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Interactions of quizalofop-p-ethyl mixed with contact herbicides in ACCase-resistant rice production

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Abstract

A field study was conducted in 2015 and 2016 near Crowley, LA, to evaluate antagonistic, synergistic, or neutral interactions of quizalofop when mixed with contact herbicides labeled for use in rice production. Quizalofop was applied at 120 g ai ha^{-1}. Mixture herbicides included bentazon at 1,050 g ai ha^{-1}, carfentrazone at 18 g ai ha^{-1}, propanil at 3,360 g ai ha^{-1}, saflufenacil at 25 g ai ha^{-1}, and thiobencarb at 3,360 g ai ha^{-1}. A second application of quizalofop at 120 g ha^{-1} was made at 28 d after the initial application (DAIT) to evaluate control of weeds escaping the initial treatment. At 14 and 28 DAIT, red rice, 'CLXL-745', and 'CL-111' treated with quizalofop plus propanil indicated an antagonistic response with an observed control of 69% to 71% compared with an expected control of 92% to 94%. Barnyardgrass treated with the same mixture also indicated an antagonistic response at 14 and 28 DAIT with an observed control of 16% compared with an expected control of 94%. Barnyardgrass treated with quizalofop plus saflufenacil indicated an antagonistic response at 14 DAIT; however, the same mixture produced a neutral response by 28 DAIT. In addition, a second application of quizalofop was not able to overcome the antagonism observed with a quizalofop plus propanil mixture at 14 and 28 DAIT for red rice, CLXL-745, CL-111, or barnyardgrass control. Quizalofop mixed with carfentrazone or thiobencarb produced a neutral response for all weeds evaluated at each evaluation date.

Introduction

Imidazolinone-resistant (IR) inbred rice was first commercialized in 2002, the IR-hybrid in 2003, providing a tool for producers to control red rice with herbicides during cultivated rice production for the very first time (Croughan 1999, 2003). In addition to red rice control, imidazolinone herbicides provide activity on other problematic weeds in rice production, such as barnyardgrass (Masson and Webster 2001). IR and IR-hybrid rice cultivars are among the most widely grown in the southern United States; however, IR weedy rice and barnyardgrass resistant to herbicides with several different modes of action present a major weed issue for rice producers and threaten the sustainability of IR rice technology (Gealy et al. 2006; Oard et al. 2000; Rustom et al. 2018; Shivrain et al. 2007; Sudianto et al. 2013; Talbert and Burgos 2007).

Crops are often associated with their respective weedy forms, and red rice has been a troublesome, conspecific pest of cultivated rice for more than 150 yr (Craigmiles 1978; De Wet and Harlan 1975; Gealy et al. 2003; Rustom et al. 2018). Consequently, red rice has the ability to naturally outcross with inbred and IR-hybrid rice, resulting in the development of IR red rice (Burgos et al. 2008; Gealy 2003, 2006; Rajguru et al. 2005; Shivrain et al. 2007). Another conspecific pest in cultivated rice is volunteer IR-hybrid rice (Rustom et al. 2018). Hybrid rice seed has a history of dormancy and becomes weedy when allowed to establish in following growing seasons (Sudianto et al. 2013). Consequently, these F_2 generations can segregate, resulting in a serious weed issue with many different phenotypes and potentially be IR (S Linscombe, LSU AgCenter Rice Breeder Emeritus, personal communication). From this point forward, the term "weedy rice" will refer to the entire complex of volunteer hybrids, outcrosses, and red rice.

Weedy rice, more specifically IR weedy rice, is a major weed management concern in cultivated rice production throughout the southern United States (Gressel and Valverde 2009). Although taxonomically classified as the same species as cultivated rice, the two can often differ phenotypically with regard to plant height, grain color, grain size, presence of awns, vegetative color, and pubescence (Rustom et al. 2015, 2018). Generally, weedy rice has superior height and tillering capabilities in comparison with cultivated rice; therefore, weedy rice can compete for nutrients and light at a higher rate than cultivated rice in a competitive environment (Estorninos et al. 2005; Kwon et al. 1992). Smith (1988) suggested red rice infestations reduced cultivated rice yield by up to 80%, and 1 red plant m^{-2} can reduce yield by 219 kg ha^{-1} after season-long competition.

