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Influence of timing of Palmer amaranth control in dicamba-resistant cotton on yield and economic return

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Research Article

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Abstract

Glyphosate-resistant (GR) Palmer amaranth continues to be challenging to control across the U.S. cotton belt. Timely application of POST herbicides and herbicides applied at planting or during the season with residual activity are utilized routinely to control this weed. Although glyphosate controls large Palmer amaranth that is not GR, herbicides such as glufosinate used in resistance management programs for GR Palmer amaranth must be applied when weeds are small. Dicamba can complement both glyphosate and glufosinate in controlling GR and glyphosate-susceptible (GS) biotypes in resistant cultivars. Two studies were conducted to determine Palmer amaranth control, weed biomass, and cotton yield, as well as to estimate economic net return when herbicides were applied 2, 3, 4, and 5 wk after planting (WAP). In one experiment POST-only applications were made. In the second experiment PRE herbicides were included. In general, Palmer amaranth was controlled at least 98% by herbicides applied at least three times regardless of timing of application or herbicide sequence. Glyphosate plus dicamba applied at 4 and 5 WAP controlled Palmer amaranth similarly compared to three applications by 8 WAP; however, yield was reduced 23% because of early-season interference. The inclusion of PRE herbicides benefited treatments that did not include herbicides applied 2 or 3 WAP. Glyphosate plus dicamba applied as the only herbicides 5 WAP provided 69% control of Palmer amaranth. PRE herbicides increased control to 96% for this POST treatment. Economic returns were similar when three or more POST applications were applied, with or without PRE herbicides.

Introduction

Early-season management of Palmer amaranth is critical in cotton production to maximize yield potential (Fast et al. 2009; MacRae et al. 2013; Norsworthy et al. 2016). Palmer amaranth continues to be one of the most challenging weed species to manage in cotton and other agronomic crops (Webster 2013). Implications of Palmer amaranth interference in cotton production have been well documented (Fast et al. 2009; MacRae et al. 2013; Morgan et al. 2001; Norsworthy et al. 2009; Rowland et al. 1999; Smith et al. 2000; Webster and Grey 2015). Vann et al. (2017a) reported cotton height reduction ranged from 7% to 57% and lint yield reductions from 8% to 42% when the first POST herbicide applications were delayed 7 to 28 d, respectively. Furthermore, prolonged insufficient control of Palmer amaranth can lead to a rapid increase in Palmer amaranth populations and contribution of seed to the soil seedbank (Inman et al. 2016).

Resistance management has been at the forefront of weed management programs in cotton production since glyphosate-resistant (GR) Palmer amaranth was first confirmed in 2005 (Culpepper et al. 2006). The use of soil-applied residual herbicides combined with timely POST applications and integrated management strategies have become requirements to effectively manage GR Palmer amaranth and other herbicide-resistant weeds (Culpepper et al. 2010; Norsworthy et al. 2012; Sosnoskie and Culpepper 2014). POST herbicide options are limited for cotton growers. Since the transition from GR cotton to glyphosate- and glufosinate-resistant cotton, growers have intensively relied on glufosinate (Barnett et al. 2013; Sosnoskie and Culpepper 2014). Glufosinate can be effective in controlling GR Palmer amaranth when timely applications are made (Barnett et al. 2013; Cahoon et al. 2015a; Corbett et al. 2004). However, control is generally reduced when glufosinate is applied to Palmer amaranth taller than 8 cm

(Coetzer et al. 2002; Culpepper et al. 2010). The rapid growth and competitive ability of Palmer amaranth (Ward et al. 2013) creates challenges for growers in making well-timed herbicide applications. In addition, at-plant residual herbicides may not control weeds adequately and may further decrease a grower's flexibility in making timely POST applications (Norsworthy et al. 2012).

