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Impact of integrated weed management practices on cotton economics and Palmer amaranth (*Amaranthus palmeri*) populations

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Research Article

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Abstract

The threat of herbicide-resistant weed species, such as Palmer amaranth, has driven the development of robust weed management programs that rely on more than chemicals for weed control. Previous research has shown that zero-tolerance weed thresholds, cover crops, deep tillage, and diverse herbicide programs are effective strategies for controlling Palmer amaranth. Unfortunately, research investigating the integration of all four of these weed management strategies in a system is lacking. To better leverage these integrated weed management strategies in cotton production systems, a long-term study was initiated in fall 2018 near Marianna, AR, with zero tolerance, deep tillage, a cereal rye cover crop, and either a dicamba or non-dicamba in-crop herbicide program as factors. Results found that total Palmer amaranth emergence was reduced 76% as the result of deep tillage in 2019 and, in the absence of a zero-tolerance strategy, 73% in 2020. In the absence of a zero-tolerance strategy, the combination of a non–cover crop strategy and dicamba herbicide program decreased total Palmer amaranth emergence by 73%, while the combination of a cover crop strategy and dicamba herbicide program decreased total Palmer amaranth emergence by 78% compared to the combination of a cover crop and non-dicamba herbicide program. Under a zero-tolerance strategy in 2019, tillage reduced cotton yield by 12% and partial returns by US\$370 ha^{-1}. In 2020, tillage reduced cotton yield by 14% and partial returns of US\$371 ha^{-1} under a non-zero-tolerance strategy, while a 12% yield reduction and a US\$260 ha^{-1} decrease in partial returns were observed under a zero-tolerance strategy. In 2019, the non-dicamba program resulted in greater partial returns than the dicamba in-crop program because of greater yield and lower program costs. However, in 2020, partial returns were greater for the dicamba in-crop herbicide program owing to greater yields achieved by this program.

Introduction

The evolution of herbicide-resistant weeds is one of the largest threats to agriculture across the United States and the world (Gaines et al. 2010; Peterson et al. 2018; Westwood et al. 2018). Palmer amaranth has already established itself as a major concern for cotton producers in the Midsouth due to its aggressive competitiveness and adaptability (Berger et al. 2015; Morgan et al. 2001; Sauer 1972). Previous research has shown yield reductions of as much as 59% at Palmer amaranth densities of 1.1 plants m^{-2} (Morgan et al. 2001). Besides the reduction in cotton lint yield, Palmer amaranth also impacts producers in the form of reductions in harvest efficiencies. Palmer amaranth densities of 3,260 plants ha^{-1} can increase the time to harvest by 200 min ha^{-1} (Smith et al. 2000).

Cotton producers have adopted various chemical weed management strategies to combat these weeds, centered around the use of genetically modified cultivars resistant to herbicides that had previously not been available for use in the crop, such as glyphosate, glufosinate, dicamba, and 2,4-D (Kniss 2018). Over time, Palmer amaranth has systematically evolved resistance to various herbicide sites of action, such as acetolactate synthase–inhibiting herbicides, including trifloxysulfuron (Burgos et al. 2001; Norsworthy et al. 2008); microtubule assembly–inhibiting herbicides, including pendimethalin (Gossett et al. 1992); synthetic auxin herbicides, such as dicamba (Shyam et al. 2021; Steckel 2020); the 5-enolpyruvylshikimate-3-phosphate–inhibiting herbicide glyphosate (Norsworthy et al. 2008); the glutamine synthetase–inhibiting herbicide glufosinate (Heap 2021); protoporphyrinogen oxidase–inhibiting herbicides, such as fomesafen (Varanasi et al. 2018); and very-long-chain fatty-acid elongase–inhibiting herbicides, such as *S*-metolachlor (Brabham et al. 2019), leaving few options for cotton producers in the Midsouth. To preserve the few chemical options remaining, alternative options must be developed for Palmer amaranth management.

The adoption of cultural and mechanical weed management practices in addition to chemical weed control methods has been found effective in delaying or preventing the development of herbicide-resistant weeds (Beckie and Reboud 2009; Beckie 2011). The use of cover crops, such as cereal rye (*Secale cereale* L.), has been shown to be an effective option for aiding in the management of Palmer amaranth, reducing Palmer amaranth densities by 63% to 83% (DeVore et al. 2012; Palhano et al. 2018). Historically, the use of tillage has been a primary, nonchemical method of weed control (DeVore et al. 2012). The use of a one-time practice, such as deep tillage, through use of a moldboard plow has potential to drastically reduce Palmer amaranth emergence, especially when densities have reached high numbers. The weed management benefit of using a moldboard plow centers around reduction in Palmer amaranth viability over time, as seed of the weed that has been buried can lose as much as 80% viability after 3 yr and as much as 98% after 4 yr (Jha et al. 2014; Korres et al. 2018). Previous research has shown that the use of deep tillage has been effective at reducing Palmer amaranth emergence by 76% to 86% when used alone and by 86% to 94% when used in combination with a cereal rye cover crop (DeVore et al. 2012, 2013). Effectiveness of these management strategies can be primarily associated with the reduction in alterations of light and heat that the Palmer amaranth seed may experience due to the burial of the seed by the deep tillage event and the shading of the soil by the cover crop (Jha et al. 2014).

A newly emerging management practice for Palmer amaranth in the Midsouth is the implementation of a "zero-tolerance" threshold for Palmer amaranth. Zero tolerance is a mind-set that producers may utilize with the main goal being that no seed should return or replenish the soil seedbank (Norsworthy et al. 2012; Norsworthy et al. 2014). These management strategies can be achieved through a multitude of methods, including, but not limited to, hand-weeding and various techniques of harvest weed seed destruction. The concept of zero tolerance was born out of studies suggesting that the economic consequences of allowing a single weed, such as Palmer amaranth, to produce and disperse seed outweigh the costs of management in the long run (Norris 1999; Norsworthy et al. 2014). By not allowing more seed to replenish the soil seedbank, Palmer amaranth populations may approach depletion within 4 yr (Jha et al. 2014). Preliminary field-scale trials in northeastern Arkansas have shown promising results where a zero-tolerance approach led to as much as a 65% reduction in Palmer amaranth seedbanks after the first year (Barber et al. 2015).

To implement integrated weed management strategies is predominantly a decision based on economics for producers (Moss 2019). A long-term study conducted over 29 yr in western Tennessee found that the cash crop yield benefit of cereal rye cover crops was not enough to offset the cost of implementation, thus resulting in a net negative compared to not utilizing cereal rye cover crops at all (Zhou et al. 2017). Other studies have found that the use of cereal rye cover crops may improve cotton yield and partial returns in some instances, while in others, there are no differences (DeLaune et al. 2020; DeVore et al. 2012; Price et al. 2021). The use of cereal rye cover crops reduces cotton yield in some instances, primarily because of losses in cotton stand due to allelopathy from cereal rye and difficult planting conditions (Palhano et al. 2018; Price et al. 2021). In the southeastern United States, the use of deep tillage with a moldboard plow for weed management has had minimal effect on cotton yield, especially when paired with cereal rye cover crops. In terms of profitability, the use of deep tillage and cover crops together was found to be too costly and reduced profitability compared to production practices without tillage (Price et al. 2016). Findings from research in Arkansas have suggested that cotton yield is not affected by using a moldboard plow, but no comparisons were made regarding partial returns (DeVore et al. 2012). For producers to implement these strategies and remain viable, there needs to be an economic incentive either in the short or long term. While research has been conducted investigating the weed management potential of cereal rye cover crops, deep tillage, and zero-tolerance thresholds with the use of effective herbicide programs, research investigating the combination of more than two of these practices is lacking in the Midsouth, necessitating research where all four of these factors can be investigated for their economic and ecological impacts.