Barnyardgrass is another weed management issue in rice production throughout the world. Historically, weed control programs in rice across the southern United States have included propanil to control barnyardgrass (Smith 1965; Smith and Hill 1990). Carey et al. (1995) reported 98% of Arkansas rice fields received at least one application of propanil per year. However, barnyardgrass resistant to propanil, quinclorac, or imidazolinone herbicides has been reported, and the potential exists for the continued spread of these biotypes (Malik et al. 2010; Riar et al. 2013; Talbert and Burgos 2007).

In light of concerns surrounding IR weedy rice and barnyardgrass resistant to several herbicides with different modes of action, BASF recently developed a new herbicide-resistant rice with resistance to Group 1 herbicides, specifically the aryloxyphenoxypropionate herbicides. The herbicide targeted for use is quizalofop, an acetyl coenzyme A carboxylase (ACCase)-inhibiting herbicide (Burton et al. 1989; Focke and Lichtenthaler 1987; Rustom et al. 2018). ACCase-resistant (ACCase-R) rice will allow the use of quizalofop applied POST to control annual and perennial grasses, including weedy rice (Rustom et al. 2018; Shaner 2014). The targeted single quizalofop application rate in ACCase-R rice production will be 92 to 155 g ai ha^{-1}, not to exceed 240 g ha^{-1} yr^{-1}. Quizalofop has historically been used to control annual and perennial grasses, including red rice, when applied at rates from 35 to 84 g ai ha^{-1} in soybean [*Glycine max* (L.) Merr.] production and 84 to 112 g ha^{-1} in non-crop areas (Askew et al. 1998; Minton et al. 1989).

Herbicide mixtures have proven to be beneficial for broadening the weed control spectrum and maximizing yield and economic returns (Carlson et al. 2011; Pellerin and Webster 2004; Pellerin et al. 2003; Rustom et al. 2018; Webster et al. 2012, 2017a, 2017b). Herbicide mixtures can produce one of three responses: synergistic, antagonistic, or neutral (Berenbaum 1981; Blouin et al. 2010; Drury 1980; Fish et al. 2015, 2016; Hatzios and Penner 1985; Morse 1978; Nash 1981; Rustom et al. 2018; Streibig et al. 1998; Webster et al. 2017a, 2017b). A neutral response refers to no difference in observed control compared with the expected control of the herbicides applied alone. ACCase herbicide activity is often antagonized when applied in combination with other herbicides (Barnwell and Cobb 1994) and in mixtures with other herbicides (Barnwell and Cobb 1994; Blackshaw et al. 2006; Rustom et al. 2018; Vidrine et al. 1995; Zhang et al. 2005). Herbicide antagonism is defined by Beste (1983) as "an interaction of two or more chemicals such that the effect when combined is less than the predicted effect based on each chemical applied separately (p xviii)."

Antagonism of ACCase herbicide activity on barnyardgrass has previously been observed in Louisiana rice production when fenoxaprop activity was reduced when applied in a mixture with halosulfuron, bensulfuron, or carfentrazone; however, fenoxaprop mixtures with bentazon or molinate resulted in a neutral response (Zhang et al. 2005). Rustom et al. (2018) reported antagonism of quizalofop activity on barnyardgrass and weedy rice when mixed with acetolactate synthase–inhibiting herbicides such as penoxsulam, penoxsulam plus triclopyr, bispyribac, halosulfuron, orthosulfamuron plus halosulfuron, orthosulfamuron plus quinclorac, bensulfuron, or imazosulfuron. This research also reports a second application of quizalofop could not overcome the initial antagonism observed for barnyardgrass previously treated with quizalofop plus penoxsulam; however, neutral responses for barnyardgrass and weedy rice control were indicated for all other mixtures following the second quizalofop application.