The commercialization of dicamba-resistant cotton has provided growers with an additional POST option for managing GR Palmer amaranth (Cahoon et al. 2015b). Dicamba has proved to be an effective tank-mix partner in combinations with glyphosate or glufosinate for control of glyphosate-susceptible (GS) and GR Palmer amaranth (Cahoon et al. 2015b; Johnson et al. 2010; Merchant et al. 2013; York et al. 2012). Depending on POST application timing and location, late-season Palmer amaranth control was increased at least 14% and 41% when dicamba was tank-mixed with glufosinate and glyphosate, respectively, compared to when they were applied without dicamba (Cahoon et al. 2015b). Regardless of rate, POST mixtures of glufosinate and dicamba were more effective at controlling 16- to 23-cm Palmer amaranth 12 d after application compared to glufosinate or dicamba alone (Vann et al. 2017b). Similar findings were reported by Merchant et al. (2013), where a 17% to 22% increase in control was observed with 20-cm-tall Palmer amaranth when dicamba was included with glufosinate compared to glufosinate alone.

The performance of a POST herbicide application is related to herbicide rate, herbicide coverage, and susceptible weed size at application. Adequate weed control could be compromised when one or more of these components are not observed, thus increasing selection pressure of the herbicides applied and potentially contributing to herbicide resistance. With unpredictable weather conditions, executing timely herbicide applications can be challenging, as weed control may be reduced because of an increase in weed size (Stewart et al. 2010). The potential increase in cost, due to the possibility of applying an increased number of different herbicides at separate application timings, may lead to growers' reluctance to follow a well-timed spraying schedule. However, short-term and long-term benefits can be attained through weed management programs that offer greater diversity of herbicides and cultural practices (Inman et al. 2017; Jordan et al. 2014).

Although the importance of weed control timing has been well reported, only limited research in North Carolina has evaluated specific POST herbicide frequency and application timings in dicamba-resistant cotton. Furthermore, the peer-reviewed literature contains few data that address the economics of various weed management herbicide intensities in dicamba-resistant cotton. It is also important to understand how PRE herbicides can influence the dynamics of POST herbicide frequency. Therefore, two separate experiments were conducted to determine the most effective POST herbicide application timings in dicamba-resistant cotton. The objective for the first experiment was to compare different timings of POST herbicide applications of glufosinate and glyphosate plus dicamba on Palmer amaranth and annual grass control, cotton yield, and economic net returns without PRE herbicides. The objective for the second experiment was to follow the same POST timings and herbicides as experiment 1, comparing Palmer amaranth control, cotton yield, and economic net returns with and without PRE herbicides.

Table 1. Herbicide common names, trade names, application rates, and manufacturers.

Common name	Trade name	Rate	Manufacturer
		g ai or ae ha^{-1}	
Acetochlor	Warrant	840	Monsanto Co., St. Louis, MO
Dicamba	Xtendimax	560	Monsanto Co., St. Louis, MO
Diuron	Direx 4L	560	ADAMA, Raleigh, NC
Fomesafen	Reflex	175	Syngenta Crop Protection, Greensboro, NC
Glufosinate	Liberty 280SL	660	Bayer CropScience, Research Triangle Park, NC
Glyphosate	Roundup PowerMAX	946	Monsanto Co., St. Louis, MO

Table 2. Cotton growth stage and Palmer amaranth height at first POST application, averaged over all environments, for experiments 1 and 2

Application timing	Cotton growth stage	Palmer amaranth heights	
		Maximum	Average
		cm	
Wk after planting			
2	One leaf	7	3.5
3	Two- to three-leaf	15	9
4	Three- to five-leaf	30	18
5	Six- to eight-leaf	61	38

Materials and Methods

Experiment 1

Experiments were established in North Carolina across six environments during 2015 and 2016 near Clayton (35.67°N, 78.51°W) and Rocky Mount (35.89°N, 77.64°W). Soils in Clayton were a Dothan loamy sand (fine-loamy, kaolinitic, thermic Plinthic Kandiudults) with 0.27% humic matter. Soils in Rocky Mount were a Norfolk loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudults) with 0.5% humic matter. Dyna-Gro® cotton '3385 B2XF' (Crop Production Services, Loveland, CO) was planted in 2015. Cotton 'DP 1522 B2XF' (Monsanto, St Louis, MO) was planted in 2016. Cotton was planted in conventionally tilled, raised beds at a seeding rate of 14 seeds m^{-1} of row. Plot sizes ranged from three to four rows (91-cm spacing) by 9 to 12 m, depending on location. Other than treatments imposed for the experiment, cotton was managed according to North Carolina Cooperative Extension Service recommendations (Edmisten et al., 2015).

