similar based on Tukey's least significant difference (α = 0.05): lowercase letters compare means within the same column.

greater weed control under conservation tillage systems, and tillage has additional weed control benefits.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

RV: Formal Analysis, Methodology, Supervision, Writing – original draft, Writing – review & editing, Data curation. SN: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing. JM: Methodology, Supervision, Writing – review & editing, Resources. BM: Validation, Resources, Writing – review & editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This research was funded by Bayer CropScience.

Acknowledgments

The authors would like to thank the Extension Weed Science group at College Station and the farm crew at College Station, Thrall, and Corpus Christi for the technical assistance.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fagro.2023.1277054/full#supplementary-material

References

Aulakh, J. S., Price, A. J., Enloe, S. F., van Santen, E., Wehtje, G., and Patterson, M. G. (2012). Integrated Palmer amaranth management in glufosinate-resistant cotton: I. Soil-inversion, high-residue cover crops and herbicide regimes. *Agronomy* 2, 295–311. doi: 10.3390/agronomy2040295

Aulakh, J. S., Price, A. J., Enloe, S. F., Wehtje, G., and Patterson, M. G. (2013). Integrated Palmer amaranth management in glufosinate-resistant cotton: II. Primary, secondary and conservation tillage. *Agronomy* 3, 28–42. doi: 10.3390/agronomy3010028

Ball, D. A. (1992). Weed seedbank response to tillage, herbicides, and crop rotation sequence. *Weed Sci.* 40, 654–659. doi: 10.1017/S0043174500058264

Bensch, C. N., Horak, M. J., and Peterson, D. (2003). Interference of redroot pigweed (Amaranthus retroflexus), Palmer amaranth (A. palmeri), and common waterhemp (A. rudis) in soybean. *Weed Sci.* 51, 37–43. doi: 10.1614/0043-1745(2003)051[0037:IORPAR]2.0.CO;2

Browne, F. B., Li, X., Price, K. J., Langemeier, R., Jauregui, A.S.-S. d, McElroy, J. S., et al. (2020). Sequential applications of synthetic auxins and glufosinate for escaped palmer amaranth control. *Agronomy* 10, 1425. doi: 10.3390/agronomy10091425

Cahoon, C. W., York, A. C., Jordan, D. L., Everman, W. J., Seagroves, R. W., Culpepper, A. S., et al. (2015). Palmer amaranth (Amaranthus palmeri) management in dicamba-resistant cotton. *Weed Technol.* 29, 758–770. doi: 10.1614/WT-D-15-00041.1

Chahal, P. S., Jugulam, M., and Jhala, A. J. (2019). Mechanism of atrazine resistance in atrazine-and HPPD inhibitor-resistant Palmer amaranth (Amaranthus palmeri S. Wats.) from Nebraska. *Can. J. Plant Sci.* 99, 815–823. doi: 10.1139/cjps-2018-0268

Chahal, P. S., Varanasi, V. K., Jugulam, M., and Jhala, A. J. (2017). Glyphosate-resistant Palmer amaranth (Amaranthus palmeri) in Nebraska: confirmation, EPSPS gene amplification, and response to POST corn and soybean herbicides. *Weed Technol.* 31, 80–93. doi: 10.1614/WT-D-16-00109.1

Chaudhari, S., Varanasi, V. K., Nakka, S., Bhowmik, P. C., Thompson, C. R., Peterson, D. E., et al. (2020). Evolution of target and non-target based multiple herbicide resistance in a single Palmer amaranth (Amaranthus palmeri) population from Kansas. *Weed Technol.* 34, 447–453. doi: 10.1017/wet.2020.32

Denton, S., Raper, T. B., Stewart, S., and Dodds, D. (2023). Cover crop termination timings and methods effect on cotton (Gossypium hirsutum L.) development and yield. *Crop, Forage & Turfgrass Management* 9, e20206. doi: 10.1002/cft2.20206

Dominguez-Valenzuela, J. A., Gherekhloo, J., Fernández-Moreno, P. T., Cruz-Hipolito, H. E., Alcántara-de la Cruz, R., Sánchez-González, E., et al. (2017). First confirmation and characterization of target and non-target site resistance to glyphosate in Palmer amaranth (Amaranthus palmeri) from Mexico. *Plant Physiol. Biochem.* 115, 212–218. doi: 10.1016/j.plaphy.2017.03.022

