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Palmer amaranth control in furrow-irrigated rice with florpyrauxifen-benzyl

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Abstract

Palmer amaranth is a common weed on levees in rice fields but has become increasingly problematic with the adoption of furrow-irrigated rice and lack of an established flood. Florpyrauxifen-benzyl previously has been found effective for controlling Palmer amaranth in rice, but the efficacy of low rates of florpyrauxifen-benzyl and the effect of Palmer amaranth size on controlling it is unknown. The objective of this research was to determine the level of Palmer amaranth control expected with single and sequential applications of florpyrauxifen-benzyl at varying weed heights. The first study was conducted near Marianna, AR, in 2019 and 2020, to determine the effect of florpyrauxifen-benzyl rate on control of <10 cm (labeled size) and 28- to 32-cm-tall (larger-than-labeled size) Palmer amaranth. The second experiment was conducted in 2020 at two locations in Arkansas to compare single applications of florpyrauxifen-benzyl at low rates to sequential applications at the same rates with a 14-d interval on 20- and 40-cm-tall Palmer amaranth. Results revealed that florpyrauxifen-benzyl at 15 g ae ha^{-1} was as effective as 30 g ae ha^{-1} in controlling <10-cm-tall Palmer amaranth (92% and 95% mortality in 2019). Sequential applications of florpyrauxifen-benzyl at 8 g ae ha^{-1} were as effective as single or sequential applications at 30 g ae ha^{-1}. However, no rate of florpyrauxifen-benzyl applied to 20- or 40-cm-tall Palmer amaranth was sufficient to provide season-long control of the weed, with the escaping female plants producing as many as 6,120 seed per plant following a single application.

Introduction

In Arkansas, 10.5% of rice hectares produced in 2019 were furrow-irrigated (Hardke 2020). Furrow irrigation is an agronomic practice in which rice is drill-seeded on elevated beds, similar to popular methods used to plant corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybean [*Glycine max* (L.) Merr.] in mid-South crop production (Norsworthy et al. 2011). While flood-irrigated rice necessitates a continuous flood from the V5 stage until rice maturity, furrow-irrigated rice uses irrigation water that is distributed throughout fields through the furrows between beds via polyethylene pipes on the elevated end of a field (Counce et al. 2000). Although yields from traditionally direct-seeded, delayed-flood rice typically surpass those of furrow-irrigated rice, there are advantages to producing rice without a continuous flood (Tacker 2007; Vories et al. 2002). Depending on soil texture, cropping systems, and other factors faced by a producer, furrow irrigation of rice can reduce water use and other input costs such as field preparation between crop rotations (Tracy et al. 1993; Vories et al. 2002).

The act of flooding a rice field provides more benefits to producers than irrigation alone. While flooded rice creates the anaerobic conditions used to stop germination of certain weed species buried in the soil seedbank, furrow-irrigated rice supplies weed species with enough moisture and oxygen to germinate and grow (Henry et al. 2018). Terrestrial weeds found to be problematic in flooded rice such as barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.], sprangletops (*Leptochloa* ssp.), and sedges (*Cyperus* ssp.) can still emerge and thrive in furrow-irrigated rice because of the moist environment. However, furrow irrigation also allows an aerobic environment that is conducive to typical upland crop pests such as Palmer amaranth (Norsworthy et al. 2011), which was recently found to be the second most problematic weed of furrow-irrigated rice in Arkansas in a 2020 survey (TRB and JKN, nonpublished data).

Palmer amaranth is the most problematic weed in cotton (*Gossypium* ssp.) and soybean (*Glycine max* ssp.) production in the mid-South and was the fifth most troublesome weed in rice production, prior to the rapid increase in popularity of furrow-irrigated rice (Riar et al. 2012; Van Wychen 2020). Palmer amaranth historically has been a nuisance on levees, but shifting from flood irrigation to furrow irrigation increases the likelihood of Palmer amaranth as a problematic pest. The impact of Palmer amaranth on cotton and soybean production in the southern United States has been well documented (Klingaman and Oliver 1994; Rowland et al. 1999). Little is known about the consequences of Palmer amaranth on rice yields because historically the crop has been grown in the southern United States with a flood established at the V5 growth stage, leading to conditions that are unsuitable for season-long survival of Palmer amaranth. However, as the acreage planted to furrow-irrigated rice continues to increase along with the prevalence of Palmer amaranth in this system, there is a need to develop strategies to manage this weed in rice and understand the impact of its presence on the crop.