Materials and Methods

A large-plot, 5-yr study in cotton was initiated in fall 2018 at the Lon Mann Cotton Research Station near Marianna, AR (34.73°N, 90.74°W) on a Convent silt loam soil (1% organic matter, 7% clay, 1% sand, and 92% silt) (USDA-NRCS 2021). In this article, observations and data collection from the 2019 and 2020 growing seasons are reported. The experiment was designed as a randomized complete block with a split-split-split plot arrangement with four replications. The whole-plot factor was the presence or absence of a zero-tolerance threshold. The subplot factor was the presence or absence of a one-time deep tillage event using a moldboard plow at initiation of the experiment in fall 2018. The sub-sub-plot factor was the presence or absence of a cereal rye cover crop, and the sub-sub-sub-plot factor was the use of either a dicamba in-crop- or non-dicamba in-crop-based herbicide program (Figure 1). The individual sub-sub-sub plots measured 37 m long and 8 m wide, which allowed for eight rows on 1-m row centers.

The moldboard plow inverted the soil to a 20- to 25-cm depth. Following the one-time deep tillage event, plots were bedded and treated as no-till for the next 2 yr. 'Wrens Abruzzi' cereal rye was drill-seeded during fall 2018 and 2019 at 84 kg ha^{-1}. Cereal rye was planted in mid-November in 2018 because of earlier wet conditions and on a more typical planting date in mid-October in 2019. In 2019, cereal rye biomass was not taken due to a lack of establishment and the observed stand measuring less than 12 cm in height. In 2020, cereal rye biomass was estimated by collecting four random 1-m^2 samples of rye prior to cotton planting. Samples were placed in a dryer for 1 wk, then weighed to determine the average biomass. At 21 d prior to planting cotton in both years, the cereal rye cover crop was terminated with glyphosate at 1,260 g ae ha^{-1} (Roundup® PowerMAX® II, Bayer Crop Sciences, St. Louis, MO, USA) plus dicamba at 560 g ae ha^{-1} (Clarity®, BASF, Research Triangle Park, NC, USA). Deltapine® 1518 B2XF cotton (Bayer Crop Sciences) was planted in both years at 114,000 seed ha^{-1} on May 16 in 2019 and May 12 in 2020 using a four-row vacuum planter. Cotton was planted on raised beds, fertilized according to local production practices, and furrow-irrigated to supplement rainfall during the growing season beginning at the 5- to 6-leaf stage.

Table 1. Herbicide information for all weed management chemicals and adjuvants used in Marianna, AR, in 2019 and 2020.

Common name	Product name	Manufacturer	Location
Acetochlor	Warrant®	Bayer Crop Science	Research Triangle Park, NC
Dicamba	Clarity®	BASF	Research Triangle Park, NC
Dicamba	XtendiMax® Plus VaporGrip®	Bayer Crop Science	Research Triangle Park, NC
Dicamba + *S*-metolachlor	Tavium® Plus VaporGrip®	Syngenta Crop Protection	Greensboro, NC
Drift reduction agent	Intact™	Precision Laboratories	Waukegen, IL
Flumioxazin	Valor®	Valent	Walnut Creek, CA
Fluometuron	Cotoran®	Syngenta Crop Protection	Greensboro, NC
Glufosinate	Liberty®	BASF	Research Triangle Park, NC
Glyphosate	Roundup® PowerMAX®	Bayer Crop Science	Research Triangle Park, NC
Monosodium methanearsonate	MSMA	Drexel Chemical	Memphis, TN
Non-ionic surfactant	Induce®	Helena Agri-Enterprises	Collierville, TN
Paraquat	Gramoxone® SL 2.0	Syngenta Crop Protection	Greensboro, NC
S-metolachlor	Dual Magnum®	Syngenta Crop Protection	Greensboro, NC

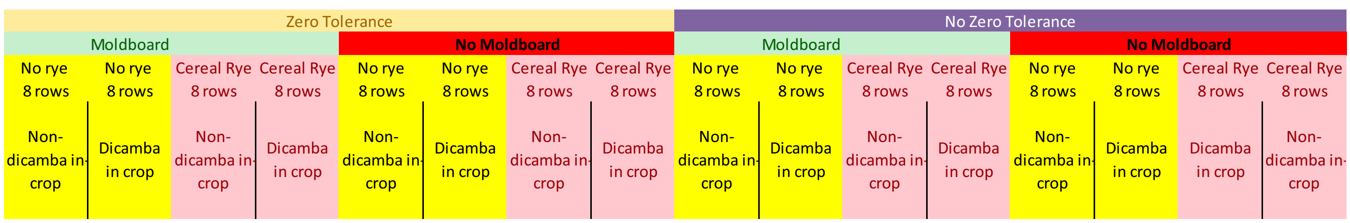

Figure 1. Layout of plots and subsequent subplots in the study.

The two herbicide programs for this study each consisted of a preplant burndown (described earlier), preemergence (PRE) application at planting, early postemergence (EPOST) application at 21 d after planting (DAP), a mid-postemergence (MPOST) application at 42 DAP, and a layby post-directed application at 63 DAP (Tables 1 and 2). The burndown, PRE, and EPOST applications were made at 140 L ha^{-1} using a self-propelled sprayer (Bowman Manufacturing, Newport, AR, USA) with an effective spray swath of 7.3 m. The MPOST application was made using a tractor-mounted hooded sprayer, and the layby post-directed application was made using a tractor-mounted post-directed sprayer, with all treatments applied at 140 L ha^{-1} for both application timings. All applications containing dicamba were made using TeeJet® TTI 11006 nozzles, the layby applications were made using TeeJet® XR 11006E flat-fan nozzles, and all other applications were made using TeeJet® AIXR 11006 nozzles (TeeJet® Technologies, Wheaton, IL, USA). Individual herbicide timings, treatments, and rates are listed in Table 2 for the dicamba and non-dicamba in-crop programs. Zero-tolerance thresholds were executed using a one-time hand-weeding event 14 d after the layby application. Hand-weeding was conducted using by graduate students per plot, and the time to hand-weed each plot was recorded in seconds using a stopwatch.

Prior to each growing season, ten 347-mL soil cores were taken from each plot at depths of 0 to 7.6 cm and 7.6 to 15.2 cm to measure soil seedbank densities through exhaustion in a greenhouse. Soil from within the same plots was mixed to homogenize the sample. Equal parts based on volume of field soil and potting mix were then placed in 52 × 40 × 5 cm black plastic flats with the weight of the field soil being recorded prior to combining with the potting soil. The flats were then placed in the greenhouse and watered twice daily to promote weed germination. Emerged weeds were counted every other week. Every 4 wk, the soil flats were placed into a −17 C freezer for 2 wk to break the dormancy of weed seeds. These procedures were repeated until no more emergence occurred for 2 wk following removal from the freezer. In both years, this was achieved after three cycles of freezing and thawing (Norsworthy et al. 2018) Throughout the season, total weed emergence was determined by counting emerged weeds in four seasonally established, 1-m^2 quadrats per plot. Palmer amaranth plants were counted at 21, 42, 63, and 70 DAP prior to each herbicide application and again 7 d prior to the hand-weeding event. Immediately prior to cotton harvest, the total number of inflorescence-producing Palmer amaranth plants within each plot was counted. Seed cotton was harvested using a two-row cotton harvester, harvesting the center six rows of cotton from each plot, and seed cotton was weighed in-field using a weigh wagon.

The seed cotton, percentage turnout, and inputs and their associated costs for each management strategy were taken into consideration to conduct an economic analysis of each management program (Table 3). Turnout was assumed to be 40% based on local practices, and costs for each management practice were attained using the University of Arkansas Extension Crop Enterprise Budgets (UAEX 2021), which report the costs for labor and horsepower for various practices associated with Arkansas agriculture. Cotton prices were based on the 10-yr average for cotton lint, set at US$1.79 kg^{-1} (USDA-AMS 2017, 2021) Chemical costs were obtained from University of Arkansas Extension Enterprise Budgets (UAEX 2021), which comprised an average of at least ten different chemical retailers in the Arkansas Mississippi Delta growing region. Costs of chemicals, adjuvants, or additives not included in these budgets were obtained from an average of three different chemical suppliers in the Midsouth and Midwest, similar to procedures done by Striegel et al. (2020) for economic analysis of herbicide programs.