Ehleringer, J. (1983). Ecophysiology of Amaranthus palmeri, a Sonoran Desert summer annual. *Oecologia* 57, 107–112. doi: 10.1007/BF00379568

Ehleringer, J. (1985). *Annuals and perennials of warm deserts* (Physiological ecology of North American plant communities (Springer), 162–180. doi: 10.1007/978-94-009-4830-3_7

Farmer, J. A., Bradley, K. W., Young, B. G., Steckel, L. E., Johnson, W. G., Norsworthy, J. K., et al. (2017). Influence of tillage method on management of Amaranthus species in soybean. *Weed Technol.* 31, 10–20. doi: 10.1614/WT-D-16-00061.1

Frans, R. (1986). Experimental design and techniques for measuring and analyzing plant responses to weed control practices. *Res. Methods Weed Sci.*, 29–46.

Franssen, A. S., Skinner, D. Z., Al-Khatib, K., Horak, M. J., and Kulakow, P. A. (2001). Interspecific hybridization and gene flow of ALS resistance in Amaranthus species. *Weed Sci.* 49, 598–606. doi: 10.1614/0043-1745(2001)049[0598:IHAGFO]2.0.CO;2

Gaines, T. A., Zhang, W., Wang, D., Bukun, B., Chisholm, S. T., Shaner, D. L., et al. (2010). Gene amplification confers glyphosate resistance in Amaranthus palmeri. *Proc. Natl. Acad. Sci.* 107, 1029–1034. doi: 10.1073/pnas.0906649107

Garetson, R., Singh, V., Singh, S., Dotray, P., and Bagavathiannan, M. (2019). Distribution of herbicide-resistant Palmer amaranth (Amaranthus palmeri) in row crop production systems in Texas. *Weed Technol.* 33, 355–365. doi: 10.1017/wet.2019.14

Grint, K. R., Arneson, N. J., Arriaga, F., DeWerff, R., Oliveira, M., Smith, D. H., et al. (2022)Cover crops and preemergence herbicides: An integrated approach for weed management in corn-soybean systems in the US Midwest (Accessed May 1, 2023).

Hand, L. C., Randell, T. M., Nichols, R. L., Steckel, L. E., Basinger, N. T., and Culpepper, A. S. (2021). Cover crops and residual herbicides reduce selection pressure for Palmer amaranth resistance to dicamba-applied postemergence in cotton. *Agron. J.* 113, 5373–5382. doi: 10.1002/agj2.20886

Heap, I. (2021). The international survey of herbicide resistant weeds. *Online Internet.*

Houston, M. M., Norsworthy, J. K., Barber, T., and Brabham, C. (2019). Field evaluation of preemergence and postemergence herbicides for control of protoporphyrinogen oxidase-resistant Palmer amaranth (Amaranthus palmeri S. Watson). *Weed Technol.* 33, 610–615. doi: 10.1017/wet.2019.37

Hwang, J.-I., Norsworthy, J. K., Piveta, L. B., Souza, M. C., de, C. R., Barber, L. T., et al. (2023). Metabolism of 2,4-D in resistant Amaranthus palmeri S. Wats. (Palmer amaranth). *Crop Prot.* 165, 106169. doi: 10.1016/j.cropro.2022.106169

Inman, M. D., Jordan, D. L., York, A. C., Jennings, K. M., Monks, D. W., Everman, W. J., et al. (2016). Long-term management of Palmer amaranth (Amaranthus palmeri) in dicamba-tolerant cotton. *Weed Sci.* 64, 161–169. doi: 10.1614/WS-D-15-00058.1

Jha, P., Norsworthy, J. K., Riley, M. B., Bielenberg, D. G., and Bridges, W. (2008). Acclimation of Palmer amaranth (Amaranthus palmeri) to shading. *Weed Sci.* 56, 729–734. doi: 10.1614/WS-07-203.1

Keeley, P. E., Carter, C. H., and Thullen, R. J. (1987). Influence of planting date on growth of Palmer amaranth (Amaranthus palmeri). *Weed Sci.* 35, 199–204. doi: 10.1017/S0043174500079054

Koo, D.-H., Sathishraj, R., Friebe, B., and Gill, B. S. (2021). Deciphering the mechanism of glyphosate resistance in amaranthus palmeri by cytogenomics. *Cytogenet. Genome Res.* 161, 578–584. doi: 10.1159/000521409

Liebman, M., and Dyck, E. (1993). Crop rotation and intercropping strategies for weed management. *Ecol. Appl.* 3, 92–122. doi: 10.2307/1941795

MacRae, A. W., Webster, T. M., Sosnoskie, L. M., Culpepper, A. S., and Kichler, J. M. (2013). Cotton yield loss potential in response to length of Palmer amaranth (Amaranthus palmeri) interference. *J. Cotton Sci.* 17, 227–232.