ACCase-R rice will provide an additional tool for producers to control weedy rice and a broad range of grass weeds with quizalofop during cultivated rice production. There are many herbicides currently labeled for use in rice production with activity on various weeds; however, given the history of ACCase antagonism by other herbicides, it is important to understand which herbicides can potentially cause an antagonistic, synergistic, or neutral response when applied in a mixture with quizalofop. These potential interactions will aid in developing weed control programs for rice producers who use this new technology. The objective of this research was to evaluate potential antagonistic, synergistic, or neutral responses of grass weeds treated with quizalofop mixed with herbicides that have primarily contact activity when used in an ACCase-R rice production system. A second objective was to evaluate the efficacy of a second independent application of quizalofop on grass weeds escaping the initial application.

Materials and methods

A field study was conducted in 2015 and 2016 near Crowley, LA (30.177147°N, 92.3477430°W) to evaluate quizalofop activity when applied independently or in a mixture with herbicides containing contact activity. The soil type at this location is a Crowley silt loam with a pH of 6.4 and 1.4% organic matter. Plot size was 5.1 by 2.2 m with eight 19.5-cm drill-seeded rows planted as follows: 4 center rows of ACCase-R 'PVL01' long grain rice, 2 rows of 'CL-111' long grain IR rice, and 2 rows of 'CLXL-745' hybrid long grain IR rice. All rice lines and the hybrid were planted at a rate of 67 kg ha^{-1}. Awnless red rice was also broadcast in the plot area before drill seeding at a rate of 50 kg ha^{-1}. The IR, IR-hybrid, and red rice were planted to represent a weedy rice population. The research area was also naturally infested with barnyardgrass. The area was surface irrigated to a depth of 2.5 cm at 24 h after planting. A permanent 10-cm flood was established when ACCase-R rice reached the 5-leaf to 1-tiller stage and was maintained until 2 wk before harvest.

Each herbicide application was made when the ACCase-R rice was at the 3- to 4-leaf growth stage with a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} with five flat-fan 110015 nozzles spaced 35 cm apart. ACCase-R rice, red rice, CL-111, and CLXL-745 were at the 3- to 4-leaf growth stage and barnyardgrass was at the 2- to 5-leaf growth stage with a population of 50 to 100 plants m^{-2} for the initial application. Halosulfuron was applied to the entire research area at 53 g ai ha^{-1} when ACCase-R rice was at the 4- to 5-leaf growth stage for maintenance of broadleaf and sedge weeds.

The study was a randomized complete block with a factorial arrangement of treatments with four replications. Sources for materials are listed in Table 1. Factor A consisted of quizalofop applied at 120 g ha^{-1} or no quizalofop. Factor B consisted of bentazon at 1,050 g ai ha^{-1}, carfentrazone at 18 g ai ha^{-1}, propanil at 3,360 g ai ha^{-1}, saflufenacil at 25 g ai ha^{-1}, thiobencarb at 3,360 g ai ha^{-1}, or no mixture herbicide (Table 1). A second quizalofop application was applied to all treatments at a rate of 120 g ha^{-1} at 28 d after the initial quizalofop treatment (DAIT) to evaluate the efficacy of quizalofop on weeds escaping the initial application. ACCase-R rice, barnyardgrass, red rice, CL-111, and CLXL-745 were at the 1- to 3-tiller stage for the second application. A crop oil concentrate was added to all herbicide applications at a rate

Table 1. Herbicide information for all products used in the study[a]

Herbicide/product common name	Trade name	Rate	Manufacturer
		g ai ha^{-1}	
Crop oil concentrate	Agri-Dex®	1% (v/v)	Helena Agri-Enterprises, Collierville, TN
Bentazon	Basagran®	1,050	BASF Corporation, Research Triangle Park, NC
Carfentrazone	Aim®	18	Bayer Crop Protection LLC, Greensboro, NC
Propanil	Stam® M4	3,360	RiceCo LLC, Memphis, TN
Quizalofop	Provisia™	120	DuPont Crop Protection, Wilmington, DE
Saflufenacil	Sharpen®	25	BASF Corporation, Research Triangle Park, NC
Thiobencarb	Bolero®	3,360	Valent U.S.A. Corporation, Walnut Creek, CA

[a]All treatments contained a crop oil concentrate, except treatments containing propanil or thiobencarb.

of 1% v/v, except the treatments containing thiobencarb or propanil due to label restrictions.

