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Evaluation of weed control in acetyl coA carboxylase-resistant rice with mixtures of quizalofop and auxinic herbicides

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Research Article

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Florpyrauxifen-benzyl, orthosulfamuron plus quinclorac, penoxsulam plus triclopyr, quinclorac, quizalofop, triclopyr; barnyardgrass, *Echinochloa crus-galli* L. Beauv. ECHCG; Palmer amaranth, *Amaranthus palmeri* S. Watts AMAPA; hemp sesbania, *Sesbania herbacea* (P. Mill.) McVaugh SEBEX; ivyleaf morningglory, *Ipomoea hederacea* (L.) Jacq. IPOHE; volunteer soybean, *Glycine max* L. Merr GLYMA; volunteer rice, *Oryza sativa* L. ORYSA; rice, *Oryza sativa* L. 'PVL01'

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Abstract

Rice with enhanced tolerance to herbicides that inhibit acetyl coA carboxylase (ACCase) allows POST application of quizalofop, an ACCase-inhibiting herbicide. Two concurrent field studies were conducted in 2017 and 2018 near Stoneville, MS, to evaluate control of grass (Grass Study) and broadleaf (Broadleaf Study) weeds with sequential applications of quizalofop alone and in mixtures with auxinic herbicides applied in the first or second application. Sequential treatments of quizalofop were applied at 119 g ai ha^{-1} alone and in mixtures with labeled rates of auxinic herbicides to rice at the two- to three-leaf (EPOST) or four-leaf to one-tiller (LPOST) growth stages. In the Grass Study, no differences in rice injury or control of volunteer rice ('CL151' and 'Rex') were detected 14 and 28 d after last application (DA-LPOST). Barnyardgrass control at 14 and 28 DA-LPOST with quizalofop applied alone or with auxinic herbicides EPOST was ≥93% for all auxinic herbicide treatments except penoxsulam plus triclopyr. Barnyardgrass control was ≥96% with quizalofop applied alone and with auxinic herbicides LPOST. In the Broadleaf Study, quizalofop plus florpyrauxifen-benzyl controlled more Palmer amaranth 14 DA-LPOST than other mixtures with auxinic herbicides, and control with this treatment was greater EPOST compared with LPOST. Hemp sesbania control 14 DA-LPOST was ≤90% with quizalofop plus quinclorac LPOST, orthosulfamuron plus quinclorac LPOST, and triclopyr EPOST or LPOST. All mixtures except quinclorac and orthosulfamuron plus quinclorac LPOST controlled ivyleaf morningglory ≥91% 14 DA-LPOST. Florpyrauxifen-benzyl or triclopyr were required for volunteer soybean control >63% 14 DA-LPOST. To optimize barnyardgrass control and rice yield, penoxsulam plus triclopyr and orthosulfamuron plus quinclorac should not be mixed with quizalofop. Quizalofop mixtures with auxinic herbicides are safe and effective for controlling barnyardgrass, volunteer rice, and broadleaf weeds in ACCase-resistant rice, and the choice of herbicide mixture could be adjusted based on weed spectrum in the treated field.

Introduction

Barnyardgrass is the most troublesome weed in Mississippi rice production (Webster 2012) due to its adaptation to flooded environments, prolific seed production, and rapid growth (Marambe and Amarasinghe 2002). Barnyardgrass has evolved resistance to several common herbicide modes of action (Heap 2019), including photosystem II (PSII) inhibitors (Carey et al. 1995; Valverde et al. 2001), synthetic auxins (Lopez-Martinez et al. 1997), clomazone (Norsworthy et al. 2007), and acetyl coA carboxylase (ACCase) inhibitors (Heap 2019). Moreover, the intensive use of the acetolactate synthase (ALS)-inhibiting herbicides imazethapyr, penoxsulam, and bispyribac-sodium led to the evolution of ALS-resistant barnyardgrass (Norsworthy et al. 2014).

Palmer amaranth and hemp sesbania are the most troublesome broadleaf weeds in Mississippi rice production (Webster 2012). Palmer amaranth is difficult to control due to its prolific seed production, rapid growth rate (Steckel 2007), and pollen distribution up to 600 m (Sosnoskie et al. 2012). Hemp sesbania population densities can range from 8,100 to 129,000 plants ha^{-1} (McWhorter and Anderson 1979) and can reduce rice quality and yield by more than 50% due to shading and competition (Boyette et al. 2014).