Martin, R. J., and Felton, W. L. (1993). Effect of crop rotation, tillage practice, and herbicides on the population dynamics of wild oats in wheat. *Aust. J. Exp. Agric.* 33, 159–165. doi: 10.1071/EA9930159

Massinga, R. A., Currie, R. S., Horak, M. J., and Boyer, J. (2001). Interference of Palmer amaranth in corn. *Weed Sci.* 49, 202–208. doi: 10.1614/0043-1745(2001)049[0202:IOPAIC]2.0.CO;2

Merchant, R. M., Sosnoskie, L. M., Culpepper, A. S., Steckel, L. E., York, A. C., Braxton, L. B., et al. (2013). Weed response to 2, 4-D, 2, 4-DB, and dicamba applied alone or with glufosinate. *J. Cotton Sci.* 17, 212–218.

Nakka, S., Thompson, C. R., Peterson, D. E., and Jugulam, M. (2017). Target site–based and non–target site based resistance to ALS inhibitors in palmer Amaranth (Amaranthus palmeri). *Weed Sci.* 65, 681–689. doi: 10.1017/wsc.2017.43

Neve, P., Diggle, A. J., Smith, F. P., and Powles, S. B. (2003). Simulating evolution of glyphosate resistance in Lolium rigidum II: past, present and future glyphosate use in Australian cropping. *Weed Res.* 43, 418–427. doi: 10.1046/j.0043-1737.2003.00356.x

Norsworthy, J. K., Ward, S. M., Shaw, D. R., Llewellyn, R. S., Nichols, R. L., Webster, T. M., et al. (2012). Reducing the risks of herbicide resistance: best management practices and recommendations. *Weed Sci.* 60, 31–62. doi: 10.1614/WS-D-11-00155.1

Oreja, F. H., Inman, M. D., Jordan, D. L., Vann, M., Jennings, K. M., and Leon, R. G. (2022). Effect of cotton herbicide programs on weed population trajectories and frequency of glyphosate-resistant Palmer amaranth (Amaranthus palmeri). *Weed Sci.* 70, 587–594. doi: 10.1017/wsc.2022.41

Palhano, M. G., Norsworthy, J. K., and Barber, T. (2018). Cover crops suppression of Palmer amaranth (Amaranthus palmeri) in cotton. *Weed Technol.* 32, 60–65. doi: 10.1017/wet.2017.97

Palma-Bautista, C., Torra, J., Garcia, M. J., Bracamonte, E., Rojano-Delgado, A. M., Alcántara-de la Cruz, R., et al. (2019). Reduced absorption and impaired translocation endows glyphosate resistance in Amaranthus palmeri harvested in glyphosate-resistant soybean from Argentina. *J. Agric. Food Chem.* 67, 1052–1060. doi: 10.1021/acs.jafc.8b06105

Price, A. J., Monks, C. D., Culpepper, A. S., Duzy, L. M., Kelton, J. A., Marshall, M. W., et al. (2016). High-residue cover crops alone or with strategic tillage to manage glyphosate-resistant Palmer amaranth (Amaranthus palmeri) in southeastern cotton (Gossypium hirsutum). *J. Soil Water Conserv.* 71, 1–11. doi: 10.2489/jswc.71.1.1

Refsell, D. E., and Hartzler, R. G. (2009). Effect of tillage on common waterhemp (Amaranthus rudis) emergence and vertical distribution of seed in the soil. *Weed Technol.* 23, 129–133. doi: 10.1614/WT-08-045.1

Rowland, M. W., Murray, D. S., and Verhalen, L. M. (1999a). Full-season Palmer amaranth (Amaranthus palmeri) interference with cotton (Gossypium hirsutum). *Weed Sci.* 47, 305–309. doi: 10.1017/S0043174500091815

Rowland, M. W., Murray, D. S., and Verhalen, L. M. (1999b). Full-season Palmer amaranth (Amaranthus palmeri) interference with cotton (Gossypium hirsutum). *Weed Sci.* 47, 305–309. doi: 10.1017/S0043174500091815

Sharma, G., Shrestha, S., Kunwar, S., and Tseng, T.-M. (2021). Crop diversification for improved weed management: A review. *Agriculture* 11, 461. doi: 10.3390/agriculture11050461

Shyam, C., Borgato, E. A., Peterson, D. E., Dille, J. A., and Jugulam, M. (2021) Predominance of metabolic resistance in a six-way-resistant palmer amaranth (Amaranthus palmeri) population (Accessed September 15, 2023).