Herbicide options for Palmer amaranth control in rice are limited. Palmer amaranth has already evolved resistance to seven known sites of action in Arkansas alone, further limiting effective herbicide options for rice producers (Heap 2021). Among the herbicides that are no longer effective for controlling Palmer amaranth are protoporphyrinogen oxidase (PPO) inhibitors (categorized as a Group 14 herbicide by the Weed Science Society of America [WSSA]) and acetolactate synthase (ALS) inhibitors (WSSA Group 2), formerly common options for the control of Palmer amaranth in rice. Applications of 2,4-D were previously recommended for Palmer amaranth control on levees; however, some regulations restrict the use of 2,4-D in certain areas due to the risk for off-target movement of the herbicide and the susceptibility of other prominent crops in the area (ASPB 2020).

Florpyrauxifen-benzyl (Loyant) is a synthetic auxin herbicide (WSSA Group 4) released by Corteva Agriscience in 2018 for pre-flood control of grass and broadleaf weed species in rice fields (Anonymous 2018). Florpyrauxifen-benzyl at the labeled rate of 30 g ae ha^{-1} has been effective in controlling Palmer amaranth in furrow-irrigated rice with greater than 97% control (Wright et al. 2020). In greenhouse studies, florpyrauxifen-benzyl at 10 g ae ha^{-1}, one-third of the labeled use rate in rice, controlled Palmer amaranth by 84%, indicating that applications under the labeled rate may provide effective control if applied to small weeds or it is used sequentially as part of a herbicide program (Miller and Norsworthy 2018). The objective of the studies conducted in this research were to 1) determine the level of Palmer amaranth control that could be expected following a single application of florpyrauxifen-benzyl to labeled and larger-than-labeled weed sizes; and 2) determine the efficacy, crop injury, and impact on weed-seed production with single versus sequential applications of florpyrauxifen-benzyl at varying rates on larger-than-labeled size Palmer amaranth.

Materials and Methods

Optimizing the Rate and Timing of Florpyrauxifen-Benzyl on Palmer Amaranth

A field experiment with a randomized complete block design with four replications was initiated to determine the efficacy of single applications of florpyrauxifen-benzyl on multiple sizes of Palmer amaranth at the Lon Mann Cotton Research Station in Marianna, Arkansas, in 2019 and 2020. The soil at the site of both experiments was a Convent silt loam consisting of 9% sand, 80% silt, 11% clay, and 1.8% organic matter, pH 6.5. Hybrid, long-grain rice cultivar 'Gemini 214CL' (RiceTec Inc., Alvin, TX) was planted in 2019. Due to discontinuation and subsequent shortages of Gemini 214CL, hybrid, long-grain rice cultivar 'Full Page RT 7521FP' (RiceTec Inc.) was sown in 2020. The ground was tilled prior to planting, hipped into 96-cm-wide beds and received a preemergence burndown application of glyphosate at 4.5 kg ha^{-1} (Roundup PowerMax II; Bayer CropScience, Research Triangle Park, NC). Following ground preparation, rice was planted at a rate of 36 seeds per meter row with an 18-cm row spacing. Plot dimensions were established as 3.6 m wide (four 96-cm-wide beds) by 6 m long, totaling 21 m^2. Native populations of Palmer amaranth were allowed to germinate following the planting of the rice. The experiment was kept free of weeds other than Palmer amaranth using applications of cyhalofop-butyl (Clincher SF; Corteva Agriscience, Wilmington, DE) and hand weeding if necessary. Once rice reached the 2-leaf stage, it was irrigated every 3 d unless rainfall occurred, and irrigation was deemed unnecessary. Nitrogen was applied at 135 kg N ha^{-1} as urea (460 kg N ha^{-1}) in three split applications with intervals of 1 wk following 5-leaf rice. Other nutrients were applied preplant based on soil test values.

The experiment was set up as a two-factor factorial with a randomized complete block design, with the first factor being application rate of florpyrauxifen-benzyl at 8, 15, 23, and 30 g ae ha^{-1}, and the second factor being Palmer amaranth height at application. All applications of florpyrauxifen-benzyl included methylated seed oil at 0.58 L ha^{-1} and pendimethalin at 363 g ai ha^{-1} to minimize further Palmer amaranth emergence throughout the trial. Applications were made to 5- to 7.5-cm-tall and 28- to 32-cm-tall Palmer amaranth, as the former is within the labeled size requirement, and the latter is a larger-than-labeled size (Anonymous 2020). All herbicides were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} at 276 kPa using four 110015 AIXR nozzles spaced 48 cm apart (TeeJet Technologies, Springfield, IL). A nontreated control was included in the design as well as a treatment that was maintained weed free via hand weeding throughout the growing season.