Visual evaluations for this study included crop injury, barnyardgrass, red rice, CL-111, and CLXL-745 control. Injury and control were recorded as a percent, with 0% meaning no injury or control and 100% meaning complete plant death at 14, 28, and 42 DAIT. ACCase-R rice plant height was recorded from four plants in each plot measured from the ground to the tip of the extended rice panicle immediately before harvest (unpublished data). The center four rows planted in ACCase-R rice were harvested with a Mitsubishi VM3 plot combine (Mitsubishi Corporation, 3-1, Marunouchi 2-chome, Chiyoda-ky, Tokyo, Japan), and grain yield was adjusted to 12% moisture.

Control data collected were analyzed using the Blouin et al. (2010) augmented mixed model to determine synergistic, antagonistic, or neutral responses for herbicide mixtures by comparing an expected control, calculated based on activity of each herbicide applied alone, to an observed control. Rough rice yield data were analyzed using the MIXED procedure in SAS (SAS Institute, Cary, NC). Tukey's HSD test was used to separate yield means at the 5% probability level. The fixed effects for all models were the herbicide treatments and evaluation timing. The random effects were years, replication within years, and plots. Considering year or combination of years as a random effect accounts for different environmental conditions each year having an effect on herbicide treatments for that year (Carmer et al. 1989; Hager et al. 2003). Normality of effects over all days after the initial quizalofop treatment was checked with the use of the UNIVARIATE procedure of SAS, and assumptions for normality were met.

Table 2. Red rice control with quizalofop applied alone or mixed with various herbicides with contact activity using Blouin's modified Colby's analysis, in 2015 and 2016

		Quizalofop g ai ha^{-1}			
		0	120		
Mixture herbicide[a]	Rate	Observed	Expected	Observed[b]	P-value[c]
	g ai ha^{-1}	————	% of control	————	
14 DAIT					
None	–	0	–	95	–
Bentazon	1,050	0	95	89	0.1434
Carfentrazone	18	0	95	90	0.1853
Propanil	3,360	0	95	75–	0.0000
Saflufenacil	25	0	95	88	0.0882
Thiobencarb	3,360	0	95	91	0.2795
28 DAIT					
None	–	0	–	94	–
Bentazon	1,050	0	94	89	0.1743
Carfentrazone	18	0	94	95	0.7799
Propanil	3,360	0	94	71–	0.0000
Saflufenacil	25	0	94	94	0.9721
Thiobencarb	3,360	0	94	95	0.4851
42 DAIT[d]					
None	–	0	–	99	–
Bentazon	1,050	79	99	97	0.4032
Carfentrazone	18	82	99	97	0.2778
Propanil	3,360	79	99	94–	0.0479
Saflufenacil	25	82	99	98	0.6112
Thiobencarb	3,360	76	99	98	0.5312

[a]Evaluation dates for each respective herbicide mixture. DAIT, days after initial treatment.
[b]Observed means followed by a minus (–) are significantly different from Blouin's modified Colby's expected responses at the 5% level, indicating an antagonistic response. No (–) indicates a neutral response.
[c]$P < 0.05$ indicates an antagonistic response; $P > 0.05$ indicates a neutral response.
[d]Control observed for each mixture herbicide with an additional independent application of quizalofop applied at 28 DAIT.

Results and discussion

Antagonistic responses were observed at 14, 28, and 42 DAIT for red rice control when quizalofop was mixed with propanil (Table 2). At 14 and 28 DAIT, the expected control of red rice treated with quizalofop plus propanil was 94% to 95% compared with an observed control of 75% and 71%, respectively. At 42 DAIT, the sequential application of quizalofop was not able to overcome the initial antagonism observed at 14 and 28 DAIT for quizalofop previously applied mixed with propanil. Red rice treated with quizalofop plus propanil followed by quizalofop indicated an observed control of 94%, with a P-value of 0.0479 compared with an expected control of 99%. All other contact herbicides mixed with quizalofop resulted in a neutral response for red rice control at all evaluation dates, indicating their potential as mix partners with quizalofop for red rice control in ACCase-R rice production.