The experimental design was a randomized complete block with four replicates. Treatments consisted of POST herbicides applied 2, 3, 4, and 5 wk after planting (WAP); 3, 4, and 5 WAP; 4 and 5 WAP; and 5 WAP only. Additional treatments included herbicides applied 2 WAP only, 2 and 3 WAP, and 2, 3, and 4 WAP. Glufosinate was applied 2 and 3 WAP. At 4 and 5 WAP, glyphosate plus dicamba was applied. A nontreated control was also included. No PRE herbicides were applied at planting. Rates for all herbicides are provided in Table 1. All herbicides were applied using CO$_2$-pressurized backpack sprayers equipped with Turbo TeeJet® Induction 110025 nozzles (TeeJet Technologies, Wheaton, IL) calibrated to deliver 140 L ha^{-1} at 165 kPa.

All environments had natural infestations of Palmer amaranth with a mixture of GS and GR Palmer amaranth; density was 75 plants m^{-2} or greater. Palmer amaranth height and crop growth stage at each application timing can be found in Table 2. Most environments had dense populations of annual grass species ranging from 25 to 100 plants m^{-2}. Broadleaf signalgrass [*Urochloa platyphylla* (Munro ex C. Wright) R.D. Webster], goosegrass [*Eleusine indica* (L.) Gaertn.], large crabgrass [*Digitaria sanguinalis* (L.) Scop.], and Texas millet [*Urochloa texana* (Buckley) R.D.

Webster] were the dominant grass species. Palmer amaranth control was estimated visually using a 0 to 100 scale (Frans et al. 1986) and Palmer amaranth density recorded in each plot by counting the number of plants from a randomly determined 1 m^2 in each plot biweekly from 2 to 8 WAP. Palmer amaranth aboveground fresh biomass was collected from row middles in treated plots (17 to 23 m^2) within 3 wk prior to harvest and from 1 m^2 in the nontreated plots. Data collected for estimated visible control, densities, and aboveground biomass for annual grass were recorded in the same manner as Palmer amaranth. All treated plots were mechanically harvested in mid-October to mid-November with a spindle picker modified for small-plot harvesting.

Experiment 2

Experiments were established in North Carolina across four environments during 2016 and 2017 near Clayton (35.67°N, 78.51°W) and Rocky Mount (35.89°N, 77.64°W). Soils in Clayton were a Goldsboro sandy loam (fine-loamy, siliceous, subactive, thermic Aquic Paleudults) with 0.41% humic matter. Soils in Rocky Mount were an Aycock very fine sandy loam (fine-silty, siliceous, subactive, thermic Typic Paleudults) with 0.5% humic matter. Cotton 'DP 1522 B2XF' (Monsanto, St Louis, MO) was planted in 2016. Cotton 'DP 1538 B2XF' (Monsanto, St Louis, MO) was planted in 2017. Cotton was planted in conventionally tilled, raised beds at a seeding rate of 14 seed m^{-1} of row. Plot sizes were four rows (91-cm spacing) by 9 to 12 m, depending on location. Other than treatments imposed for the experiment, cotton was managed according to North Carolina Cooperative Extension Service recommendations (Edmisten et al., 2015).

The experimental design was a randomized complete block with four replicates. Treatments consisted of the same POST herbicide treatments as experiment 1 with and without PRE herbicides applied immediately after planting. The PRE herbicide program consisted of acetochlor plus diuron plus fomesafen. A nontreated control was also included. Rates for all herbicides are provided in Table 1. Each site received a minimum of 10 mm of rainfall within 2 wk of PRE herbicides being applied.