Prior to application, two 1-m^2 quadrats were established per plot and Palmer amaranth densities were recorded from each quadrat (Table 1). Visible estimations of Palmer amaranth control (control ratings) were taken 21 and 28 d after final treatment (DAT) on a 0 to 100 scale, with 0 indicating no plant symptomology and 100 representing plant death. Before the plots were harvested, Palmer amaranth plants in each designated quadrat were counted to determine the percent mortality achieved by the herbicide application, based on the assumption that no Palmer amaranth emerged following application, with suppression of further emergence provided by the pendimethalin application and rice canopy cover. The center of each plot was harvested once the rice had matured using an Almaco (Almaco, Nevada, IA) plot combine with a 1.7 m width. Yields from each plot were adjusted to 12% moisture and reported relative to the corresponding weed-free check to determine the percent reduction in yield caused by the presence of Palmer amaranth.

Salvage Applications of Florpyrauxifen-Benzyl on Palmer Amaranth

An experiment was conducted in 2020 at the Lon Mann Cotton Station in Marianna, Arkansas (Convent silt loam, 9% sand, 80% silt, 11% clay, and 1.8% organic matter, pH 6.5) and at the Pine Tree Research Station near Colt, Arkansas (Calhoun silt loam, 10% sand, 69% silt, 21% clay, and 1.3% organic matter, pH 7.5) to determine the efficacy of variable rates of florpyrauxifen-benzyl applied once and in sequential applications on 20- and 40-cm-tall

Table 1. Palmer amaranth densities and average heights from experiment analyzing single applications of multiple rates of florpyrauxifen-benzyl conducted at the Lon Mann Cotton Research Station in 2019 and 2020.

Species	Application timing	2019		2020	
		Height	Density	Height	Density
		cm	# m^{-2}	cm	# m^{-2}
Palmer amaranth	First	5	61	7.5	80
	Second	28	102	32	104

Table 2. Palmer amaranth heights and densities collected from studies determining the optimum rate and number of applications of florpyrauxifen-benzyl on large Palmer amaranth conducted at both locations in 2020.

Species	Marinna 2020		Colt 2020	
	Height	Density	Height	Density
	Cm	# m^{-2}	cm	# m^{-2}
Palmer amaranth	20	22	20	4
	40	48	40	4

Palmer amaranth. The trials were planted and maintained similarly to the previously described experiment; however, in both trials, hybrid rice 'Full Page RT 7521FP' (RiceTec Inc.) was planted at 36 seeds per meter row on 96-cm-wide beds at Marianna and 76-cm-wide beds at Colt. Plots were four hip-rows wide and 6 m long at both locations, making plots 21 m^2 at Marianna and 18.24 m^2 at Colt. An application of clomazone (Command 3ME; FMC Corporation, Philadelphia, PA) at 560 g ha^{-1} was made at planting to minimize emergence of weed species other than Palmer amaranth. Clomazone has no activity on Palmer amaranth, as indicated by the Command 3ME label (Anonymous 2019). The experiment was again kept free of grass weeds using fenoxaprop, cyhalofop, and hand weeding when necessary. Three applications of nitrogen at 56 kg N ha^{-1} as urea (460 g N kg^{-1}) were applied at 1-wk intervals following the 5-leaf rice growth stage, and the test area was irrigated every 3 d following the 2-leaf stage of rice unless rainfall occurred.

The experiment was conducted as a randomized complete block design with a three-factor factorial treatment structure. The first factor was florpyrauxifen-benzyl rates of 8, 15, 23, and 30 g ae ha^{-1}. All applications included 0.58 L ha^{-1} of methylated seed oil and pendimethalin at 363 g ai ha^{-1} to minimize further weed emergence. The second factor was Palmer amaranth size: 20- and 40-cm-tall plants. The third factor was number of applications made. Single applications of the aforementioned rates were used as well as sequential applications of the same rates at a 14-d interval. A weedy nontreated control and a hand-weeded weed-free control were included.