Flooding is the principal cultural weed control practice for rice (Chauhan and Johnson 2010; Kent and Johnson 2001; McClung 2003; Odero and Rainbolt 2014). Broadleaf weed species do not emerge once a flood is established unless germinated prior to flooding on levees or field areas that are allowed to dry after flooding (Scott et al. 2013). Therefore, herbicides that control broadleaf weed species are usually applied shortly before or after flooding (Scott et al. 2013). Although clomazone and imazethapyr are among the most commonly used herbicides for barnyardgrass and volunteer rice control in rice, these herbicides provide inadequate control of broadleaf weed species (Camargo et al. 2011). Propanil, another commonly used rice herbicide, can control grass and broadleaf weed species when applied POST; however, barnyardgrass has evolved resistance to propanil (Baltazar and Smith 1994; Carey et al. 1995).

Provisia™ rice exhibits enhanced tolerance to herbicides that inhibit ACCase, allowing POST applications of quizalofop, an ACCase-inhibiting herbicide (Burton et al. 1989; Focke and Lichtenthaler 1987; Rustom et al. 2018). Quizalofop was first registered for use in soybean [*Glycine max* (L.) Merr.] in the late 1980s, followed by registration for use in cotton (*Gossypium hirisutum* L.) in the early 1990s (Shaner 2014). A member of the aryloxyphenoxy propionate herbicide family, quizalofop is used to target non-ACCase-resistant red rice [*Oryza sativa* (L.) Lombardy], volunteer conventional rice, hybrid rice, imidazolinone-resistant rice types, and other common annual and perennial grasses, including barnyardgrass (Anonymous 2017; Konishi and Sasaki 1994; Shaner 2014). However, previous research indicates that efficacy can be compromised when quizalofop is mixed with broadleaf and/or nonselective herbicides, including penoxsulam, penoxsulam plus triclopyr, bispyribac, propanil, and propanil plus thiobencarb (Blackshaw et al. 2006; Chahal and Jhala 2015; Rustom et al. 2018).

Florpyrauxifen-benzyl is a new active ingredient from the arylpicolinate herbicide family (Epp et al. 2016). A synthetic auxin, florpyrauxifen-benzyl exhibits activity on grass and broadleaf weeds in rice (Miller and Norsworthy 2018). Florpyrauxifen-benzyl can be used on inbred and hybrid rice cultivars, including herbicide-resistant cultivars (Anonymous 2018). Therefore, florpyrauxifen-benzyl represents a new management option for control of ALS-, ACCase-, PSII-, and synthetic auxin-resistant broadleaf and grass weed species (Epp et al. 2016).

Quizalofop is effective at controlling grass weed species but it offers no control of broadleaf weed species; therefore, mixtures of florpyrauxifen-benzyl with quizalofop could be beneficial to increase the spectrum of weed control in ACCase-resistant rice. However, previous research reported negative interactions when quizalofop was mixed with some broadleaf herbicides (Blackshaw et al. 2006; Chahal and Jhala 2015). Rustom et al. (2018) reported reductions in barnyardgrass control as great as 54% when quizalofop was mixed with penoxsulam, penoxulam plus triclopyr, or bispyribac. Therefore, this research was conducted to evaluate rice response and control of grass and broadleaf weed species with sequential applications of quizalofop including auxinic herbicides in the first or second treatment.

Materials and Methods

Grass Study

A field study was conducted at the Mississippi State University Delta Research and Extension Center in Stoneville, MS, in 2017 (33.4412°N, 90.9049°W) and 2018 (33.4430°N, 90.9049°W) to evaluate control of barnyardgrass and volunteer rice with sequential applications of quizalofop (Provisia 0.88 EC; BASF Crop Protection, 26 Davis Dr., Research Triangle Park, NC 27709) mixed with auxinic herbicides in the first or second treatment. Soil was a Sharkey clay (very-fine, smectitic, thermic Chromic Eqiaquerts) with a pH of 8.2 and an organic matter content of 2.1%. The experimental site had a rice-fallow rotation with rice seeded every other year. During the fallow year, weeds were allowed to grow and produce seed to maintain the soil seed bank. Glyphosate (Roundup PowerMax 4.5 L, 1,120 g ae ha^{-1}; Monsanto Company, 800 N. Lindburgh Blvd., St. Louis, MO 63167), paraquat (Gramoxone 2.0 SL, 560 g ai ha^{-1}; Syngenta Crop Protection, P.O. Box 18300, Greensboro, NC 27409), or 2,4-D (2,4-D Amine 3.8 SL, 1,120 g ae ha^{-1}; Agri Star, 1525 NE 36th St., Ankeny, IA 50021) were applied in late March to early April each year to control emerged vegetation. Barnyardgrass was surface-seeded prior to rice seeding to ensure uniform infestation.