Data were subjected to analysis of variance (ANOVA) using SAS version 9.4 (SAS Institute Inc., Cary, NC, USA). Assumptions of normality and equal variance were checked prior to analysis using the Shapiro–Wilks test and residuals plots (Kniss and Streibig 2018). All response variables were subjected to ANOVA using the GLIMMIX procedure, and treatment means were

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Table 2. Herbicide weed management programs for 2019 and 2020 in Marianna, AR.[a]

Program	Timing	Product name	Common name	Rate
				g ai or ae ha^{-1}
Dicamba in-crop	burndown	Roundup® PowerMAX® + Clarity®	glyphosate + dicamba	1,260 + 280
	PRE	XtendiMax® Plus VaporGrip® + Cotoran® + Roundup® PowerMAX®	dicamba + fluometuron + glyphosate	1,120 + 1,120 + 1,260
	EPOST	Tavium® Plus VaporGrip® + Roundup® PowerMAX®	dicamba + *S*-metolachlor + glyphosate	560 + 1,068 + 1,260
	MPOST	Liberty® + Roundup® PowerMAX® + Warrant®	glufosinate + glyphosate + acetochlor	656 + 1,260 + 1,260
	layby	Valor® + MSMA	flumioxazin + MSMA	71.5 + 2,240
Non-dicamba in-crop	burndown	Roundup® PowerMAX® + Clarity®	glyphosate + dicamba	1,260 + 280
	PRE	Gramoxone® + Cotoran® + Roundup® PowerMAX®	paraquat + fluometuron + glyphosate	700 + 1,120 + 1,260
	EPOST	Liberty® + Roundup® PowerMAX® + Dual Magnum®	glufosinate + glyphosate + *S*-metolachlor	656 + 1,260 + 1,068
	MPOST	Liberty® + Roundup® PowerMAX® + Warrant®	glufosinate + glyphosate + acetochlor	656 + 1,260 + 1,260
	layby	Valor® + MSMA	flumioxazin + MSMA	71.5 + 2,240

[a]Abbreviations: EPOST, early postemergence; MSMA, monosodium methanearsonate; MPOST, mid-postemergence; PRE, preemergence.

Table 3. Weed management programs and the costs associated with each weed management strategy for 2019 and 2020 near Marianna, AR.

Year	Program				Cost				
	Deep tillage	Cover crop	Herbicide program[a]	Zero tolerance	Deep tillage	Cover crop	Herbicide program	Zero tolerance[b]	
					US$ ha^{-1}			hr ha^{-1}	US$ ha^{-1}
2019	yes	no	non-dicamba	yes	39.52	0.00	542.34	4.20	50.40
	yes	no	dicamba	yes	39.52	0.00	605.96	3.96	47.52
	yes	yes	non-dicamba	yes	39.52	86.63	542.34	4.06	48.72
	yes	yes	dicamba	yes	39.52	86.63	605.96	4.99	59.88
	no	no	non-dicamba	yes	0.00	0.00	542.34	4.82	57.84
	no	no	dicamba	yes	0.00	0.00	605.96	4.71	56.52
	no	yes	non-dicamba	yes	0.00	86.63	542.34	5.93	71.16
	no	yes	dicamba	yes	0.00	86.63	605.96	4.96	59.52
	yes	no	non-dicamba	no	39.52	0.00	542.34	0.00	0.00
	yes	no	dicamba	no	39.52	0.00	605.96	0.00	0.00
	yes	yes	non-dicamba	no	39.52	86.63	542.34	0.00	0.00
	yes	yes	dicamba	no	39.52	86.63	605.96	0.00	0.00
	no	no	non-dicamba	no	0.00	0.00	542.34	0.00	0.00
	no	no	dicamba	no	0.00	0.00	605.96	0.00	0.00
	no	yes	non-dicamba	no	0.00	86.63	542.34	0.00	0.00
	no	yes	dicamba	no	0.00	86.63	605.96	0.00	0.00
2020	yes	no	non-dicamba	yes	0.00	0.00	542.34	16.06	192.72
	yes	no	dicamba	yes	0.00	0.00	605.96	3.27	39.24
	yes	yes	non-dicamba	yes	0.00	86.63	542.34	6.99	83.88
	yes	yes	dicamba	yes	0.00	86.63	605.96	3.70	44.46
	no	no	non-dicamba	yes	0.00	0.00	542.34	13.78	165.36
	no	no	dicamba	yes	0.00	0.00	605.96	3.86	46.32
	no	yes	non-dicamba	yes	0.00	86.63	542.34	7.93	95.16
	no	yes	dicamba	yes	0.00	86.63	605.96	3.52	42.24
	yes	no	non-dicamba	no	0.00	0.00	542.34	0.00	0.00
	yes	no	dicamba	no	0.00	0.00	605.96	0.00	0.00
	yes	yes	non-dicamba	no	0.00	86.63	542.34	0.00	0.00
	yes	yes	dicamba	no	0.00	86.63	605.96	0.00	0.00
	no	no	non-dicamba	no	0.00	0.00	542.34	0.00	0.00
	no	no	dicamba	no	0.00	0.00	605.96	0.00	0.00
	no	yes	non-dicamba	no	0.00	86.63	542.34	0.00	0.00
	no	yes	dicamba	no	0.00	86.63	605.96	0.00	0.00

[a]Dicamba in-crop herbicide program or non-dicamba in-crop herbicide program.
[b]Values are based on averages for the program.

separated using Tukey's adjustment ($\alpha = 0.05$). Total Palmer amaranth emergence was evaluated prior to the implementation of the zero-tolerance strategy in 2019. In contrast, the Palmer amaranth seedbank in 2020 had been subjected to these strategies. Therefore data for total Palmer amaranth emergence were analyzed separately by year, with zero tolerance excluded from the 2019 total Palmer amaranth emergence model. Greenhouse soil seedbank exhaustion data were also subjected to ANOVA using an

Table 4. P-values for total Palmer amaranth emergence, time to hand-weed, inflorescence-producing Palmer amaranth, cotton lint yield, and partial returns by year, zero tolerance, deep tillage, cover crop, and herbicide program in Marianna, AR.[a,b]