Before application, two 1-m^2 quadrats were established in each plot, and Palmer amaranth densities were recorded in each meter square before the initial application at each size (Table 2). Visual estimations of Palmer amaranth control (control ratings) were rated 21 and 28 d after final application on the same 0 to 100 scale as described previously. All Palmer amaranth plants in each plot were counted at the time of harvest. All female Palmer amaranth plants in each plot were counted and harvested by hand, dried to constant mass, and ground. A 0.5-g subsample of the ground plant matter from each plot was weighed, and the number of Palmer amaranth seeds in each subsample was recorded (Schwartz et al. 2016). The average seed production per female Palmer amaranth plant was calculated by dividing the total seeds produced by the number of female Palmer amaranth per plot. The number of seeds per square meter was calculated using the total number of Palmer amaranth seeds produced and the area of the plot. Rough rice grain yield was determined by harvesting the center two hip-rows and beds of each plot using an Almaco small-plot combine with a 1.7-m-wide header. Grain yield was adjusted to 12% moisture.

Data Analysis

Data were analyzed using R statistical software v. 4.0.3 (R Core Team, Vienna, Austria). Data were checked to determine whether the assumptions of normality and homogeneous variance were met using the Shapiro-Wilk test and Levene's test. The test result suggested that nonparametric analysis (Kniss and Streibig 2018) was appropriate. Specifically, weed control ratings from both experiments, as well as live Palmer amaranth counts, seed production per female Palmer amaranth plant, and seed per square meter estimates were analyzed using the RANKFD package in R (Brunner et al. 1997, 2019), which is known to be useful to evaluate the interaction effect in factorial models. Rough rice grain yield data from both trials were reported and analyzed as a percent of the nontreated control. Site-year was originally included as a factor in the model for both experiments and was found to be highly significant ($P < 0.0001$) in most interactions due to differing levels of efficacy observed by site-year in both experiments; therefore, the experiments were analyzed separately by site-year to simplify results.

Results and Discussion

Optimizing the Rate and Timing of Florpyrauxifen-Benzyl on Palmer Amaranth

Florpyrauxifen-benzyl rate and Palmer amaranth size significantly ($P < 0.05$) affected Palmer amaranth control when it was recorded 21 and 28 d after treatment in both site years, and florpyrauxifen-benzyl rate was also significant when mortality in 2020 was analyzed (Table 3). Weed control ratings from 21 and 28 DAT in 2019 and 2020 led to the conclusion that Palmer amaranth control was increased over the rates tested when florpyrauxifen-benzyl was applied at 23 or 30 g ae ha^{-1}, averaged over Palmer amaranth sizes (82% to 89% control, 28 DAT in 2019; Table 4). Observations from mortality data indicated that florpyrauxifen-benzyl at 15 g ae ha^{-1} was as effective at 23 or 30 g ae ha^{-1}, albeit there was a 19-percentage point numerical decrease in mortality in 2020 as florpyrauxifen-benzyl rate decreased from 23 to 15 g ae ha^{-1} averaged across Palmer amaranth size. The difference in results from percent mortality versus weed control ratings can be attributed to Palmer amaranth being injured, malformed, and stunted by applications of florpyrauxifen-benzyl at 15 g ae ha^{-1}, and eventually succumbing to the rice canopy. Based on the mortality data, it appears that florpyrauxifen-benzyl applied at lower-than-labeled rates can achieve similar control to that of labeled applications. These findings are comparable to those reported by Miller and Norsworthy (2018) when florpyrauxifen-benzyl at 20 g ae ha^{-1} controlled 20-cm-tall Palmer amaranth by 84%, whereas 23 g ae ha^{-1} achieved 82% control in this experiment. However, applications of florpyrauxifen-benzyl at any rate tested did not achieve 100% Palmer amaranth control or mortality, with the surviving plants producing seed.

Table 3. P-values derived by factor of Palmer amaranth control ratings, rough rice grain yield, and Palmer amaranth mortality by site year from the experiment conducted at the Lon Mann Cotton Station in 2019 and 2020.[a,b]

	2019				2020			
	Palmer amaranth control				Palmer amaranth control			
Factor	21 DAT	28 DAT	Yield	Mortality	21 DAT	28 DAT	Yield	Mortality
	Prob. > *F*							
Rate	0.0013*	0.0073*	0.1062	0.0802	0.0019*	0.0003*	0.5147	0.0001*
Timing	<0.0001*	0.0002*	0.8076	0.0669	<0.0001*	<0.0001*	0.1689	0.1004
Rate × Timing	0.0692	0.4008	0.1891	0.3034	0.1282	0.7062	0.2937	0.0771

[a]Abbreviation: DAT, days after treatment.
[b]P-values followed by * are significant (α = 0.05).