All environments had natural infestations of Palmer amaranth with a mixture of GS and GR Palmer amaranth; density was 100 plants m^{-2} or greater. Average Palmer amaranth height and crop growth stage at each application timing can be found in Table 2. Palmer amaranth control was estimated visually using a 0 to 100 scale (Frans et al. 1986) and Palmer amaranth density recorded in each plot by counting the number of plants from a randomly determined 1 m^2 in each plot biweekly from 2 to 8 WAP. Palmer amaranth aboveground fresh biomass was collected from row middles in treated plots (17 to 23 m^2) within 3 wk prior to harvest and from 1 m^2 in the nontreated plots. All treated plots were mechanically harvested in mid-October to mid-November with a spindle picker modified for small-plot harvesting.

For both experiments, estimated economic net return was calculated based on the North Carolina Cooperative Extension Service budget for cotton (Edmisten et al., 2015), with a total production cost of \$1,268.12 ha^{-1}, excluding herbicide cost. Herbicide cost was based on pricing from local chemical retailers and factored into total production cost. Ginning cost was based on seed cotton yield for each plot at a price of \$0.27 ha^{-1}. Economic return was calculated for three lint prices as the difference between the product of yield (45% lint at \$1.54 ha^{-1}, \$1.76 ha^{-1}, and \$1.98 ha^{-1} with 55% seed at \$0.30 ha^{-1}) and total production cost.

Data for both experiments were analyzed using the PROC Mixed procedure in SAS (v. 9.4; SAS Institute, Cary, NC). Treatments were considered a fixed factor, and replication and environment were considered random factors, as this allows inferences over a broad range of environments (Blouin et al. 2011; Carmer et al. 1989). Significant treatment-by-environment interactions for Palmer amaranth control, lint yield, and economic returns were observed for both experiments. Similar trends were found when environments were analyzed individually; therefore, analyses were combined across environments. Furthermore, the treatment mean square was at least 3-fold greater than the treatment-by-environment interaction mean square, providing justification to combine results over environments. Type III statistics were used to test all fixed effects, and least square means were calculated based on $P \le 0.05$ (Moore and Dixon 2015). Treatment means were separated using Fisher's Protected LSD at $P \le 0.05$.

Results and Discussion

Experiment 1. POST-Only Herbicide Treatments

Regardless of herbicide sequence, Palmer amaranth was controlled 98% or greater 8 WAP when herbicides were applied three times. When glyphosate and dicamba were applied twice (4 and 5 WAP), no difference in Palmer amaranth control was observed 8 WAP compared to treatments with at least three herbicide applications (Table 3). Control of Palmer amaranth declined to 71% when a single glyphosate plus dicamba application was delayed to 5 WAP. Vann et al. (2017a) reported 75% control of Palmer amaranth when the first POST application of glufosinate plus dicamba was delayed to 5 WAP. Glufosinate alone applied 2 WAP and 2 and 3 WAP controlled Palmer amaranth 58% and 82% 8 WAP, respectively. Although effective control was observed 14 d after treatment, longevity of herbicide applications at only 2 WAP and 2 and 3 WAP are not sufficient for season-long weed control. Trends among treatments for annual grass control were like that of Palmer amaranth control (Table 3). The greatest control was observed when at least three herbicide applications were delivered or when glyphosate and dicamba was applied 4 and 5 WAP. A single application of glyphosate plus dicamba 5 WAP controlled annual grasses 85%, compared to glufosinate alone 2 WAP or 2 and 3 WAP resulting in 60% and 89% control, respectively. Glyphosate is generally more effective than glufosinate on grass species, especially goosegrass (Corbett et al. 2004; Culpepper et al. 2000). Average aboveground biomass for the nontreated check was 21,500 kg ha^{-1} and 11,200 kg ha^{-1} for Palmer amaranth and annual grasses, respectively (data not shown). Treatments comprising three or more herbicide applications reduced Palmer amaranth biomass at least 96% (data not shown). Annual-grass biomass was reduced at least 93% with three or more herbicide applications or sequential applications of glyphosate plus dicamba at 4 and 5 WAP.