Source	Total PA emergence		HWT	IPPA	Lint yield	Partial returns
	2019	2020				
Year	—	—	0.0674	**<0.0001**	**<0.0001**	**<0.0001**
Zero tolerance	—	0.7747	—	0.3650	**0.0347**	**0.0168**
Deep tillage	**0.0258**	**0.0030**	0.8560	**0.0001**	**0.0004**	**0.0002**
Cover crop	0.3861	0.5259	0.2804	0.1695	**0.0002**	**0.0129**
Herbicide program	0.6381	**<0.0001**	**0.0093**	0.2472	0.9275	0.4445
Year × Zero Tolerance	—	—	—	**0.0024**	**0.0002**	**<0.0001**
Year × Deep Tillage	—	—	0.7227	**0.0008**	0.0979	0.1738
Zero Tolerance × Deep Tillage	—	**0.0137**	—	0.2212	0.1545	0.1686
Year × Cover Crop	—	—	0.1446	**0.0328**	**0.0483**	**0.0312**
Zero Tolerance × Cover Crop	—	**0.0474**	—	0.8996	0.1901	0.1476
Deep Tillage × Cover Crop	0.9047	0.1076	0.8022	0.6619	0.1323	0.1283
Year × Herbicide Program	—	—	**0.0112**	0.1153	**0.0031**	**0.001**
Zero Tolerance × Herbicide Program	—	0.8765	—	0.5835	0.1204	0.2491
Deep Tillage × Herbicide Program	0.6959	0.4117	0.9985	0.9157	0.1987	0.2046
Cover Crop × Herbicide Program	0.4308	0.9063	0.1904	0.7651	0.9366	0.9098
Year × Zero Tolerance × Deep Tillage	—	—	—	0.1451	**0.0198**	**0.0245**
Year × Zero Tolerance × Cover Crop	—	—	—	0.6525	0.8564	0.6949
Year × Deep Tillage × Cover Crop	—	—	0.8652	0.7371	0.6151	0.6026
Zero Tolerance × Deep Tillage × Cover Crop	—	0.0710	—	0.8107	0.2251	0.2176
Year × Zero Tolerance × Herbicide Program	—	—	—	0.7648	0.9920	0.7145
Year × Deep Tillage × Herbicide Program	—	—	0.7634	0.7315	0.2491	0.2741
Zero Tolerance × Deep Tillage × Herbicide Program	—	0.1018	—	0.9541	0.2405	0.2467
Year × Cover Crop × Herbicide Program	—	—	0.2091	0.9407	0.9115	0.9409
Zero Tolerance × Cover Crop × Herbicide Program	—	**0.0465**	—	0.7344	0.8781	0.7317
Deep Tillage × Cover Crop × Herbicide Program	0.7923	0.1018	0.6057	0.7047	0.1510	0.1360
Year × Zero Tolerance × Deep Tillage × Cover Crop	—	—	—	0.6826	0.9204	0.9412
Year × Zero Tolerance × Deep Tillage × Herbicide Program	—	—	—	0.5716	0.4300	0.4624
Year × Zero Tolerance × Cover Crop × Herbicide Program	—	—	—	0.6110	0.8667	0.7268
Year × Deep Tillage × Cover Crop × Herbicide Program	—	—	0.8678	0.8969	0.2315	0.2284
Zero Tolerance × Deep Tillage × Cover Crop × Herbicide Program	—	0.2094	—	0.1642	0.8049	0.8663
Year × Zero Tolerance × Deep Tillage × Cover Crop × Herbicide Program	—	—	—	0.4120	0.5904	0.5787

[a]Abbreviations: HWT, hand-weeding time; IPPA = inflorescence-producing Palmer amaranth; PA, Palmer amaranth.
[b]Boldface indicates significant P-values ($\alpha = 0.05$).

additional factor of depth as the whole-plot factor in the linear mixed model, and means were separated with a Tukey's adjustment ($\alpha = 0.05$). Correlation estimates were made between the quantitative variables total Palmer amaranth emergence, inflorescence-producing Palmer amaranth, time to hand-weed, partial return, yield, and weed management costs to determine the relationships, if any, between each variable using R version 4.0.2 (R Foundation for Statistical Computing, Vienna, Austria). A correlation coefficient matrix was created using the *rcorr* function in the HMISC package (Harrell and Dupont 2022).

Results and Discussion

Total Palmer Amaranth Emergence

In 2019, the three-way and two-way interactions were not significant ($P > 0.05$) (Table 4). Total Palmer amaranth emergence was not affected by cover crop or by herbicide program. In contrast, implementing a deep tillage strategy reduced total Palmer amaranth emergence by 76% (Table 5). Use of the moldboard plow in fall 2018 reduced Palmer amaranth to 63,000 plants ha^{-1} from 260,000 plants ha^{-1} in its absence, averaged across other factors. In 2020, the four-way interaction was not significant ($P = 0.2094$) (Table 4). In contrast, the three-way interaction Zero Tolerance × Cover Crop × Herbicide Program ($P = 0.0465$) and the two-way interaction Zero Tolerance × Deep Tillage ($P = 0.0137$) were significant, leading to a further analysis of the simple effects of these factors (Table 6). No differences were detected between fields with and without a zero-tolerance strategy under both the presence and the absence of a deep tillage strategy (Table 6). Also, under a zero-tolerance strategy, no differences were detected in the total Palmer amaranth emergence between fields that received a deep tillage and the ones that did not. In contrast, in the absence of a zero-tolerance strategy, the implementation of deep tillage with the moldboard plow provoked a 73% decrease in the total emergence of Palmer amaranth in 2020 (Table 5). This revealed that the effect of the one-time deep tillage event was noticeable in Year 2, as Palmer amaranth emergence was reduced from 130,000 plants ha^{-1} in the absence of tillage to 35,000 plants ha^{-1} in plots deep-tilled in fall 2018. The reduction of Palmer amaranth emergence by 76% in Year 1 and 73% in Year 2 is similar to the findings of DeVore et al. (2012, 2013) and Aulakh et al. (2012), where the inversion of the soil reduced Palmer amaranth emergence 70% to 81% in crop production situations.

In 2020, in the absence of a zero-tolerance strategy, the combination of a non–cover crop strategy and a dicamba herbicide program decreased total Palmer amaranth emergence by 73%, while the combination of a cover crop strategy and a dicamba herbicide program decreased total Palmer amaranth emergence by 78% compared to the combination of a cover crop program and a non-dicamba herbicide program (Table 5). The same year, in the presence of a zero-tolerance strategy, the combination of a

Table 5. Total Palmer amaranth emergence in 2019 and 2020 by tillage, cover crop, and zero-tolerance use and herbicide program near Marianna, AR.[a]

			Total Palmer amaranth emergence	
			2019	2020
			plants ha^{-1}	
Deep tillage				
No			260,000 a	—
Yes			63,000 b	—
Cover crop				
No			150,000 a	—
Yes			180,000 a	—
Zero tolerance				
No	Cover crop	Herbicide program		
	No	Dicamba in-crop	—	42,000 b
		Non-dicamba in-crop	—	100,000 ab
	Yes	Dicamba in-crop	—	33,000 c
		Non-dicamba in-crop	—	150,000 a
Yes	Cover crop	Herbicide program		
	No	Dicamba in-crop	—	50,000 b
		Non-dicamba in-crop	—	180,000 a
	Yes	Dicamba in-crop	—	41,000 b
		Non-dicamba in-crop	—	100,000 b

[a]Values followed by the same letter are statistically similar based on Tukey's least significant difference ($\alpha = 0.05$).

Table 6. Total Palmer amaranth emergence as a function of a significant interaction between tillage and zero-tolerance use in Marianna, AR.[a]

	Zero tolerance	
	No	Yes
	plants ha^{-1}	
Deep tillage		
No	130,000 aA	98,000 aA
Yes	35,000 bA	88,000 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.