Table 4. Palmer amaranth control 21 and 28 d after treatment and percent mortality, and rough rice grain yield at the Lon Mann Cotton Research Station in 2019 and 2020.[a–f]

		2019				2020			
		PA Control				PA Control			
Factor		21 DAT	28 DAT	Yield	Mortality	21 DAT	28 DAT	Mortality	Yield
Rate	g ha^{-1}	%							
	8	68 b	76 b	66	82	49 b	44 b	35 b	63
	15	70 ab	79 b	72	92	54 b	53 b	63 ab	64
	23	72 ab	82 ab	72	91	65 ab	72 a	84 a	70
	30	87 a	89 a	71	95	75 a	66 a	88 a	76
Timing cm									
	5–7.5	84 a	87 a	74	97	71 a	79 a	73	70
	28–32	64 b	76 b	66	89	51 b	38 b	63	66

[a]Abbreviations: PA, Palmer amaranth; DAT, days after treatment.
[b]Rough rice grain yield as a percentage of weed-free check.
[c]Mortality represented as percentage of Palmer amaranth population at time of harvest divided by density at time of application.
[d]All applications included 0.58 L ha^{-1} methylated seed oil and pendimethalin at 363 g ai ha^{-1}.
[e]Means within the same column followed by the same letter are not different according to Tukey's adjusted honestly significant difference test (α = 0.05); if no letter is present, no statistical difference was observed.
[f]Rice in the weed-free control produced 8,790 kg ha^{-1}in 2019 and 9,280 kg ha^{-1} in 2020.

Thus, there is a need for sequential applications of florpyrauxifen-benzyl or its use with other herbicides as noted elsewhere (Wright et al. 2020).

For herbicides labeled for Palmer amaranth control in other crops, such as dicamba (WSSA Group 4), it is recommended that applications be made before plants reach 10 cm in height (Anonymous 2020). Palmer amaranth control ratings from our studies show the importance of florpyrauxifen-benzyl being applied timely to labeled-sized weeds to maximize control, which should translate into higher mortality of the weed and possibly greater crop yield, although statistical differences in these latter two assessments could not be detected (Table 4).

Rough rice grain yield, averaged across Palmer amaranth size, ranged from 66% to 72% of the weed-free check in 2019, and 63% to 76% in 2020, but no differences were determined via florpyrauxifen-benzyl rate or Palmer amaranth size (Table 4). End-of-season mortality ratings of Palmer amaranth also never exceeded 95%. At the Palmer amaranth densities present in this study, rice yields were often reduced by more than 25% relative to the weed-free check, even when florpyrauxifen-benzyl was applied (Table 4). The yield losses caused by Palmer amaranth in these studies further strengthen the recommendation of beginning with an effective residual herbicide at planting and overlaying residual herbicides in furrow-irrigated rice, with postemergence herbicides like florpyrauxifen-benzyl used only to control the few escapes not controlled by the residual herbicides (Bagavathiannan et al. 2012). The significant seed production from Palmer amaranth plants escaping the florpyrauxifen-benzyl application also justifies the need for a zero-tolerance approach for management of Palmer amaranth in furrow-irrigated rice, especially considering that the crop will most likely be rotated to soybean where auxin herbicides are now heavily relied upon for control of this troublesome, resistance-prone weed.

Salvage Applications of Florpyrauxifen-Benzyl on Palmer Amaranth

Findings indicated the importance of florpyrauxifen-benzyl rate, Palmer amaranth size, and the number of applications made when attempting to control Palmer amaranth in furrow-irrigated rice (Table 5). Weed control ratings collected from this study again lead to the conclusion that when using single applications of florpyrauxifen-benzyl, control of 20-cm-tall Palmer amaranth is maximized using florpyrauxifen-benzyl at 23 to 30 g ae ha^{-1}; however, sequential applications of florpyrauxifen-benzyl at as little as 8 g ae ha^{-1} with a 14-d interval are equally as effective (Table 6). When applied to 20-cm-tall Palmer amaranth, single applications of florpyrauxifen-benzyl at 23 g ae ha^{-1} achieved 79% Palmer amaranth control, while sequential applications of 8 g ae ha^{-1} reached 76% by 28 DAT (Table 6). Once Palmer amaranth reached an

Table 5. P-values derived by factor from control ratings, rough rice grain yield, Palmer amaranth mortality, and seed production by site year from experiments conducted at both locations in 2020.[a–d]