Rice was drill-seeded May 18, 2017, and May 2, 2018, to a depth of 2 cm using a small-plot grain drill (Great Plains 1520; Great Plains Mfg, Inc., 1525 East North St., Salina, KS 67401) at 356 seed m^{-2}. Plots consisted of eight rows of rice spaced 20 cm apart and 4.6 m in length and were flooded to an approximate depth of 6 to 10 cm when rice reached the one- to two-tiller stage. Rows 3 through 6 in each plot were seeded with 'Provisia PVL01' (Horizon Ag, LLC, 8275 Tournament Dr., Memphis, TN 38125). Rows 1 and 8 were seeded with 'CL151' (Horizon Ag, LLC), and rows 2 and 7 were seeded with 'Rex' (Reg. No. CV-136, PI 661111) to simulate an infestation of volunteer rice. Treated plots were bordered on either end by a 1.5-m alley that contained no rice. Saflufenacil (Sharpen 2.85 SC, 50 g ai ha^{-1}; BASF Crop Protection) was applied at planting followed by halosulfuron (Permit 75 DF, 39 g ai ha^{-1}; Gowan Company, P.O. Box 5569, Yuma, AZ 85364) applied prior to flooding to maintain the experimental site free of broadleaf weeds. Nitrogen fertilizer was applied at 168 kg ha^{-1} as urea (46-0-0) immediately prior to flood establishment (Norman et al. 2013). Rice was managed throughout the growing season utilizing local guidelines to optimize yield (Buehring 2008).

Treatments were arranged as a two-factor factorial within a randomized complete block design and four replications. Factor A was application timing for inclusion of auxinic herbicides and consisted of treatments applied to rice in the two- to three-leaf (EPOST) and four-leaf to one-tiller (LPOST) growth stages. Factor B was auxinic herbicide and consisted of no auxinic herbicide and the herbicide products listed in Table 1. Quizalofop at 119 g ai ha^{-1} was applied to all plots at the EPOST and LPOST timings and auxinic herbicides were mixed with quizalofop at the designated timings. The no-auxinic-herbicide treatment consisted of quizalofop alone EPOST followed by LPOST. A nontreated control was included for comparison. All treatments contained crop oil concentrate (Herbimax, 83% petroleum oil; Loveland Products, P.O. Box 1286, Greeley, CO 80632) at 1% (v/v) and were applied using a CO_2-pressurized backpack sprayer equipped with flat-fan nozzles (Airmix 11002 nozzle; Greenleaf Technologies, 230 E Gibson St., Covington, LA 70433) set to deliver 140 L ha^{-1} at 206 kPa using water as a carrier.

Visible estimates of aboveground rice injury and control of barnyardgrass, 'CL151' and 'Rex' were recorded 7 d after EPOST (DA-EPOST) and 14 and 28 d after LPOST (DA-LPOST) on a scale of 0% to 100% where 0% indicated no visual effect of herbicides and 100% indicated complete plant death or weed control. Rice plant height was determined 14 DA-LPOST by measuring from the soil surface to the upper most extended leaf and calculating the mean height of five randomly selected

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Table 1. Herbicide common and tradenames, application rates, and herbicide manufacturer information for treatments in the Grass and Broadleaf studies conducted at Stoneville, MS, in 2017 and 2018.

Common name	Trade name	Rate	Manufacturer
		g ai ha^{-1}	
Florpyrauxifen-benzyl	Loyant	29	Corteva AgriSciences, LLC, 9330 Zionsville Rd., Indianapolis, IN 46268
Quinclorac	Facet L	420	BASF Crop Protection, 26 Davis Dr., Research Triangle Park, NC 27709
Triclopyr	Grandstand R	235	Corteva AgriSciences, LLC, 9330 Zionsville Rd., Indianapolis, IN 46268
Penoxsulam plus triclopyr	Grasp Xtra	68 plus 403	Corteva AgriSciences, LLC, 9330 Zionsville Rd., Indianapolis, IN 46268
Orthosulfamuron plus quinclorac	Strada XT2	52 plus 315	Nichino America, Inc., 4550 New Linden Hill Road, Wilmington, DE 19808

Table 2. 'CL151', 'Rex', and barnyardgrass height and density at time of treatment applications in the Grass Study at Stoneville, MS, in 2017 and 2018.[a]

Year	Application timing	'CL151'		'Rex'		Barnyardgrass	
		Height	Density	Height	Density	Height	Density
		cm	no. m^{-2}	cm	no. m^{-2}	cm	no. m^{-2}
2017	EPOST	13	312	13	312	3	43
	LPOST	25	312	25	312	3	22
2018	EPOST	15	312	15	312	1	11
	LPOST	20	312	20	312	3	11

[a]Herbicide application timings included rice in the two- to three-leaf (EPOST) and four-leaf to one-tiller (LPOST) growth stages.

plants in each plot. Plant height (cm) and density (no. m^{-2}) for 'CL151', 'Rex', and barnyardgrass at each application timing are presented in Table 2. Plots were drained approximately 2 wk before harvest maturity. Rice was harvested with a small-plot combine (Wintersteiger Delta; Wintersteiger, Inc., 4705 W. Amelia Earhart Dr., Salt Lake City, UT 84116) at a moisture content of approximately 20% on September 7, 2017, and October 8, 2018. Final rough rice grain yield was adjusted to 12% moisture content.