non–cover crop and a dicamba herbicide program decreased total Palmer amaranth emergence by 72%, while the combination of a cover crop and a non-dicamba herbicide program reduced total Palmer amaranth emergence 44% in comparison to the combination of a non–cover crop strategy and non-dicamba herbicide program. Also, combination of a cereal rye cover crop and the dicamba herbicide program induced a 77% decrease in total Palmer amaranth emergence compared to the combination of the non–cover crop strategy and non-dicamba herbicide program. Previous research has shown that the use of cereal rye typically reduces Palmer amaranth emergence or does not significantly affect weed emergence (DeVore et al. 2012, 2013; Wiggins et al. 2016; Palhano et al. 2018; Price et al. 2021). It should be noted that in 2019, the cereal rye cover crop was not planted until mid-November, leaving very little time for cover crop growth and establishment prior to dormancy. Consequently, the cereal rye biomass and groundcover were greatly reduced when compared to 2020, where the cereal rye in 2019 measured less than 40 cm in height and the cereal rye in 2020 was approximately 150 cm tall. Cereal rye biomass at planting was not measured in 2019, but biomass of the cereal rye at planting in 2020 averaged 4,500 kg ha^{-1}, which is similar to biomass recovered in other studies where weed emergence was suppressed at biomass levels ≥ 3,100 kg ha^{-1} (Palhano et al. 2018; Price et al. 2021). Differences in herbicide programs between 2019 and 2020 can be attributed to differences in climatic conditions between the two years (Figure 2). Within 5 d of planting in 2019, there were a series of rainfall events that activated fluometuron PRE (Figure 2; Anonymous 2021), which was included in both herbicide programs and subsequently allowed for similar Palmer amaranth control in the first 21 DAP, a critical time period for cotton growth and development (Klingaman and Oliver 1994; Zimdahl 2004; Korres and Norsworthy 2015). Conversely, there were no rainfall events for the first 11 DAP in 2020 (Figure 2). The lack of rainfall did not allow for the fluometuron to be activated, thus reducing its residual activity. However, dicamba PRE, which was coapplied with fluometureon in the dicamba in-crop herbicide program, suppressed Palmer amaranth emergence. Others have documented that the herbicidal activity of dicamba on Palmer amaranth emergence was not impacted by the lack of irrigation or rainfall (Byker et al. 2013; Johnson et al. 2010; Meyer et al. 2015; Smith et al. 2016). With new updates to dicamba product labels in 2021, the use of 1,120 g ae ha^{-1} PRE in cotton is no longer permitted, reducing the maximum application rate at this time to 560 g ae ha^{-1} (Anonymous 2021). As no differences were observed between the two herbicide programs when both zero tolerance and cereal rye were implemented as well as when neither were utilized at the same time, it can be hypothesized that the integration of these two strategies may overcome poor PRE herbicide activation. The presence of both the cereal rye cover crop and the zero-tolerance strategy may have resulted in lower seedbank pressures that would have made determining differences difficult. Likewise, the absence of both programs may have resulted in an increased seedbank pressure that may have made determining differences difficult as well. Findings also suggest that without the use of these strategies, Palmer amaranth will continue to emerge in large quantities throughout the season, regardless of effective herbicide activation. These results are similar to findings by others, particularly when cereal rye cover crops were utilized as part of integrated weed management systems. Korres and Norsworthy (2015) determined that with the use of a cereal rye cover crop, the initiation of the critical weed-free period could be delayed due to the suppressive characteristics of the cereal rye.

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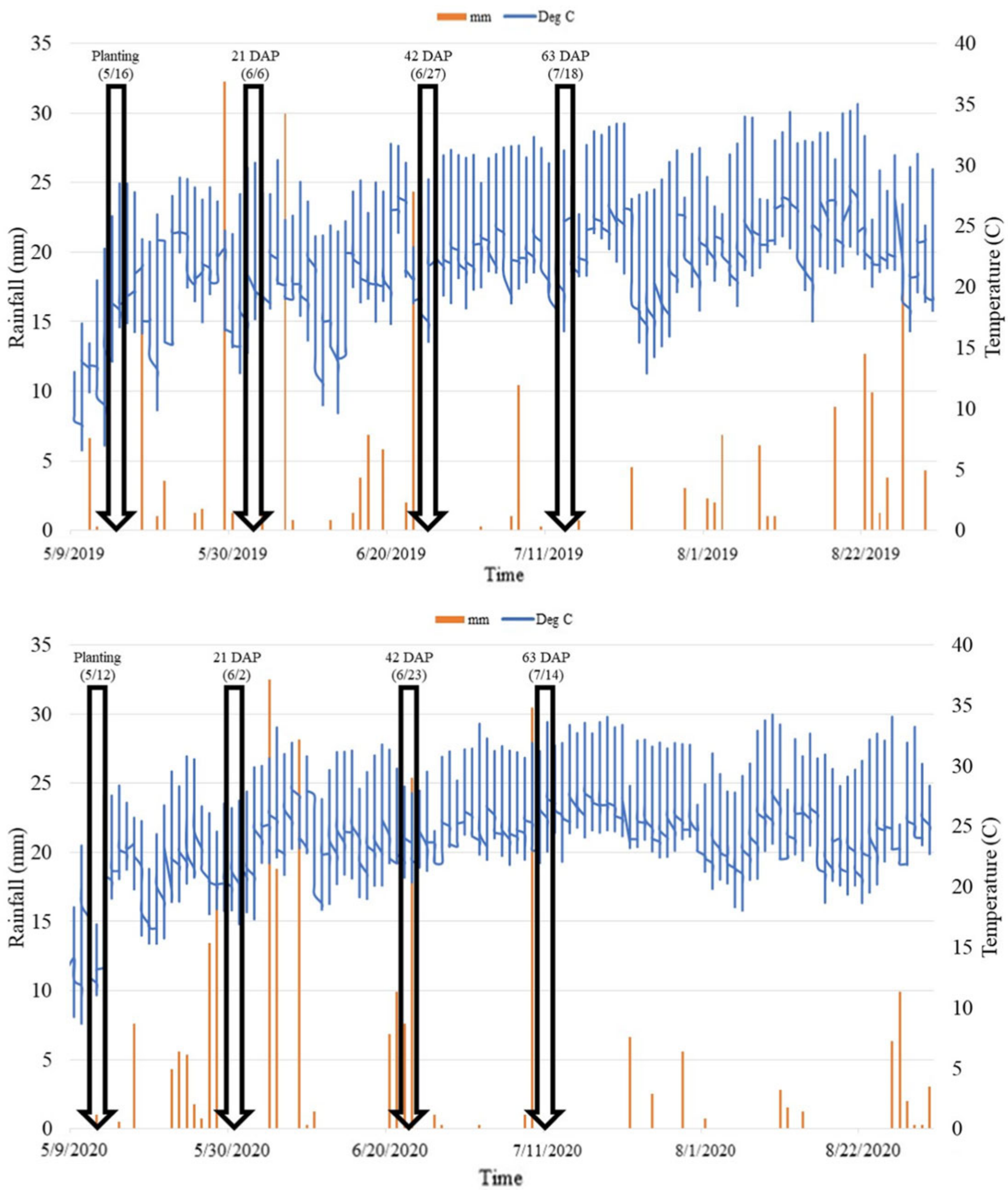

Figure 2. Planting and herbicide application dates, air temperature, and rainfall at Marianna, AR, in 2019 (top) and 2020 (bottom). Preemergence herbicide applications occurred immediately after planting.

Inflorescence-Producing Palmer Amaranth Plants

The two-way interactions Year × Tillage, Year × Zero Tolerance, and Year × Cover Crop were significant for the number of inflorescence-producing Palmer amaranth plants at harvest (Table 4). In 2019, the implementation of a deep tillage strategy induced a 75% decrease in the total number of inflorescence-producing Palmer amaranth plants, while no differences existed between the presence and absence of deep tillage in 2020 (Table 7). Also, when no tillage strategy was implemented, the number of inflorescence-producing Palmer amaranth plants was greater in 2019 than in 2020, while no differences were detected between 2019 and 2020, when a deep tillage strategy was used, probably due to the already 75% lower number of inflorescence-producing Palmer amaranth plants in the tilled plots in 2019 (Table 7). The use of a moldboard plow in 2018 already reduced the number of inflorescence-producing Palmer amaranth plants from 1,400 plants ha^{-1} with the absence of a one-time deep tillage event to 360 plants ha^{-1} with tillage, averaged over all other factors in 2019 (Table 7). DeVore et al. (2012) also observed the weed density reduction benefits of a moldboard plow tillage event. In 2019, the number of inflorescence-producing Palmer amaranth plants was greater when a cereal rye cover crop was used compared to when it was not used, while no differences existed between the presence or absence of a cereal rye cover crop program in 2020 (Table 7). However, the use of a cereal rye cover crop in fall 2018 and 2019 led to a decrease of inflorescence-producing Palmer amaranth plants by 83% in 2020 (Table 7). This trend was similar to the effect of a zero-tolerance strategy. In 2019, the number of inflorescence-producing Palmer amaranth plants was greater when a zero-tolerance strategy was used compared to when it was not used, whereas no differences

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Table 7. Inflorescence-producing Palmer amaranth as a function of a significant interaction between year and management strategy in Marianna, AR.[a,b]

	IPPA	
	2019	2020
	—— plants ha^{-1} ——	
Zero tolerance		
No	480 bA	300 aA
Yes	1,300 aA	220 aB
Deep tillage		
No	1,400 aA	290 aB
Yes	360 bA	220 aA
Cover crop		
No	640 bA	310 aA
Yes	1,100 aA	200 aB