Location	Variable	Rate	Size	App	Rate × Size	Rate × App	Size × App	Rate × Size × App
		———	———	———	Prob. > *F*	———	———	———
Marianna	PA control 21 DAT	<0.0001*	<0.0001*	0.0493*	0.0170*	0.3958	0.3912	0.0150*
	PA control 28 DAT	<0.0001*	<0.0001*	<0.0001*	0.0023*	0.9931	0.0295*	< 0.0001*
	Yield	0.2804	0.6809	0.1139	0.3432	0.0002*	0.0118*	0.0707
	Live counts per hectare	0.0011*	0.0202*	<0.0001*	0.1997	0.4582	0.5649	0.6342
	Seed per female plant	0.1838	0.0024*	<0.0001*	0.2294	04288	0.3247	0.3157
	Seed per square meter	0.0476*	0.0006*	<0.0001*	0.6366	0.4842	0.8642	0.7768
Colt	PA control 21 DAT	0.0002*	0.4041	<0.0001*	0.2558	0.9937	0.9731	0.7707
	PA control 28 DAT	<0.0001*	<0.0001*	<0.0001*	0.0297*	0.0251*	0.1439	0.0029*
	Yield	0.0247*	0.0031*	0.0191*	0.1306	0.4735	0.1758	0.0281*
	Live counts per hectare	0.0021*	0.1472	0.0009*	0.4853	0.4160	0.8319	0.5257
	Seed per female plant	0.0047*	0.0184*	0.0031*	0.9759	0.9326	0.3247	0.3157
	Seed per square meter	0.0088*	0.0289*	0.0026*	0.0939	0.8586	0.3330	0.3347

[a]Rate of florpyrauxifen-benzyl (8, 15, 23, 30 g ae ha^{-1}).
[b]Height of Palmer amaranth at time of application (20 and 40 cm), number of applications made (1 versus 2 with 14-d interval).
[c]P-values followed by * are significant ($\alpha = 0.05$).
[d]Abbreviations: PA, Palmer amaranth; DAT, days after treatment.

Table 6. Palmer amaranth control 21 and 28 d after treatment and rough rice grain yield as affected by florpyrauxifen-benzyl rate, number of applications, and Palmer amaranth size at application at both locations in 2020.[a–g]

				Marianna			Colt		
				Control			Control		
Factor				21 DAT	28 DAT	Yield	21 DAT	28 DAT	Yield
	cm	#	g ae ha^{-1}	———	———	———	%	———	———
Size × Appl × Rate	20	Single	8	40 c	44 d-f	64	23	22 H	79 ab
			15	58 bc	61 cd	53	62	62 d-f	69 b
			23	74 ab	78 a-c	54	70	85 ab	94 ab
			30	85 a	91 ab	70	85	88 ab	78 ab
		Sequential	8	73 ab	76 a-c	51	73	90 ab	93 ab
			15	78 ab	84 ab	69	86	92 ab	94 ab
			23	86 a	84 ab	74	98	94 ab	111 a
			30	88 a	94 a	53	99	98 a	92 ab
	40	Single	8	39 c	33 f	62	41	45 fg	58 b
			15	40 c	36 ef	59	72	42 g	73 ab
			23	44 c	38 ef	65	75	55 e-g	84 ab
			30	40 c	31 f	70	73	55 e-g	76 ab
		Sequential	8	41 c	46 d-f	55	79	60 d-g	85 ab
			15	44 c	53 de	67	96	65 c-e	59 b
			23	74 ab	74 bc	55	93	83 a-c	69 b
			30	56 bc	74 a-c	48	96	77 b-d	95 ab
Size × Appl	20	Single		64	68	61 ab	60	64	80
		Sequential		81	84	67 a	89	93	95
	40	Single		40	34	62 ab	65	49	72
		Sequential		53	62	57 b	91	71	77
Rate × Appl		Single	8	39	38	63 a-c	32	33	68
			15	48	49	61 a-c	67	52	71
			23	58	58	60 a-c	73	73	89
			30	62	61	71 a	79	71	76
		Sequential	8	57	61	52 bc	77	75	84
			15	61	69	69 ab	91	78	77
			23	80	79	65 a-c	95	89	90
			30	72	84	51 c	98	87	94
Rate			8	48	50	58	55 b	54	76
			15	55	59	64	79 a	65	74
			23	69	68	63	83 a	82	89
			30	67	73	62	88 a		85
Appl		Single		52	51	64	62 b	56	76
		Sequential		67	73	60	90 a	82	86

[a]Abbreviations: Appl, Application; DAT, days after treatment.
[b]Rough rice grain yield as percentage of weed free control.
[c]Height of Palmer amaranth at time of application (20 and 40 cm).
[d]Number of applications made (1 versus 2 with 14-day interval).
[e]Florpyrauxifen-benzyl rate plus 0.58 L ha^{-1} methylated seed oil plus 363 g ai ha^{-1} pendimethalin.
[f]Means within the same column followed by the same letter are not different according to Tukey's adjusted HSD (α=0.05).
[g]Rice in weed-free control produced 9,175 kg ha^{-1} in Marianna and 6,806 kg ha^{-1} in Colt.