The square roots of visible injury and control estimates were arcsine transformed. The transformations did not improve homogeneity of variance based on visual inspection of plotted residuals; therefore, nontransformed data were used in analyses. Data from the nontreated control plots were not included in the analysis of crop injury and weed control estimates to stabilize variance. Data from nontreated control plots were not included in rough rice yield analysis because no data were collected due to severe barnyardgrass infestation. Nontransformed data were subjected to the Mixed Procedure (statistical software Release 9.3; SAS Institute Inc., 100 SAS Campus Drive, Cary, NC 27513-2414) with year and replication (nested within year) as random effect parameters (Blouin et al. 2011). Type III statistics were used to test the fixed effects of application timing, auxinic herbicide, and the interaction between these variables. Least square means were calculated and mean separation ($P \leq 0.05$) was produced using PDMIX800 in SAS, which is a macro for converting mean separation output to letter groupings (Saxton 1998).

Broadleaf Study

A field study similar to that described for the Grass Sudy was conducted at the Mississippi State University Delta Research and Extension Center in Stoneville, MS, in 2017 (33.4412°N, 90.9049°W) and 2018 (33.4430°N, 90.9049°W). However, this study evaluated control of broadleaf weed species with sequential applications of quizalofop mixed with auxinic herbicides in the first or second treatment. Soil description, site maintenance, plot size, and planting information were the same as for the Grass Study. Hemp sesbania, ivyleaf morningglory, volunteer soybean (Asgrow 4632; Monsanto Company), and Palmer amaranth were surface-seeded prior to rice seeding each year to ensure uniform infestation. Clomazone (Command 3 ME, 560 g ai ha^{-1}; FMC Corporation, 1735 Market St., Philadelphia, PA 19103) was applied PRE followed by bispyribac-sodium (Regiment 80 WP, 28 g ai ha^{-1}; Valent U.S.A. Corporation, P.O. Box 8025, Walnut Creek, CA 94596-8025) as needed to maintain the experimental site free of grass weeds.

The experimental design, treatment structure, and treatment application for the Broadleaf Study was the same as that for the Grass Study. Visible estimates of aboveground rice injury and control of hemp sesbania, ivyleaf morningglory, volunteer soybean, and Palmer amaranth were recorded 7 DA-EPOST and 14 and 28 DA-LPOST on the previously described scale. Rice plant heights were determined 14 DA-LPOST as previously described. Plant height and density of hemp sesbania, ivyleaf morningglory, volunteer soybean, and Palmer amaranth at each application timing are presented in Table 3. Rice was harvested with a small-plot combine on September 7, 2017, and October 8, 2018, and final rough rice grain yield was adjusted to 12% moisture content. Data analyses were performed as previously described for the Grass Study.

Results and Discussions

Grass Study

Main effects of application timing ($P = 0.091$ to 0.425) and auxinic herbicide treatment ($P = 0.075$ to 0.542) and the interaction of these variables ($P = 0.09$ to 0.952) were not significant for rice injury across all evaluations. Rice injury was <10% at all evaluations (data not presented). Additionally, rice plant height 14 DA-LPOST was not influenced by the treatments imposed in this study ($P = 0.16$ to 0.481).

Control of 'CL151' 7 DA-EPOST was influenced by a main effect of auxinic herbicide treatment ($P = 0.005$). Pooled across application timings, all auxinic herbicide treatments except orthosulfamuron plus quinclorac controlled 'CL151' greater than quizalofop alone 7 DA-EPOST (Table 4). Additionally, florpyrauxifen-benzyl controlled more 'CL151' than orthosulfamuron plus quinclorac did. Control of 'CL151' and 'Rex' was 97% to 98% 14 and 28 DA-LPOST and neither were influenced by treatments imposed in this study ($P = 0.424$ to 0.979; data not presented). In similar research, mixtures of quinclorac and triclopyr with quizalofop at 120 g ha^{-1} resulted in a neutral response for control of volunteer rice utilizing 'CLXL-745' and 'CL 111' (Webster et al. 2019).

Main effects of application timing ($P = 0.478$) and auxinic herbicide treatment ($P = 0.530$) and the interaction of these variables

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Table 3. Height and density of hemp sesbania, ivyleaf morningglory, volunteer soybean, and Palmer amaranth at time of treatment applications in the Broadleaf Study at Stoneville, MS, in 2017 and 2018.[a]

Year	Application timing	Hemp sesbania		Ivyleaf morningglory		Volunteer soybean		Palmer amaranth	
		Height	Density	Height	Density	Height	Density	Height	Density
		cm	no. m^{-2}	cm	no. m^{-2}	cm	no. m^{-2}	cm	no. m^{-2}
2017	EPOST	8	43	8	11	8	22	8	22
	LPOST	13	32	5	1	15	22	10	22
2018	EPOST	10	32	3	5	5	1	10	54
	LPOST	15	22	5	5	5	1	15	32

[a]Herbicide application timings included rice in the two- to three-leaf (EPOST) and four-leaf to one-tiller (LPOST) growth stages.