Shyam, C., Peterson, D. E., and Jugulam, M. (2022). Resistance to 2,4-D in Palmer amaranth (Amaranthus palmeri) from Kansas is mediated by enhanced metabolism. *Weed Sci.* 70, 390–400. doi: 10.1017/wsc.2022.29

Singh, S., Singh, V., Lawton-Rauh, A., Bagavathiannan, M. V., and Roma-Burgos, N. (2018). EPSPS gene amplification primarily confers glyphosate resistance among Arkansas Palmer amaranth (Amaranthus palmeri) populations. *Weed Sci.* 66, 293–300. doi: 10.1017/wsc.2017.83

Sosnoskie, L. M., Webster, T. M., Grey, T. L., and Culpepper, A. S. (2014). Severed stems of Amaranthus palmeri are capable of regrowth and seed production in Gossypium hirsutum. *Ann. Appl. Biol.* 165, 147–154. doi: 10.1111/aab.12129

Tehranchian, P., Norsworthy, J. K., Powles, S., Bararpour, M. T., Bagavathiannan, M. V., Barber, T., et al. (2017). Recurrent sublethal-dose selection for reduced susceptibility of Palmer amaranth (Amaranthus palmeri) to dicamba. *Weed Sci.* 65, 206–212. doi: 10.1017/wsc.2016.27

USDA Agricultural Marketing Service - Cotton and Tobacco Program Memphis (2020). *Cotton Varieties Planted 2020 Crop*. Available at: https://usda.library.cornell.edu/concern/publications/n870zq82k?locale=en.

USDA ERS (2023a) *Cotton Wool.* Available at: https://www.ers.usda.gov/topics/crops/cotton-and-wool/ (Accessed May 3, 2023).

USDA ERS (2023b) *Adopt. Genet. Eng. Crops US.* Available at: https://www.ers.usda.gov/data-products/adoption-of-genetically-engineered-crops-in-the-u-s/ (Accessed May 3, 2023).

USDA - NRCS (2022) *Web Soil Survey*. Available at: https://websoilsurvey.nrcs.usda.gov/app/ (Accessed 09-11-2022).

Van Wychen, L. (2019). *WSSA survey Ranks Most Common and Most Troublesome Weeds in Broadleaf Crops, Fruits and Vegetables.*

Vulchi, R., Bagavathiannan, M., and Nolte, S. A. (2022). History of herbicide-resistant traits in cotton in the US and the importance of integrated weed management for technology stewardship. *Plants* 11, 1189. doi: 10.3390/plants11091189

Ward, S. M., Webster, T. M., and Steckel, L. E. (2013). Palmer amaranth (Amaranthus palmeri): a review. *Weed Technol.* 27, 12–27. doi: 10.1614/WT-D-12-00113.1

Webster, T. M., and Grey, T. L. (2015). Glyphosate-resistant Palmer amaranth (Amaranthus palmeri) morphology, growth, and seed production in Georgia. *Weed Sci.* 63, 264–272. doi: 10.1614/WS-D-14-00051.1

Weisberger, D., Nichols, V., and Liebman, M. (2019). Does diversifying crop rotations suppress weeds? A meta-analysis. *PloS One* 14, e0219847. doi: 10.1371/journal.pone.0219847

Whitaker, J. R., York, A. C., Jordan, D. L., Culpepper, A. S., and Sosnoskie, L. M. (2011). Residual herbicides for Palmer amaranth control. *J. Cotton Sci.* 15, 89–99.

Wiggins, M. S., Hayes, R. M., Nichols, R. L., and Steckel, L. E. (2017). Cover crop and postemergence herbicide integration for Palmer amaranth control in cotton. *Weed Technol.* 31, 348–355.60. doi: 10.1017/wet.2017.10