Table 7. Palmer amaranth counts and seed production after treatment by florpyrauxifen-benzyl rate, number of applications, and Palmer amaranth size at application at both locations in 2020.[a–f]

Factor		Marianna			Colt		
		Count	Palmer amaranth seed		Count	Palmer amaranth seed	
Rate	g ha^{-1}	# ha^{-1}	# females	# ha^{-1}	# ha^{-1}	# females	# ha^{-1}
	8	3,780 a	2,720 a	249 ab	3,370 a	3,720 a	656 a
	15	3,490 ab	6,820 a	874 a	2,050 ab	3,060 a	331 a
	23	1,360 b	350 a	47 b	606 b	1,310 b	126 ab
	30	2,300 ab	2,990 a	135 ab	530 b	1,740 b	74 b
Size	(cm)						
	20	3,510 a	6,120 a	578 a	1,893 a	3,370 a	438 a
	40	1,960 b	623 b	51 b	1,382 a	1,550 b	156 b
Applications	(#)						
	Single	3,980 a	5,675 a	599 a	2,420 a	3,690 a	470 a
	Sequential	1,490 b	1,024 b	67 b	852 b	1,230 b	124 b

[a]Living Palmer amaranth counted at the time of rice harvest in each plot (23 m^2 in Marianna and 18.4 m^2 in Colt, adjusted to hectares).
[b]Average number of Palmer amaranth seeds produced by each female per hectare.
[c]Average number of Palmer amaranth seeds produced per square meter.
[d]Rate of florpyrauxifen-benzyl (8, 15, 23, 30 g ae ha^{-1}); all applications included 0.58 L ha^{-1} methylated seed oil and 363 g ai ha^{-1} pendimethalin.
[e]Height of Palmer amaranth at time of application (20 and 40 cm).
[f]Number of applications made (1 versus 2 with 14-d interval).

average height of 40 cm, single applications of florpyrauxifen-benzyl were less effective, providing 55% control when applied as a single application at 30 g ae ha^{-1}. Consequently, sequential applications of florpyrauxifen-benzyl at 23 or 30 g ae ha^{-1} provided the most effective control of the treatments evaluated on 40-cm-tall Palmer amaranth. When averaged over rate and Palmer amaranth size, sequential applications proved to be more effective than single applications at Colt 21 DAA, providing 67% and 52% control, respectively. Observations from the same weed control ratings from Colt at 21 DAT led to the conclusion that when averaged over Palmer amaranth size and number of applications, florpyrauxifen-benzyl at 15 to 30 g ae ha^{-1} was most effective, ranging from 55% to 67% Palmer amaranth control (Table 6).

Differences determined in yield data from these studies can be attributed to Palmer amaranth density throughout the growing season. Rice yield in Marianna never surpassed 71% of the nontreated control and rice grown in Colt had a maximum of 41% yield reduction (Tables 2 and 6). Palmer amaranth interference with rice appears to be a factor of weed density, and the majority of the interference occurred prior to the applications of florpyrauxifen-benzyl or from the remaining Palmer amaranth following florpyrauxifen-benzyl application. Yield loss as a result of Palmer amaranth density has been reported in other crops (Klingaman and Oliver 1994; Massinga et al. 2001; Morgan et al. 2001; Rowland et al. 1999). Therefore, it is most likely that the yield loss observed in this study can be attributed to the Palmer amaranth density throughout the field or possible rice injury caused by multiple applications of florpyrauxifen-benzyl.