Table 4. Control of 'CL151' 7 d after first application (DA-EPOST) of quizalofop at 119 g ai ha^{-1} alone and in mixtures with auxinic herbicides in the Grass Study at Stoneville, MS, in 2017 and 2018.[a,b]

Auxinic herbicide treatment	Rate	Control
	g ai ha^{-1}	%
No auxinic herbicide	–	24 c
Florpyrauxifen-benzyl	29	32 a
Orthosulfamuron plus quinclorac	52 plus 315	26 bc
Penoxsulam plus triclopyr	68 plus 403	31 ab
Quinclorac	420	30 ab
Triclopyr	235	31 ab

[a]Data were pooled across two application timings and two experiments. Means followed by the same letter are not different at $P \leq 0.05$.
[b]All treatments included quizalofop at 119 g ai ha^{-1} in the two- to three-leaf (EPOST) and four-leaf to one-tiller (LPOST) applications.

(P = 0.571) were not significant for control of barnyardgrass 7 DA-EPOST. However, interactions between application timing and auxinic herbicide treatments were detected for barnyardgrass control 14 (P = 0.004) and 28 (P = 0.002) DA-LPOST. Barnyardgrass control at 14 and 28 DA-LPOST with quizalofop applied alone or with auxinic herbicides included in EPOST and LPOST applications was similar, and 96% to 98% for all auxinic herbicide treatments except penoxsulam plus triclopyr in the EPOST treatment, which controlled barnyardgrass 84% at both evaluations (Table 5).

Rough rice yield was also influenced by an interaction between application timing and auxinic herbicide treatment (P = 0.045). Rough rice yield was similar whether auxinic herbicides were included with quizalofop EPOST or LPOST for all auxinic herbicide treatments except penoxsulam plus triclopyr (Table 5). As with barnyardgrass control 14 and 28 DA-LPOST, rough rice yield was reduced when penoxsulam plus triclopyr was included with quizalofop in EPOST compared with LPOST treatments. Furthermore, rough rice yield was 10% less when orthosulfamuron plus quinclorac was mixed with quizalofop LPOST compared with florpyrauxifen-benzyl LPOST or quinclorac EPOST or LPOST.

Acetyl CoA carboxylase-resistant rice allows POST applications of quizalofop to control troublesome grass weed species in rice (Epp et al. 2016; Rustom et al. 2018). Lancaster et al. (2018) reported that quizalofop controlled barnyardgrass >96% at the two- to three-leaf growth stage and >90% at the five- to six-leaf growth stage in ACCase-resistant rice. Webster et al. (2019) reported that quinclorac and triclopyr antagonized barnyardgrass control 28 d after application when mixed with quizalofop at 120 g ha^{-1}. In the current study, barnyardgrass was controlled ≥96% with quizalofop applied alone or with auxinic herbicide treatments except penoxsulam plus triclopyr EPOST. Therefore, to optimize barnyardgrass control, penoxsulam plus triclopyr should not be mixed with quizalofop for applications to ACCase-resistant rice.

Broadleaf Study

Main effects of application timing (P = 0.091 to 0.170) 7 DA-EPOST and 14 and 28 DA-LPOST, and auxinic herbicide treatment (P = 0.075 to 0.083) 14 and 28 DA-LPOST and the interaction of these variables (P = 0.312 to 0.842) 7 DA-EPOST and 14 and 28 DA-LPOST did not result in significant rice injury. A main effect of auxinic herbicide treatment (P ≤ 0.001) was detected as rice injury 7 DA-EPOST; however, rice injury was <10% at all evaluations (data not presented).

An interaction of application timing and auxinic herbicide treatment (P = 0.025) was significant for rice height 14 DA-LPOST. Rice heights 14 DA-LPOST were similar (≥88 cm for quizalofop alone and in mixture with auxinic herbicide treatments in EPOST treatments); however, rice heights were reduced 12% and 13% with penoxsulam plus triclopyr and quinclorac, respectively, compared to no auxinic herbicide LPOST (Table 6). Rice height was reduced when treatments containing quinclorac were delayed from EPOST to LPOST.