Similar to red rice responses at 14 and 28 DAIT, the addition of propanil to quizalofop resulted in an observed control of CLXL-745 IR-hybrid rice of 75% and 69%, respectively, compared with an expected control of 92% to 94% (Table 3). Additional antagonistic mixtures for CLXL-745 control included quizalofop mixed with bentazon or saflufenacil at 14 DAIT, with an observed control of 89% to 88% with P-values of 0.0427 and 0.0048, respectively, compared with an expected control of 93%. However, these same mixtures indicated neutral responses at 28 DAIT, similar to what was observed for red rice control. At 42 DAIT, the sequential quizalofop application at 28 DAIT was not able to overcome the antagonism observed at 14 and 28 DAIT with a quizalofop plus propanil mixture, with an observed control of 92% compared with

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Table 3. Hybrid CLXL-745 imidazolinone-resistant rice control with quizalofop applied alone or mixed with various herbicides with contact activity using Blouin's modified Colby's analysis, in 2015 and 2016

		Quizalofop g ai ha^{-1}			
		0	120		
Mixture herbicide[a]	Rate	Observed	Expected	Observed[b]	P-value[c]
	g ai ha^{-1}	——% of control——			
14 DAIT					
None	–	0	–	94	–
Bentazon	1050	0	93	89–	0.0427
Carfentrazone	18	0	93	90	0.0765
Propanil	3360	0	93	75–	0.0000
Saflufenacil	25	0	93	88–	0.0048
Thiobencarb	3360	0	93	91	0.1122
28 DAIT					
None	–	0	–	92	–
Bentazon	1050	0	92	87	0.3180
Carfentrazone	18	0	92	88	0.7670
Propanil	3360	0	92	69–	0.0000
Saflufenacil	25	0	92	84	0.8822
Thiobencarb	3360	0	92	88	0.6568
42 DAIT[d]					
None	–	0	–	99	–
Bentazon	1050	82	99	97	0.3169
Carfentrazone	18	81	99	96	0.1603
Propanil	3360	73	99	92–	0.0043
Saflufenacil	25	80	99	98	0.6031
Thiobencarb	3360	76	99	97	0.2689

[a]Evaluation dates for each respective herbicide mixture. DAIT, days after initial treatment.
[b]Observed means followed by a minus (–) are significantly different from Blouin's modified Colby's expected responses at the 5% level, indicating an antagonistic response. No (–) indicates a neutral response.
[c]$P < 0.05$ indicates an antagonistic response; $P > 0.05$ indicates a neutral response.
[d]Control observed for each mixture herbicide with an additional independent application of quizalofop applied at 28 DAIT.

Table 4. CL-111 imidazolinone-resistant rice control with quizalofop applied alone or mixed with various herbicides with contact activity using Blouin's modified Colby's analysis, in 2015 and 2016

		Quizalofop g ai ha^{-1}			
		0	120		
Mixture herbicide[a]	Rate	Observed	Expected	Observed[b]	P-value[c]
	g ai ha^{-1}	——% of control——			
14 DAIT					
None	–	0	–	94	–
Bentazon	1050	0	94	82–	0.0022
Carfentrazone	18	0	94	86	0.0581
Propanil	3360	0	94	71–	0.0000
Saflufenacil	25	0	94	86	0.0581
Thiobencarb	3360	0	94	87	0.1219
28 DAIT					
None	–	0	–	92	–
Bentazon	1050	0	92	89	0.3072
Carfentrazone	18	0	92	93	0.7779
Propanil	3360	0	92	71–	0.0000
Saflufenacil	25	0	92	91	0.6981
Thiobencarb	3360	0	92	91	0.6216
42 DAIT[d]					
None	–	0	–	99	–
Bentazon	1050	78	99	97	0.3169
Carfentrazone	18	80	99	96	0.1603
Propanil	3360	79	99	92–	0.0043
Saflufenacil	25	77	99	98	0.6031
Thiobencarb	3360	77	99	98	0.2689