The number of live Palmer amaranth plants per hectare at rice maturity was reduced by applications of florpyrauxifen-benzyl at 15 to 30 g ae ha^{-1} at both locations, averaged over size and number of applications. Applications of florpyrauxifen-benzyl at 23 and 30 g ae ha^{-1}, respectively, allowed an average of 530 and 606 Palmer amaranth plants ha^{-1} to survive at the Colt location, respectively, and 47 and 135 plants ha^{-1} at the Marianna site, respectively (Table 7). The remaining Palmer amaranth in plots point to the importance of using sequential applications, as a single application left >2,400 remaining plants ha^{-1} in both Marianna and Colt, while sequential applications allowed <1,400 plants ha^{-1} to survive in each location. However, as in the previous study, Palmer amaranth that survived applications were still able to reproduce.

Female Palmer amaranth plants are prolific reproducers and are known to produce as many as 600,000 seeds having 7% to 40% germination if not faced with any competition for nutrients, and 11,000 to 60,000 seeds per female when competing with soybean (Keeley et al. 1987; Schwartz et al. 2016). When in competition with soybean on 97- and 19-cm row spacing, Palmer amaranth produced 211,000 and 139,000 seeds m^{-2}, respectively, indicating the influence of crop spacing on Palmer amaranth seed production (Jha et al. 2008). Considering the vast differences of seed produced by Palmer amaranth in different cropping scenarios, it is important to quantify the number of Palmer amaranth seeds being produced following herbicide application to determine the number of seeds returned to the soil seedbank. Generally, applications of florpyrauxifen-benzyl at 23 and 30 g ae ha^{-1} reduced seed production at both locations, allowing the production of only 47 to 135 seeds m^{-2} (Table 7). Palmer amaranth (20-cm-tall) that survived applications produced more seeds (6,120 seeds per female) than those treated at a 40-cm height (623 seeds per female). These findings indicate that if applications of florpyrauxifen-benzyl are made early, Palmer amaranth that survives the application has enough time to recover, producing more seed than larger Palmer amaranth, which was still possibly injured while entering or during reproductive stages. These findings are similar to those for crops injured by herbicide drift, where early-season exposure often has less impact on grain yield than later exposures (Castner et al. 2021).

Sequential applications also provided an advantage over single applications in reducing Palmer amaranth seed production. Sequential applications reduced the number of seeds per female and square meter when averaged over florpyrauxifen-benzyl rate and Palmer amaranth size. Although there was a reduction in viable Palmer amaranth seeds returned to the soil seedbank, the fact that seed was produced points to the importance of a zero-tolerance approach to managing Palmer amaranth, a strategy that has been widely promoted for management of this weed in other cropping systems. Exhaustion of the soil seedbank and prevention of seed production are necessary for preserving the effectiveness of florpyrauxifen-benzyl for controlling Palmer amaranth in the long term (Bagavathiannan and Norsworthy 2012; Norsworthy et al. 2014).

Practical Implications

Findings from these studies indicate that early, timely removal of Palmer amaranth is necessary to maintain rice yield. Although the critical period of weed removal cannot be determined using these data, it is obvious that interference of Palmer amaranth with rice at the densities present in these trials was sufficient to cause yield loss even when florpyrauxifen-benzyl was applied to plants averaging 5 to 7.5 cm in height. Adequate control of Palmer amaranth (<10 cm height) can be achieved by applications of florpyrauxifen-benzyl at 15 to 30 g ae ha^{-1}; however, some Palmer amaranth plants, especially at the high densities that occurred in these trials, will likely survive and reproduce, indicating the need for sequential applications of florpyrauxifen-benzyl or another effective herbicide to maintain a high level of control (Miller and Norsworthy 2018). If Palmer amaranth plants escape control and are present at harvest, these plants are likely to make significant contributions to the soil seedbank, making management of this weed in subsequent crops an ever-increasing challenge.

If Palmer amaranth is allowed to remain in the field until it reaches a height of 20 cm, sequential applications of florpyrauxifen-benzyl at 8 to 30 g ae ha^{-1} will provide equal levels of control. However, results from experiments at the Colt location indicate a tendency for greater seed production at the low rate (8 g ha^{-1}) of florpyrauxifen-benzyl and greater seed production when a single rather than sequential applications are employed. Florpyrauxifen-benzyl is better able to control smaller Palmer amaranth (~20 cm tall) than larger (~40 cm tall) plants; however, smaller Palmer amaranth plants treated earlier in the growing season that survive an application of florpyrauxifen-benzyl have the propensity to produce more viable seed than Palmer amaranth injured closer to reproduction. These results indicate that lower-than-labeled rates can be successfully used for the management of Palmer amaranth, but more than one application will often be needed, and additional measures may be warranted to ensure that Palmer amaranth does not successfully produce seed in a furrow-irrigated rice system.

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