Interactions between application timing and auxinic herbicide treatments were detected for control of hemp sesbania 7 DA-EPOST (P ≤ 0.001) and 14 DA-LPOST (P ≤ 0.001), ivyleaf morningglory 7 DA-EPOST (P ≤ 0.001) and 14 DA-LPOST (P ≤ 0.001), and Palmer amaranth 7 DA-EPOST (P ≤ 0.001) and 14 DA-LPOST (P ≤ 0.001). Hemp sesbania control 7 DA-EPOST was greatest (85% with penoxsulam plus triclopyr in EPOST treatments; Table 7). Other auxinic herbicide treatments resulted in ≤77% control of hemp sesbania 7 DA-EPOST. Hemp sesbania was controlled 60% 14 DA-LPOST with triclopyr EPOST compared with ≥96% control with other EPOST auxinic treatments. Mixtures containing florpyrauxifen-benzyl and penoxsulam plus triclopyr LPOST provided the greatest control (≥96% control compared with other auxinic treatments LPOST). Among LPOST treatments, triclopyr controlled hemp sesbania the least.

No differences in ivyleaf morningglory control 7 DA-EPOST and 14 DA-LPOST were detected among treatments that included an auxinic herbicide with quizalofop EPOST (Table 7). Control was reduced with no auxinic herbicide treatment because quizalofop does not control broadleaf weed species. Ivyleaf morningglory control 14 DA-LPOST was ≥91% with florpyrauxifen-benzyl, penoxsulam plus triclopyr, and triclopyr LPOST. Control 14 DA-LPOST with quinclorac was greater than with orthosulfamuron plus quinclorac LPOST.

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Table 5. Barnyardgrass control 14 and 28 d after final application (DA-LPOST) and rough rice yield following sequential applications of quizalofop at 119 g ai ha^{-1} alone and in mixtures with auxinic herbicides in the Grass Study at Stoneville, MS, in 2017 and 2018.[a,b,c]

		Barnyardgrass control					
		14 DA-LPOST		28 DA-LPOST		Rough rice yield	
Auxinic herbicide treatment	Rate	EPOST	LPOST	EPOST	LPOST	EPOST	LPOST
	g ai ha^{-1}	———————%	———————			———kg ha^{-1}	———
No auxinic herbicide	–	98 a	98 a	98 a	98 a	12,000 ab	12,400 ab
Florpyrauxifen-benzyl	29	98 a	98 a	97 a	98 a	12,600 ab	12,900 a
Orthosulfamuron plus quinclorac	52 plus 315	96 a	98 a	96 a	98 a	12,600 ab	11,600 bc
Penoxsulam plus triclopyr	68 plus 403	84 b	97 a	84 b	98 a	10,900 c	12,100 ab
Quinclorac	420	97 a	98 a	96 a	98 a	12,700 a	12,800 a
Triclopyr	235	98 a	98 a	98 a	96 a	12,100 ab	12,400 ab

[a]Data were pooled across two experiments. Means followed by the same letter for each parameter are not different at $P \leq 0.05$.
[b]Herbicide application timings included application to rice in the two- to three-leaf (EPOST) and four-leaf to one-tiller (LPOST) growth stages.
[c]All treatments included quizalofop at 119 g ai ha^{-1} in the EPOST and LPOST applications.

Table 6. Rice plant height 14 d after final application (DA-LPOST) of quizalofop at 119 g ai ha^{-1} alone and in mixtures with auxinic herbicides in the Broadleaf Study at Stoneville, MS, in 2017 and 2018.[a,b,c]

Auxinic herbicide treatment	Rate	EPOST	LPOST
	g ai ha^{-1}	———cm	———
No auxinic herbicide	–	91 ab	95 a
Florpyrauxifen-benzyl	29	90 abc	91 ab
Orthosulfamuron plus quinclorac	52 plus 315	88 bcd	91 ab
Penoxsulam plus triclopyr	68 plus 403	90 abc	83 d
Quinclorac	420	92 ab	84 cd
Triclopyr	235	93 ab	90 abc

[a]Data were pooled across two experiments. Means followed by the same letter are not different at $P \leq 0.05$.
[b]Herbicide application timings included application to rice in the two- to three-leaf (EPOST) and four-leaf to one-tiller (LPOST) growth stages.
[c]All treatments included quizalofop at 119 g ai ha^{-1} in the EPOST and LPOST applications.

Although Palmer amaranth control 7 DA-EPOST varied with auxinic herbicide treatment, no treatment was able to control Palmer amaranth >64% (Table 8). Palmer amaranth control 14 DA-LPOST was 98% and 88% with florpyrauxifen-benzyl included in EPOST and LPOST treatments, respectively, compared with lower control with other auxinic herbicide treatments. Palmer amaranth was controlled least with mixtures that included quinclorac or orthosulfamuron plus quinclorac.