When at least three herbicide applications were made, no difference in cotton lint yield was observed regardless of timing sequence (Table 4). However, yields following three applications at 2, 3, and 4 WAP were lower compared to yields following herbicides applied at 3, 4, and 5 WAP and 2, 3, 4, and 5 WAP. Buchanan and Burns (1970) suggested that cotton should be maintained weed-free for approximately 8 WAP to protect maximum yields. Although weed control 8 WAP was similar between these application timings, the lack of herbicide beyond 4 WAP proved to be critical by the end of the season. Despite sequential applications of glyphosate plus

Table 3. Palmer amaranth and annual grass control 8 wk after planting (WAP) as affected by POST only application timing in experiment 1, conducted in North Carolina in 2015 and 2016.[a]

Herbicides and application timings WAP					
2	3	4	5	Palmer amaranth control	Annual grass control[b]
				%	%
Glufosinate	Glufosinate	Glyphosate + dicamba	Glyphosate + dicamba	100 a	100 a
–	Glufosinate	Glyphosate + dicamba	Glyphosate + dicamba	99 a	99 a
–	–	Glyphosate + dicamba	Glyphosate + dicamba	92 ab	94 ab
–	–	–	Glyphosate + dicamba	71 c	85 c
Glufosinate	–	–	–	58 d	60 d
Glufosinate	Glufosinate	–	–	82 bc	89 bc
Glufosinate	Glufosinate	Glyphosate + dicamba	–	98 a	97 a

[a]Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at $P \leq 0.05$. Data are pooled over six environments. Nontreated control was not included in data analysis.
[b]Annual grass consisted of broadleaf signalgrass, goosegrass, large crabgrass, and Texas millet.

Table 4. Lint yield and economic net return as affected by POST application timing, in experiment 1, conducted in North Carolina in 2015 and 2016.[a]

					Economic net return[c]		
Herbicides and application timings WAP[b]					Cotton price \$ kg^{-1}		
2	3	4	5	Lint yield	1.54	1.76	1.98
				kg ha^{-1}	\$ ha^{-1}	\$ ha^{-1}	\$ ha^{-1}
Glufosinate	Glufosinate	Glyphosate + dicamba	Glyphosate + dicamba	780 a	−151 a	21 a	193 a
–	Glufosinate	Glyphosate + dicamba	Glyphosate + dicamba	740 a	−175 a	−12 a	151 ab
–	–	Glyphosate + dicamba	Glyphosate + dicamba	545 bc	−456 ab	−337 ab	−217 bc
–	–	–	Glyphosate + dicamba	300 de	−814 cd	−746 cd	−680 de
Glufosinate	–	–	–	135 e	−1,088 de	−1,058 de	−1,029 ef
Glufosinate	Glufosinate	–	–	470 cd	−582 bc	−478 bc	−375 cd
Glufosinate	Glufosinate	Glyphosate + dicamba	–	710 ab	−231 a	−75 a	82 ab
–	–	–	–	2 f	−1,265 e	−1,265 e	−1,265 f

[a]Means within each column followed by the same letter are not different according to Fisher's Protected LSD test at $P \leq 0.05$. Data are pooled over six environments.
[b]Abbreviations: WAP, weeks after planting.
[c]Cotton price based on 45% lint and 55% cottonseed.

dicamba applied 4 and 5 WAP providing similar weed control compared to three or more herbicide applications, early-season weed interference reduced lint yield 23% to 30% (Table 3). Vann et al. (2017a) reported a 23% reduction in lint yield when the first POST application was delayed 14 d. Furthermore, Everman et al. (2007) reported a 72% reduction in lint yield when no early-POST herbicide was used compared to glufosinate alone early POST. Glufosinate alone at 2 WAP provided the lowest yields. Similar yields were observed with glufosinate at 2 and 3 WAP and a single application of glyphosate plus dicamba 5 WAP (Table 4). Comparable to yield trends, economic net returns were highest following three or four herbicide applications. Although cotton lint yield was lower for sequential applications of glyphosate plus dicamba (4 and 5 WAP), reductions in herbicide cost allowed for similar returns compared to three and four applications (Table 4).