[a]Abbreviation: IPPA, inflorescence-producing Palmer amaranth.
[b]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 8. Time required to hand-weed plots as a function of an interaction between year and herbicide program in Marianna, AR.[a]

	Time to hand-weed	
	2019	2020
	—— hr ha^{-1} ——	
Herbicide program		
Dicamba in-crop	2.33 aA	1.79 bA
Non-dicamba in-crop	2.38 aB	5.59 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 9. Cotton lint yield and partial return based on year, zero tolerance, and deep tillage in Marianna, AR.[a]

Year	Zero tolerance	Deep tillage	Yield	Partial return
			kg ha^{-1}	US\$ ha^{-1}
2019	no	no	2,000 ab	1,100 ab
		yes	2,000 ab	1,100 a
	yes	no	2,200 a	1,300 a
		yes	1,900 b	880 b
2020	no	no	2,000 a	1,100 a
		yes	1,700 b	740 b
	yes	no	1,600 b	530 b
		yes	1,400 c	270 c

[a]Values followed by the same letter are statistically similar based on Tukey's least significant difference (α = 0.05).

Table 10. Cotton lint yield and partial return based on year, herbicide program, and cover crop use in Marianna, AR.[a]

	Yield		Partial return	
	2019	2020	2019	2020
	— kg ha^{-1} —		— US\$ ha^{-1} —	
Herbicide program				
Dicamba in-crop	1,600 bA	1,500 aB	970 bA	740 aB
Non-dicamba in-crop	1,700 aA	1,400 bB	1,200 aA	590 bB
Cover crop				
No	1,600 aA	1,300 bB	1,081 aA	520 bB
Yes	1,700 aA	1,500 aB	1,102 aA	810 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.

existed between the presence or absence of a zero-tolerance strategy in 2020 (Table 7). However, when a zero-tolerance strategy was used, the number of inflorescence-producing Palmer amaranth plants decreased by 83% the second year.

Time Required for Hand-Weeding

The two-way interaction Year × Herbicide Program was significant for the time it took to rid plots of Palmer amaranth (Table 4). In 2019, using a dicamba or a non-dicamba herbicide program resulted in the same impact on the time it took to hand-weed each plot (Table 8). In contrast, in 2020, using a dicamba herbicide program reduced the time to hand-weed plots by 68% (Table 8). No differences were detected between 2019 and 2020 for time taken to hand-weed plots when dicamba herbicide programs were used, while the time required to hand-weed plots was increased by 68% in 2020 when a non-dicamba herbicide program was used. The lack of differences between the use of different herbicide programs in 2019 can be related to the overall effectiveness of weed control programs up to this point. At 77 DAP, there were few weed escapes as a result of three successful POST herbicide applications in both the non-dicamba and dicamba programs, allowing for relatively efficient hand-removal of weeds. In 2020, it took 5.9 hr ha^{-1} to hand-weed plots that used the non-dicamba herbicide program, which was the greatest amount of time required of any treatment (Table 8). The trends shown with the time to hand-weed are similar to trends observed with total Palmer amaranth emergence in 2020, where poor activation of PRE herbicides allowed for increased weed emergence in those plots utilizing the non-dicamba herbicide program. These escapes were problematic throughout the season, as the Palmer amaranth that emerged early were 15 to 25 cm tall at the first POST application, which consequently resulted in reduced control compared to weeds that would have emerged later and were smaller at application. Similar issues have been observed by Craigmyle et al. (2013), Merchant et al. (2017), and Vann et al. (2017), where weed control and cotton yield decreased as Palmer amaranth height at time of application increased. The use of cereal rye did appear to suppress Palmer amaranth growth, which allowed for fewer weeds to be present at the end of the season, decreasing the time needed to hand-weed.

Seedbank Exhaustion Study in Greenhouse

Results from the soil seedbank exhaustion studies conducted in the greenhouse found no differences between any of the management factors (P > 0.05). The inconclusiveness of these results is similar to findings by DeVore et al. (2013), Cardina and Sparrow (1996), and Espeland et al. (2010) that suggested that quantifying soil seedbank populations over time using similar methods does not accurately capture the total variability in the field and does not capture the same environmental conditions that would affect those weed populations in the field. In the future, a more effective way to capture changes in weed soil seedbank populations may be to monitor total weed emergence the season following completion of the long-term study in the absence of a crop or other management practices.

Table 11. P-values and correlation coefficients for correlation analyses between total Palmer amaranth emergence, inflorescence-producing Palmer amaranth, cotton lint yield, weed management cost, partial return, and time to hand-weed in Marianna, AR, in 2019 and 2020.[a,b]

	Total PA emergence	Inflorescence-producing PA	Lint yield	Weed manage. cost	Partial return	Time to hand-weed
			P-values			
Total PA emergence		**<0.0001**	0.0504	0.2145	0.0805	**0.0070**
Inflorescence-producing PA	**<0.0001**		0.0566	0.1093	0.0991	0.0611
Lint yield	0.0504	0.0566		0.5709	**<0.0001**	**<0.0001**
Weed manage. cost	0.2145	0.109	0.5709		**0.0331**	**<0.0001**
Partial return	0.0805	0.0991	**<0.0001**	**0.0331**		**<0.0001**
Time to hand-weed	**0.0070**	0.0611	**<0.0001**	**<0.0001**	**<0.0001**	
			Correlation coefficients			
Total PA emergence	1.00	0.69	0.17	0.11	0.16	0.24
Inflorescence-producing PA	0.69	1.00	0.17	0.14	0.15	0.17
Lint yield	0.17	0.17	1.00	−0.05	0.99	−0.38
Weed manage. cost	0.11	0.14	−0.05	1.00	−0.19	0.55
Partial return	0.16	0.15	0.99	−0.19	1.00	−0.45
Time to hand-weed	0.24	0.17	−0.38	0.55	−0.45	1.00

[a]Abbreviation: PA = Palmer amaranth.
[b]Boldface indicates significant values (α = 0.05).