Control of hemp sesbania 28 DA-LPOST ($P \leq 0.001$), ivyleaf morningglory 28 DA-LPOST ($P \leq 0.001$), volunteer soybean 14 ($P \leq 0.001$) and 28 DA-LPOST ($P \leq 0.001$), Palmer amaranth 28 DA-LPOST ($P \leq 0.001$), and rough rice yield ($P \leq 0.001$) were influenced by a main effect of auxinic herbicide treatment. Hemp sesbania control 28 DA-LPOST was ≥97% with florpyrauxifen-benzyl and penoxsulam plus triclopyr (Table 9). At 28 DA-LPOST, hemp sesbania control with orthosulfamuron plus quinclorac and quinclorac was greater than with triclopyr. Potential causes of poor control with triclopyr EPOST were unclear. Ivyleaf morningglory control 28 DA-LPOST was ≥97% with treatments that included an auxinic herbicide.

Volunteer soybean control 14 and 28 DA-LPOST was ≥94% with florpyrauxifen-benzyl, penoxsulam plus triclopyr, and triclopyr, and control with these treatments was greater than with orthosulfamuron plus quinclorac and quinclorac (Table 9). Less control with orthosulfamuron plus quinclorac was attributed to utilization of a sulfonylurea-tolerant soybean cultivar to simulate volunteer soybean infestation, and orthosulfamuron is not effective for control of sulfonylurea-tolerant soybeans (Edwards et al. 2016). For control of broadleaf weeds, quinclorac at the labeled rate of 420 g ha^{-1} should be applied to weeds that are 0 to 5 cm high (Anonymous 2016). Volunteer soybean height at the time of LPOST application was 8 to 13 cm. Additionally, quinclorac is not recommended for control of volunteer soybean (Bond et al. 2019). Palmer amaranth control 28 DA-LPOST was 98% and 96% with florpyrauxifen-benzyl and penoxsulam plus triclopyr, respectively. Control was reduced with all other auxinic treatments; however, triclopyr provided greater control than orthosulfamuron plus quinclorac and quinclorac.

Control of all four broadleaf weed species was lowest at each evaluation interval with the no-auxinic-herbicide treatment (Table 9). Quizalofop controls grass weed species but has no activity on broadleaf weed species; therefore, nominal broadleaf weed control observed from the no-auxinic-herbicide treatment (quizalofop alone) at the later evaluations resulted from flooding the experimental area.

Rough rice yield was greater in plots receiving auxinic herbicide treatments compared with plots with no auxinic herbicide (Table 9). Rough rice yield was similar following application of mixtures with florpyrauxifen-benzyl, orthosulfamuron plus quinclorac, penoxsulam plus triclopyr, and quinclorac; however, rough rice yield was lower in plots treated with triclopyr.

A main effect of application timing was detected for control of Palmer amaranth 28 DA-LPOST ($P \leq 0.001$). Palmer amaranth control 28 DA-LPOST was 90% with EPOST compared with 84% with LPOST treatments (data not presented). Palmer amaranth can grow 5 to 8 cm per day (Horak and Loughlin 2000). Therefore, reduced control with LPOST treatments was likely due to larger Palmer amaranth at application compared with EPOST treatments.

Herbicide timing is a critical component of weed control (Montgomery et al. 2015; Parker et al. 2006). Timely herbicide applications improve weed control and increase crop yield (Parker et al. 2006). Weeds are generally easier to control with POST herbicides when applied to small (< cm) plants that have not reached reproductive stages (Montgomery et al. 2015). Doll (1981) stated that weeds in the two- to three-leaf growth stages are ideal for POST herbicide applications. Previous research reported >96% control of Palmer amaranth with POST

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Table 7. Hemp sesbania and ivyleaf morningglory control 7 d after first application (DA-EPOST) and 14 d after final application (DA-LPOST) following quizalofop at 119 g ai ha^{-1} alone and in mixtures with auxinic herbicides in the Broadleaf Study at Stoneville, MS, in 2017 and 2018.[a,b,c]

		Hemp sesbania				Ivyleaf morningglory			
		7 DA-EPOST		14 DA-LPOST		7 DA-EPOST		14 DA-LPOST	
Auxinic herbicide treatment	Rate	EPOST	LPOST	EPOST	LPOST	EPOST	LPOST	EPOST	LPOST
	g ai ha^{-1}	%							
No auxinic herbicide	–	0 f	0 f	0 f	0 f	0 d	0 d	26 d	26 d
Florpyrauxifen-benzyl	29	77 b	0 f	98 a	98 a	56 a	0 d	96 a	91 ab
Orthosulfamuron plus quinclorac	52 plus 315	45 d	0 f	96 a	82 c	49 a	0 d	95 a	64 c
Penoxsulam plus triclopyr	68 plus 403	85 a	0 f	98 a	96 a	53 a	0 d	98 a	98 a
Quinclorac	420	61 c	0 f	98 a	90 b	58 a	0 d	93 a	83 b
Triclopyr	235	34 e	0 f	60 e	71 d	58 a	0 d	98 a	98 a

[a]Data were pooled across two experiments. Means followed by the same letter for each parameter are not different at $P \le 0.05$.
[b]Herbicide application timings included application to rice in the two- to three-leaf (EPOST) and four-leaf to one-tiller (LPOST) growth stages.
[c]All treatments included quizalofop at 119 g ai ha^{-1} in the EPOST and LPOST applications.