Experiment 2. PRE and POST Herbicide Treatments

All POST herbicide sequences provided similar or greater control of Palmer amaranth when following PRE herbicides (Table 5). Palmer amaranth was controlled 99% or greater 8 WAP when three POST herbicide applications were made, with or without the use of PRE herbicides. Palmer amaranth control increased by 30%, 27%, 8%, and 8% with POST timings 2 WAP only, 5 WAP only, 2 and 3 WAP, 4 and 5 WAP with PRE herbicides compared to no PRE, respectively. The PRE herbicide program alone provided 79% control of Palmer amaranth, like sequential POST herbicide applications at 2 and 3 WAP. Previous studies have shown excellent Palmer amaranth control by fomesafen applied PRE alone or in combination with acetochlor and/or diuron (Cahoon et al. 2015c; Whitaker et al. 2011). The importance of PRE herbicides has been well documented in combating herbicide-resistant Palmer amaranth and reducing early-season weed interference (Everman et al. 2009; Norsworthy et al. 2012; Whitaker et al. 2011).

Although not always significant, greater cotton lint yields were observed when the PRE herbicide program was used compared with no PRE herbicides (Table 5). There were no differences in lint yields when at least three POST applications were applied, regardless of timing sequence or PRE herbicides. The PRE herbicide program alone resulted in yields similar to that of POST-only applications at 2 WAP, 2 and 3 WAP, and 5 WAP. The inclusion of PRE herbicides allowed for greater flexibility in the number of POST application timings. This was more evident with later POST application timings, 4 and 5 WAP, and 5 WAP only, compared to early application timings, 2 WAP and 2 and 3 WAP. Everman et al. (2007) reported similar findings, showing that cotton lint yields were comparable when PRE and POST-directed herbicide applications were made regardless of a mid-POST application.

Trends for economic returns among treatments were similar to that of cotton lint yield. Although inclusion of a PRE treatment increased costs, greater returns were observed when the PRE

Table 5. Palmer amaranth control 8 wk after planting (WAP) and lint yield in response to POST application timing with and without PRE herbicides, in experiment 2 conducted in North Carolina in 2016 and 2017.[a]

POST Herbicides and application timings WAP				Palmer amaranth control		Lint yield	
2	3	4	5	No PRE	PRE	No PRE	PRE
				%		kg ha^{-1}	
Glufosinate	Glufosinate	Glyphosate + dicamba	Glyphosate + dicamba	100 a	100 a	770 a	780 a
–	Glufosinate	Glyphosate + dicamba	Glyphosate + dicamba	99 ab	100 a	700 ab	820 a
–	–	Glyphosate + dicamba	Glyphosate + dicamba	91 abc	99 ab	500 bc	770 a
–	–	–	Glyphosate + dicamba	69 e	96 ab	150 de	685 ab
Glufosinate	–	–	–	55 f	85 cd	80 e	390 cd
Glufosinate	Glufosinate	–	–	81 bc	89 bcd	310 cd	370 cd
Glufosinate	Glufosinate	Glyphosate + dicamba	–	99 ab	100 a	670 ab	755 a
–	–	–	–	–	79 de	14 e	225 de

[a] Means within columns (Palmer amaranth control or lint yield) followed by the same letter are not different according to Fisher's Protected LSD test at $P \leq 0.05$. Data are pooled over four environments. Nontreated for Palmer amaranth control was not included in data analysis.