[a]Evaluation dates for each respective herbicide mixture. DAIT, days after initial treatment.
[b]Observed means followed by a minus (–) are significantly different from Blouin's modified Colby's expected responses at the 5% level, indicating an antagonistic response. No (–) indicates a neutral response.
[c]$P < 0.05$ indicates an antagonistic response; $P > 0.05$ indicates a neutral response.
[d]Control observed for each mixture herbicide with an additional independent application of quizalofop applied at 28 DAIT.

an expected control of 99%. All other mixtures indicated a neutral response at 42 DAIT for CLXL-745 control following the sequential quizalofop application.

CL-111 responses were similar to CLXL-745, except a neutral response was observed for quizalofop mixed with saflufenacil at 14 DAIT (Table 4). As with red rice and CLXL-745 treated with quizalofop plus propanil, quizalofop activity on CL-111 was also antagonized, and this response was consistent throughout all DAIT evaluations. These data for control of each rice line indicate propanil should be avoided in ACCase-R rice production for weedy rice management.

Barnyardgrass was also evaluated each year of this study. Similar to red rice, CLXL-745, and CL-111, propanil antagonized quizalofop activity on barnyardgrass at 14 and 28 DAIT with an observed control of 38% and 16%, respectively, compared with an expected control of 92% to 94% (Table 5). By 42 DAIT, the second quizalofop application at 28 DAIT could not overcome the antagonism observed at the earlier evaluations at 14 and 28 DAIT, with an observed control of 83% compared with an expected control of 99%. Similar to quizalofop mixed with propanil, Rustom et al. (2018) reported severe antagonism when barnyardgrass was treated with quizalofop mixed with penoxsulam or bispyribac for the initial application; however, the second application was only able to overcome the antagonism observed for barnyardgrass previously treated with quizalofop plus bispyribac. Quizalofop activity on barnyardgrass was antagonized by saflufenacil at 14 DAIT. By 28 DAIT, the same mixture resulted in a neutral response for quizalofop activity on barnyardgrass. Saflufenacil slowed the initial activity of quizalofop; however, by 28 DAIT, the activity of quizalofop was similar to quizalofop applied alone. Bentazon mixed with quizalofop resulted in a neutral response for barnyardgrass control at all evaluation dates; however, this mixture antagonized quizalofop activity on CLXL-745 and CL-111 at 14 DAIT. As with red rice, CLXL-745, and CL-111 at all DAIT, barnyardgrass treated with quizalofop plus carfentrazone or thiobencarb resulted in a neutral response, indicating the potential for use as a mixture in an ACCase-R rice production system for control of these weeds.

ACCase-R rice injury was less than 10% across all evaluations (unpublished data). ACCase-R rice treated with two independent applications of quizalofop resulted in a rough rice yield of 5,450 kg ha^{-1} (Table 6). ACCase-R rice treated with quizalofop plus carfentrazone or thiobencarb followed by quizalofop yielded 5,250 and 5,070 kg ha^{-1}, respectively, with no differences compared with ACCase-R rice treated with two independent applications of quizalofop. In comparison, ACCase-R rice treated with quizalofop plus propanil yielded 1,970 kg ha^{-1}, and this yield did not differ when compared with the nontreated ACCase-R rice. This yield reduction is a result of surviving red rice, CLXL-745, CL-111, and barnyardgrass competition with ACCase-R rice across all evaluations due to antagonism of quizalofop when mixed with propanil. Yields for ACCase-R rice treated with quizalofop plus bentazon or saflufenacil were reduced to 4,110 and 4,570 kg ai ha^{-1}, respectively, and these yield reductions are likely a result of the antagonism observed at

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Table 5. Barnyardgrass control with quizalofop applied alone or mixed with various herbicides with contact activity using Blouin's modified Colby's analysis, in 2015 and 2016