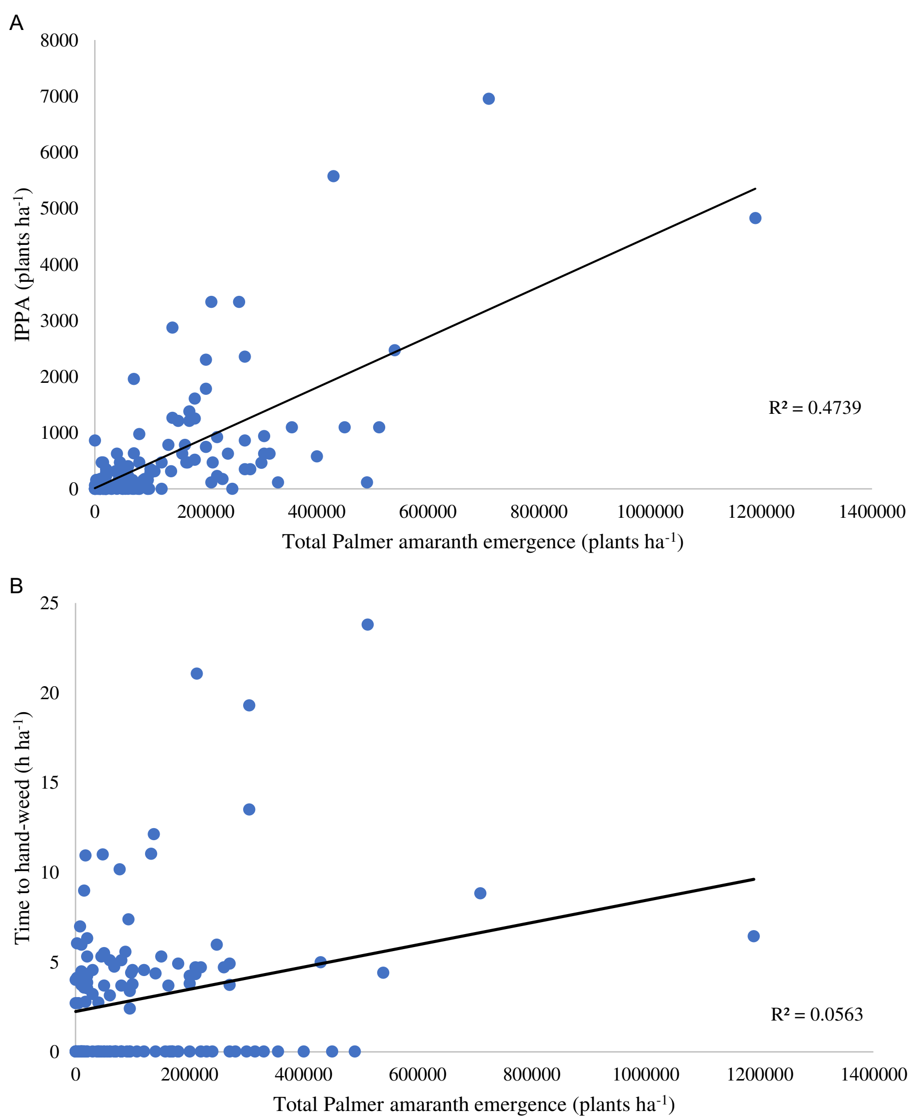

Figure 3. Correlation between total Palmer amaranth emergence and number of inflorescence-producing Palmer amaranth (A) and time to hand-weed (B) near Marianna, AR.

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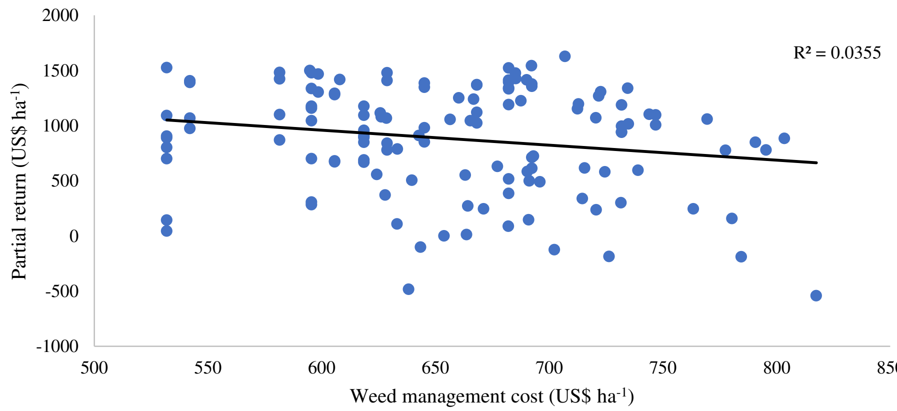

Figure 4. Correlation between weed management cost and partial return near Marianna, AR.

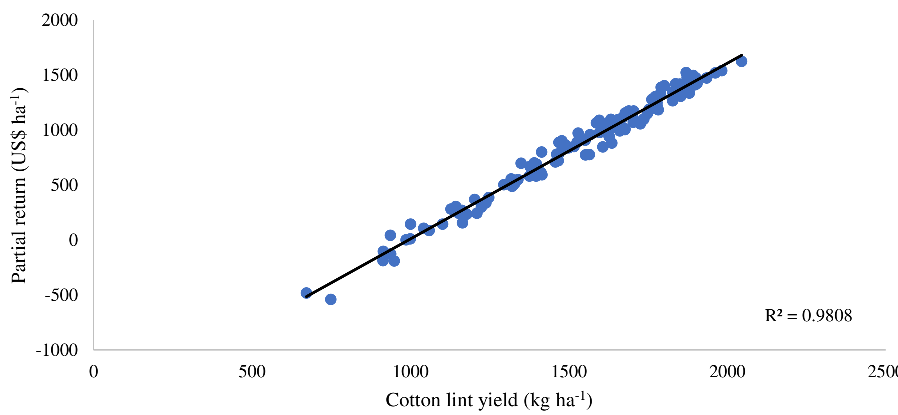

Figure 5. Correlation between cotton lint yield and partial return near Marianna, AR.

Impact on Cotton Production Economics

The three-way interaction Year × Zero Tolerance × Deep Tillage and the two-way interactions Year × Zero Tolerance, Year × Cover Crop, and Year × Herbicide Program were significant for cotton lint yield and partial returns (Table 4), meaning that the zero-tolerance strategy, cover crop strategy, and herbicide programs all influenced cotton yields and partial returns, but the effects were dependent on year. In 2019, the combination of a zero-tolerance strategy and the absence of deep tillage had a greater cotton lint yield than the combination of a zero-tolerance strategy and implementation of deep tillage (Table 9). In 2020, the greatest lint yield was obtained under the combination of non–zero tolerance and non–deep tillage, and the lowest yield was obtained using the combination of zero tolerance and deep tillage. Therefore the use of a one-time deep tillage event negatively impacted cotton yields. Under a zero-tolerance strategy in 2019, tillage reduced cotton lint yield by 12% and consequently reduced partial returns by US$370 ha^{-1} (Table 9). In 2020, tillage reduced cotton yield by 14% with reduced partial returns of US$370 ha^{-1} under a non-zero-tolerance strategy, while a 12% reduction was observed when a zero-tolerance strategy was implemented with reduced partial returns of US$260 ha^{-1} (Table 9). This is contrary to findings of other studies, in which the use of one-time deep tillage resulted in similar or greater cotton yields (Aulakh et al. 2012; DeVore et al. 2012). A possible explanation for the reduction in cotton yield following the use of a one-time deep tillage event may be a reduction in potassium in the top portion of the soil that may not have been noticed in soil samples due to stratification. Where potassium has typically been broadcast-applied at the site, potassium levels were likely stratified, with the greatest levels being found near the soil surface (Howard et al. 1999). The deep tillage event likely buried the soil that was rich with potassium to a depth at which the cotton was unable to utilize the nutrient until later in the season, after yield reduction had already occurred (Singh et al. 2009).

The use of a cereal rye cover crop influenced cotton yields during the study, but the effect was dependent on year (Table 10). In 2019, there were no differences between the presence and absence of a cereal rye cover crop. This result can be predominantly attributed to the lack of adequate cover crop establishment caused by wet conditions in fall 2018 that delayed planting until November. In 2020, the use of cereal rye improved cotton yields by 220 kg ha^{-1} and profit by US$280 ha^{-1}. The improvement in cotton yield because of cereal rye is similar to findings in Alabama and Tennessee, where the use of a cover crop did improve cotton yields in some years, while there were negligible differences in others (Price et al. 2021; Zhou et al. 2017). Findings from other studies in Arkansas and Texas suggested that the use of cereal rye cover crops had no effect on cotton yield or net returns (DeLaune et al. 2020; DeVore et al. 2012).