Table 6. Influence of POST application timing with and without PRE herbicides on economic net return.[a]

Herbicides and application timings WAP[b]				Economic net return					
				Cotton price \$ kg^{-1}					
				1.54		1.76		1.98	
2	3	4	5	No PRE	PRE	No PRE	PRE	No PRE	PRE
				\$ ha^{-1}					
Glufosinate	Glufosinate	Glyphosate + dicamba	Glyphosate + dicamba	–172 a	–184 ab	–3 a	–11 ab	166 a	161 ab
–	Glufosinate	Glyphosate + dicamba	Glyphosate + dicamba	–244 ab	–88 a	–91 ab	92 a	63 ab	272 a
–	–	Glyphosate + dicamba	Glyphosate + dicamba	–529 bc	–122 a	–420 bc	48 a	–310 bc	218 a
–	–	–	Glyphosate + dicamba	–1,059 def	–226 ab	–1,026 def	–75 ab	–933 def	75 ab
Glufosinate	–	–	–	–1,174 ef	–715 cd	–1,156 ef	–630 cd	–1,137 ef	–544 cd
Glufosinate	Glufosinate	–	–	–847 cde	–788 cde	–779 cde	–707 cd	–710 cde	–625 cd
Glufosinate	Glufosinate	Glyphosate + dicamba	–	–293 ab	–194 ab	–146 ab	–27 ab	2 ab	139 ab
–	–	–	–	–1,245 f	–942 def	1,240 f	–892 de	1,240 f	–843 de

[a] Means within pricing columns (comparison of No PRE and PRE) followed by the same letter are not different according to Fisher's Protected LSD test at $P \leq 0.05$. Data are pooled over four environments.

[b] Abbreviation: WAP, weeks after planting.

was implemented with one or two POST application timings compared to programs without a PRE (Table 6). This was more evident when POST timings were delayed until 4 WAP, compared to timings at 2 WAP. Excellent weed control was obtained with the PRE herbicide program, and the POST application 2 WAP was not warranted in most cases, as no weeds had emerged. Highest economic returns were observed when the PRE herbicide program was included with POST application timings of 4 followed by 5 WAP and 5 WAP alone (Table 6). This can further be attributed to the differences in weed interference at critical growth stages (Buchanan and Burns 1970). There was no difference in economic returns when herbicides were applied at least three times, irrespective of PRE herbicide treatment. These data show the importance of timely herbicide applications and herbicide program cost in relation to cotton lint prices. When cotton lint prices are low, it would be more cost-efficient to ensure timely herbicide applications compared to a delay, as this would help prevent follow-up herbicide applications. As cotton lint prices increase, there may be more flexibility in costs associated with increased herbicide use or applications.

Total POST herbicide programs can be successful in some situations (Askew and Wilcut 1999; Burke et al. 2005; Culpepper and York 1998; Jordan et al. 1993). However, timely applications are critical when soil-applied herbicides are not included (Culpepper and York 1999; Vann et al. 2017a). These data show that excellent Palmer amaranth control was achieved when three or more timely POST applications were utilized. Similar weed control can be obtained with sequential applications of glyphosate plus dicamba at 4 and 5 WAP. However, cotton lint yields could be reduced as a result of early-season weed interference. Although effective at the time, POST-only weed management programs most likely contributed to a more rapid evolution of herbicide resistance due to less diversity of herbicide mechanisms of action and spraying of larger weeds resulting in partial control (Beckie 2006). Furthermore, soil weed seedbank dynamics should be included in weed management programs (Buhler et al. 1997; Norsworthy et al. 2018). Control of larger weeds is obtainable, but weed seed contribution is unknown when weeds are not completely controlled. This research demonstrates that even when adequate weed control is obtained with larger weeds, early-season weed interference can still adversely affect cotton yield. The use of PRE herbicides can offset missed early-season weed control efforts by providing similar yields and economic returns compared to timely, early-POST applications. Timely POST herbicide applications contribute to greater weed efficacy that leads to higher yields, and though not quantified in this study, reduce weed seed contribution to the soil seedbank. Yield was consistently greater across all POST treatments that included PRE herbicides. Economic returns were greater among treatments that included PRE applications, except for the four POST application program, where returns were similar. Management tactics aside from herbicides should be better understood. Future research should explore how herbicide frequency and timings in combination with other control factors such as cover crops, tillage, and rotation of herbicide-resistant crop varieties can be used most efficiently.

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