		Quizalofop g ai ha^{-1}			
		0	120		
Mixture herbicide[a]	Rate	Observed	Expected	Observed[b]	P-value[c]
	g ai ha^{-1}	% of control			
14 DAIT					
None	–	0	–	89	–
Bentazon	1050	0	89	82	0.1315
Carfentrazone	18	0	89	82	0.1315
Propanil	3360	27	92	38–	0.0000
Saflufenacil	25	17	91	81–	0.0340
Thiobencarb	3360	20	91	85	0.1443
28 DAIT					
None	–	0	–	92	–
Bentazon	1050	0	92	87	0.2705
Carfentrazone	18	7	92	94	0.7340
Propanil	3360	32	94	16–	0.0000
Saflufenacil	25	12	93	93	0.9701
Thiobencarb	3360	15	93	92	0.7721
42 DAIT[d]					
None	–	0	–	99	–
Bentazon	1050	79	99	98	0.6124
Carfentrazone	18	77	99	95	0.2358
Propanil	3360	77	99	83–	0.0000
Saflufenacil	25	80	99	98	0.7129
Thiobencarb	3360	80	99	97	0.4016

[a]Evaluation dates for each respective herbicide mixture. DAIT, days after initial treatment.
[b]Observed means followed by a minus (–) are significantly different from Blouin's modified Colby's expected responses at the 5% level, indicating an antagonistic response. No (–) indicates a neutral response.
[c]P < 0.05 indicates an antagonistic response; P > 0.05 indicates a neutral response.
[d]Control observed for each mixture herbicide with an additional independent application of quizalofop applied at 28 DAIT.

Table 6. Rough rice yields of ACCase-resistant rice treated with quizalofop and each respective mixture in 2015 and 2016

		Quizalofop g ai ha^{-1}	
Mixture herbicide[a]	Rate	0	120
	g ai ha^{-1}	kg ha^{-1}	
None	–	1,980 f	5,450 a
Bentazon	1,050	2,900 e	4,110 c
Carfentrazone	18	2,850 e	5,250 a
Propanil	3,360	3,610 d	1,970 f
Saflufenacil	25	2,650 e	4,570 b
Thiobencarb	3,360	2,950 e	5,070 a

[a]Respective contact herbicide mixed with quizalofop.
[b]Means followed by a common letter are not significantly different at P = 0.05 with Tukey's HSD.

14 DAIT on CLXL-745, CL-111, and/or barnyardgrass. These data indicate that early-season antagonism of quizalofop activity for red rice, CLXL-745, CL-111, and/or barnyardgrass control can negatively affect ACCase-R rice yield.

In conclusion, it is essential to understand the compatibility between quizalofop and the herbicides evaluated in this study before developing a herbicide program for ACCase-R rice production. When comparing all contact herbicides evaluated, these data suggest propanil is least compatible when mixed with quizalofop, and activity can be severely antagonized when applied on red rice, CLXL-745, CL-111, or barnyardgrass, even with a follow-up treatment of quizalofop applied alone at 28 DAIT. Furthermore, this antagonism can result in significant yield reduction and can potentially have a negative impact on overall economic returns. ACCase herbicides require a metabolic conversion in plants to become active; however, Ottis et al. (2005) reported this metabolism was hindered by an interaction of propanil with an apoplastic esterase enzyme, resulting in antagonism. Quizalofop activity can also be antagonized when applied in a mixture with saflufenacil or bentazon, and this antagonism can correspond to an overall yield reduction. These data contradict Zhang et al. (2005), who reported fenoxaprop antagonism by carfentrazone on barnyardgrass; however, these data are consistent with the reporting of a neutral response for barnyardgrass treated with fenoxaprop plus bentazon. Although weedy rice and barnyardgrass treated with quizalofop plus bentazon or saflufenacil indicated neutral responses at 28 DAIT, an antagonistic interaction was observed at 14 DAIT for red rice, CLXL-745, CL-111, or barnyardgrass control, indicating that these weeds can compete with ACCase-R rice early in the growing season and result in a yield reduction. Yield data for ACCase-R rice and control data for red rice, CLXL-745, CL-111, and barnyardgrass treated with quizalofop plus carfentrazone or thiobencarb indicate potential as mixture herbicides with quizalofop.

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