Cotton yield was lower when the dicamba herbicide program was used in 2019. Similarly, in 2019, the non-dicamba program resulted in greater partial returns than the dicamba program (Table 10) because of the greater yield coupled with differences in program costs, as the cost of herbicides and associated technology

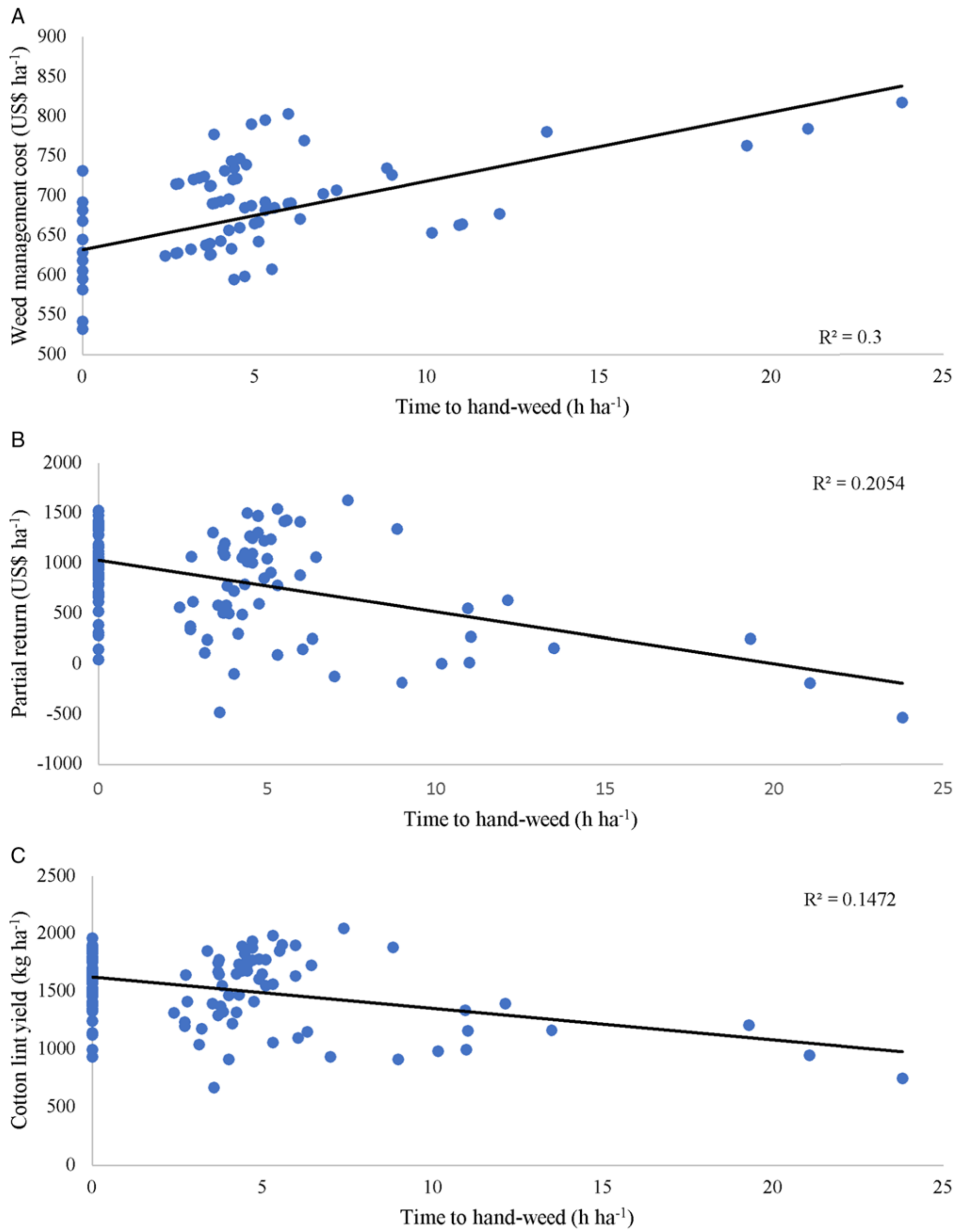

Figure 6. Correlation between the time to hand-weed and weed management cost (A), partial return (B), and cotton lint yield (C) near Marianna, AR.

fees for the dicamba program was US$63 ha^{-1} greater than that of the non-dicamba program (Table 3). In contrast, cotton lint yield was greater when the dicamba herbicide program was used in 2020. The increase in cotton yield in 2020 is likely a direct result of the greater Palmer amaranth control early in the season by the dicamba herbicide program, which reduced competition for resources between Palmer amaranth and the cotton. Consequently, partial returns were greater for the dicamba herbicide program. Differences in herbicide programs between 2019 and 2020 discussed previously and differences in climatic conditions (particularly early-season rainfall) between the two years might have played a key role in cotton lint yield variations between the two years. The improved activation of fluometuron PRE in Year 1 allowed similar Palmer amaranth control in the first 21 DAP, a critical time period for cotton growth and development (Klingaman and Oliver 1994; Zimdahl 2004; Korres and Norsworthy 2015). Conversely, the decrease in fluometuron activation resulted from a lack of rainfall in 2020, thereby reducing the effectiveness of the non-dicamba herbicide program for Palmer amaranth control. The herbicidal activity of dicamba on Palmer amaranth emergence, previously shown to be unaffected by the lack irrigation or rainfall (Byker et al. 2013; Johnson et al. 2010; Meyer et al. 2015; Smith et al. 2016), contributed to better control of Palmer amaranth in the dicamba herbicide program in 2020. The poor activation of PRE herbicides and the increased weed emergence in the non-dicamba herbicide program were detrimental for cotton yield. Early-season weed control is known to be critical for proper cotton development as well as yield potential (Klingaman and Oliver 1994; Korres and Norsworthy 2015). Additionally, according to Craigmyle et al. (2013), Merchant et al. (2017), and Vann et al. (2017), weed control and cotton yield decrease as Palmer amaranth height at time of application increases.

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Correlation Analyses

As total Palmer amaranth emergence increased, the number of inflorescence-producing Palmer amaranth plants also increased (Figure 3). A positive relationship existed between total Palmer amaranth emergence and the time required to hand-weed, further suggesting that the time required to hand-weed is best reduced by effective management strategies beforehand (Table 9; Figure 3). Correlation analyses also indicated that several factors influenced cotton yield and partial returns (Table 11). Unsurprisingly, as the cost of weed management increased, partial returns decreased (Figure 4), though the relationship is not near as strong as that between yield and partial returns (Figure 5). As the time to hand-weed a plot increased, weed management costs increased, while partial returns and lint yield decreased (Figure 6). The increase in weed management costs is directly related to the increased cost of hand-weeding. As the time to hand-weed increased, the subsequent cost increased by virtue of the cost being based on the hours needed to complete the task. With lint yields, the reduction from the increase in time required may be indicative of two influences: the increase in the number of Palmer amaranth plants in the plots that needed to be removed, which were subsequently competing with the cotton for resources, and inadvertent damage to cotton from the hand-weeding due to the large densities and sizes of Palmer amaranth. As the time required to hand-weed plots increased, partial returns decreased due to a reduction in cotton yield as well as the increased cost of management. As the cost of weed management increased, partial returns decreased, while cotton lint yields were not significantly impacted, suggesting that the use of simple, low-cost management strategies will result in similar yields and profits as the use of management strategies that cost more. These results should be taken with context, as this study only encompasses 2 yr of management and changes in soil seedbank dynamics may not be fully observational at this point in time, as Palmer amaranth seed may remain viable for approximately 4 to 5 yr (Jha et al. 2014; Korres et al. 2018). The risk of herbicide resistance development also may not be fully understood with this time frame, as previous studies have indicated that it takes at least two to three generations to develop resistance to herbicides like dicamba (Tehranchian et al. 2017; Vieira et al. 2019). Cotton yield and partial returns were influenced by a multitude of factors throughout the course of this study. Multiple correlation analyses revealed that yield and partial return were positively and linearly related to each other (Table 11) with an R^2 of 0.9808, an indication of the fact that the greatest influence on partial returns as they relate to weed management came from cotton yield (Figure 5).

Further research should be conducted to understand the long-term implications of these management strategies both ecologically and economically. The environmental conditions to which this long-term study was subjected were drastically different than each other, necessitating a continuation of this study to assess the impact of these management factors more accurately over a longer period and to generate better predictive and decision-making models for Palmer amaranth management. The findings from this research exemplify the need for integrated weed management practices to effectively manage Palmer amaranth. No single management practice effectively prevented Palmer amaranth from emerging and competing for resources in the field. Climatic factors also impacted the ability of several management factors to be effective. As a result, multiple integrated weed management strategies should be utilized to overcome any shortcomings and failures of other strategies. These recommendations echo and further reiterate the importance of utilizing best management practices when developing weed management programs in cotton (Norsworthy et al. 2012).

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