Table 8. Palmer amaranth control 7 d after first application (DA-EPOST) and 14 d after final application (DA-LPOST) following quizalofop at 119 g ai ha^{-1} alone and in mixtures with auxinic herbicides at two application timings at Stoneville, MS, in 2017 and 2018.[a,b,c]

		7 DA-EPOST		14 DA-LPOST	
Auxinic herbicide treatment	Rate	EPOST	LPOST	EPOST	LPOST
	g ai ha^{-1}	%			
No auxinic herbicide		0 e	0 e	56 f	63 e
Florpyrauxifen-benzyl	29	64 a	0 e	98 a	88 b
Orthosulfamuron plus quinclorac	52 plus 315	39 c	0 e	73 cd	72 cd
Penoxsulam plus triclopyr	68 plus 403	51 b	0 e	89 b	76 c
Quinclorac	420	30 d	0 e	68 d	74 cd
Triclopyr	235	31 cd	0 e	85 b	76 c

[a]Data were pooled across two experiments. Means followed by the same letter for each parameter are not different at $P \le 0.05$.
[b]Herbicide application timings included application to rice in the two- to three leaf (EPOST) and four-leaf to one-tiller (LPOST) growth stages.
[c]All treatments included quizalofop at 119 g ai ha^{-1} in the EPOST and LPOST applications.

Table 9. Control of hemp sesbania, ivyleaf morningglory, volunteer soybean, and Palmer amaranth at different intervals after final application (DA-LPOST) and rough rice yield following quizalofop at 119 g ai ha^{-1} alone and in mixtures with auxinic herbicides in the Broadleaf Study at Stoneville, MS, in 2017 and 2018.[a,b]

		Hemp sesbania	Ivyleaf morningglory	Volunteer soybean		Palmer amaranth	
Auxinic herbicide treatment	Rate	28 DA-LPOST	28 DA-LPOST	14 DA-LPOST	28 DA-LPOST	28 DA-LPOST	Yield
	g ai ha^{-1}	%					kg ha^{-1}
No auxinic herbicide	–	0 e	62 b	33 d	56 c	76 d	40 c
Florpyrauxifen-benzyl	29	98 a	98 a	94 a	98 a	98 a	9,100 a
Orthosulfamuron plus quinclorac	52 plus 315	95 b	97 a	63 b	77 b	84 c	8,700 a
Penoxsulam plus triclopyr	68 plus 403	97 ab	98 a	98 a	98 a	96 a	8,900 a
Quinclorac	420	95 b	98 a	52 c	75 b	79 d	8,700 a
Triclopyr	235	74 c	98 a	98 a	98 a	89 b	3,400 b

[a]Data were pooled across two application timings and two experiments. Means followed by the same letter for each parameter are not different at $P \le 0.05$.
[b]All treatments included quizalofop at 119 g ai ha^{-1} in the EPOST and LPOST applications.

applications of florpyrauxifen-benzyl at the three-to four-leaf growth stage with less control from other auxinic herbicides (Miller and Norsworthy 2018). The same study reported 80% and 92% control of hemp sesbania with quinclorac and triclopyr, respectively. In this study, differences in control varied by application timing and auxinic herbicide treatment. Auxinic herbicide treatments applied EPOST controlled the broadleaf weed species evaluated equally or better than LPOST applications. This was true for all auxinic herbicide mixtures with quizalofop except hemp sesbania control 14 DA-LPOST with triclopyr.

Flooding rice reduces infestation of grass weed species (Smith and Shaw 1966); however, broadleaf weeds can grow under flooded conditions if they emerge before flooding (Kendig et al. 2003, Scott et al. 2013). In the current study, flooding influenced control of ivyleaf morningglory, volunteer soybean, and Palmer amaranth. Because quizalofop has no activity on broadleaf weeds, control of these weeds with treatments containing no auxinic herbicide was a result of flooding. Flooding had no effect on hemp sesbania; therefore, control with the no auxinic herbicide treatment was 0% at each evaluation.

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Although previous research reported negative interactions when quizalofop was mixed with some broadleaf herbicides (Blackshaw et al. 2006; Chahal and Jhala 2015), rice injury from quizalofop plus the auxinic herbicides evaluated in the current studies was <10% at all evaluations. Therefore, this research demonstrates that quizalofop mixtures with auxinic herbicides are safe and effective for grass and broadleaf weed control. Additionally, choice of mixture could be adjusted based on weed spectrum.

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