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Quizalofop-P-Ethyl Herbicide Interactions in Accase-Resistant Rice Production

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QUIZALOFOP-P-ETHYL HERBICIDE INTERACTIONS IN ACCASE-RESISTANT RICE PRODUCTION

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Abstract

A field study was conducted in 2015 and 2016 at the H. Rouse Caffey Rice Research Station (RRS) to evaluate mixture interactions of quizalofop and ALS-inhibiting herbicides. Quizalofop was applied at 120 g ai ha^{-1}. Mixture herbicides included penoxsulam at 40 g ha^{-1}, penoxsulam plus triclopyr at 352 g ha^{-1}, halosulfuron at 53 g ha^{-1}, bispyribac at 34 g ha^{-1}, orthosulfamuron plus halosulfuron at 94 g ha^{-1}, orthosulfamuron plus quinclorac at 491 g ha^{-1}, imazosulfuron at 211 g ha^{-1}, and bensulfuron at 43 g ha^{-1}. All ALS herbicides mixed with quizalofop indicated antagonistic responses for weedy rice or barnyardgrass control at either 14 or 28 days after treatment (DAT). At 28 DAT, quizalofop mixed with penoxsulam or bispyribac controlled barnyardgrass 33 to 38%, compared with an expected control of 91 to 92%.

A study was conducted at the RRS to evaluate interactions of quizalofop applied in mixtures with contact herbicides. Quizalofop was applied at 120 g ha^{-1}. Mixture herbicides included carfentrazone at 18 g ha^{-1}, propanil at 3360 g ha^{-1}, saflufenacil at 25 g ha^{-1}, or thiobencarb at 3360 g ha^{-1}. Propanil severely antagonized quizalofop activity on weedy rice and barnyardgrass at all evaluations. At 28 DAT, barnyardgrass treated with quizalofop mixed propanil indicated an observed control of 16%, compared with an expected control of 93%.

A study was conducted at the RRS evaluating sequential applications of quizalofop at 120 g ha^{-1} and propanil plus thiobencarb at 672 g ai ha^{-1}. A prepackage mixture of propanil plus thiobencarb was applied for each timing treatment when ACCase-R rice was at the 2- to 3-leaf growth stage (day 0). Application timing treatments consisted of quizalofop applied at 7, 3, and 1 days before (DBPT) and after (DAPT) the propanil plus thiobencarb application at day 0. Additionally, quizalofop was applied alone and in a mixture with propanil plus thiobencarb at day 0. Quizalofop activity was reduced on weedy rice and barnyardgrass when applied at 1 and 3 DAPT or mixed with propanil plus thiobencarb at day 0; however, quizalofop activity was not reduced when applied before propanil plus thiobencarb.

Chapter 1

Introduction

Imidazolinone-resistant (IR) rice, also known as Clearfield (CL), became available to rice producers in 2002, offering an opportunity to control red rice with imidazolinone herbicides (Croughan 2003). IR-hybrid rice was introduced in 2003. For the first time, rice producers could selectively control red rice (*Oryza sativa* L.) with a herbicide during cultivated rice production.

Crops are often associated with their respective weedy forms and for over 150 years red rice has been a troublesome, conspecific weed of cultivated rice (Craigmiles 1978; De Wet and Harlan 1975; Gealy et al. 2003). Clearfield hybrid rice seed has a history of dormancy and rapid seed shattering, and can become weedy when allowed to establish in succeeding growing seasons as a volunteer (Sudianto et al. 2013). Outcrossing between cultivated rice and its weedy and wild relatives, red rice and *O. rufipogon*, has been reported (Chen et al. 2004; Majumder et al. 1997; Messeguer et al. 2004; Oka and Chang 1961; Song et al. 2002; 2003). Research conducted by Rajguru et al. (2005) suggested the IR technology used in IR rice production could be transferred by natural outcrossing to produce IR red rice. Red rice is a serious weed pest in rice production in the United States, Brazil, Australia, Spain, and in most other rice-producing countries (Croughan 1999). From this point forward, the entire complex of red rice, volunteer hybrid rice, and outcrosses will be referred to as weedy rice.

Red rice can become the dominant weed when present because of its high competitive ability (Smith 1988). Smith (1988) suggested red rice competition reduced cultivated rice yield by 80% and one plant per m^2 can reduce cultivated rice yield by 219 kg ha^{-1} after season-long competition. Fischer and Ramirez (1993) conducted growth analysis and competition studies involving red rice and cultivated rice, concluding red rice populations of 5 and 20 plants m^2 reduced cultivated rice yield by 40 and 60%, respectively. In a separate study, red rice infestations of 2, 5, 10, 20, and 40 plants m^{-2} reduced cultivated rice yield by 19, 29, 45, 74, and 87%, respectively. Research also suggests red rice densities of 108 and 215 plants per m^2 can reduce cultivated rice yield 77 and 82%, respectively (Diarra 1985). In the southern United States, the total loss from red infestations was estimated to be $50 million in 1979 (Smith 1981).

Weedy rice plants can have many phenotypic characteristics including pubescent or glabrous leaves, medium or long grains, awned and/or awnless seed, and dark to light green vegetation color (Rustom et al. 2015). Weedy rice grain color can vary from deep red, black to tan (Diarra 1985). Because of its superior height and tillering capability in comparison to cultivated rice, weedy rice can utilize resources such as nutrients and light at a higher rate than cultivated rice in a competitive environment (Estorninos et al. 2005; Kwon et al. 1992).

Barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv.) is also a troublesome weed in rice production throughout the world and can reduce yields of direct seeded and transplanted rice (Holm and Herberger 1969; Noda et al. 1968; Smith 1968). Historically, weed control programs in rice in the southern United States included propanil for the control of annual grass and broadleaf weeds (Smith 1965; Smith and Hill 1990). Propanil was commercialized in the early 1960s and was one of the first herbicides that controlled barnyardgrass in rice. In 1995, 98% of Arkansas rice fields received at least one application of propanil per year (Carey et al. 1995). Barnyardgrass resistant to propanil and quinclorac has become a common problem in rice production and the potential exists for the continued spread of resistant biotypes (Talbert and Burgos 2007). Arkansas greenhouse studies in 1990 and 1991 suggested barnyardgrass collections from six farms in Poinsett Co., AR were not controlled by propanil at rates as high as 11 kg ha^{-1} (Smith and Baltazar 1992). Malik et al. (2010) reported propanil and quinclorac applications had little to no activity on certain barnyardgrass samples taken in Arkansas. Some barnyardgrass populations in Arkansas and Mississippi have indicated resistance to acetolactate synthase (ALS) herbicides such as imazamox, imazethapyr, penoxsulam, or bispyribac-sodium (Riar et al. 2013).

With the evolution of IR weedy rice and barnyardgrass resistant to herbicides with several different modes of action, BASF is currently developing a new herbicide resistant cultivar called Provisia® (BASF, Research Triangle Park, NC 27709). The herbicide targeted for use in Provisia rice is quizalofop, which inhibits acetyl coenzyme A carboxylase (ACCase), the enzyme catalyzing the first committed step of *de novo* fatty acid synthesis (Burton et al. 1989; Focke and Lichtenthaler 1987). The aim of the ACCase-resistant rice (ACCase-R) system is to provide a new technology that can be used to manage weedy rice and other grass species during cultivated rice production that are resistant or susceptible to currently available herbicides.

Quizalofop provides postemergence (POST) activity on nearly all annual and perennial grasses (Shaner 2014). Quizalofop has been used to substantially reduce red rice infestations during soybean production in both field and glasshouse trials (Minton et al. 1989; Askew et al. 1998). The application rate of quizalofop in soybean production is 35 to 84 g ai ha^{-1} and 84 to 112 g ai ha^{-1} in non-crop areas (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 ai ha^{-1} per year.

Herbicide mixtures have proven to be beneficial in improving efficacy, broadening the weed control spectrum, and maximizing yield and economic returns (Carlson et al. 2011; Pellerin et al. 2003, 2004; Webster et al. 2012). Herbicides used in mixtures often have different modes of action (Blouin et al. 2010; Hydrick and Shaw 1994; Lanclos et al. 2002; Zhang et al. 2005), and mixtures can have one of three responses: synergistic, antagonistic, or additive/neutral (Berenbaum 1981; Blouin 2010; Hatzios and Penner 1985; Morse 1978; Nash 1981; Streibig et al. 1998; Fish et al. 2015, 2016). In IR rice production, imazethapyr mixed with propanil or propanil plus thiobencarb resulted in a synergistic response for red rice control. However, antagonism was observed on barnyardgrass with the same mixtures (Fish et al

2015). Fish (2016) observed synergistic responses for red rice control with imazamox plus propanil mixtures, but responses for barnyardgrass control were antagonistic or neutral.

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." However, previous research has indicated ACCase herbicide activity is often antagonized when mixed with broadleaf and/or sedge herbicides (Barnwell and Cobb 1994). Zhang et al. (2005) observed antagonism of fenoxaprop on barnyardgrass when applied in a mixture with bensulfuron, carfentrazone, halosulfuron, or triclopyr. Scherder et al. (2005) observed antagonism on barnyardgrass and broadleaf signalgrass (*Urochloa platyphylla* Munro ex. C. Wright) with halosulfuron, triclopyr, or propanil applied in a mixture with cyhalofop. Antagonism of quizalofop has been observed when mixed with bromoxynil, pyrithiobac, or chlorimuron on yellow foxtail (*Setaria pumila* Pior), johnsongrass (*Sorghum halepense* L.), and broadleaf signalgrass, respectively (Culpepper 1999; Snipes and Allen 1996; Bjelk and Monaco 1992). Blackshaw et al. (2006) observed quizalofop antagonism by 2,4-D amine on volunteer wheat (*Triticum aestivum* L.) seedlings. Vidrine et al. (1995) determined quizalofop to be least susceptible to antagonism on johnsongrass and barnyardgrass when compared with clethodim, fluazifop, sethoxydim, and fenoxaprop when mixed with lactofen, imazaquin, chlorimuron, or fomesafen.

Colby's method is a statistical linear model commonly used to determine a synergistic, antagonistic, or additive/neutral response among herbicide mixtures by examining the herbicides applied alone and calculating an expected response when they are combined (Colby 1967). This model was utilized by Lanclos et al (2002) to determine antagonistic effects of various rice herbicides mixed with glufosinate in glufosinate-resistant rice. Blouin et al. (2004) suggests if the expected response is defined as a multiplicative, nonlinear function of the means for the herbicides when applied alone, then standard linear model methodology for tests of hypotheses does not apply directly, thus, the Blouin et al. (2004) nonlinear mixed-model is more sensitive than Colby's linear model in detecting significant differences in herbicide response. Zhang et al. (2005) employed the Blouin et al. (2004) nonlinear model to determine antagonistic effects of fenoxaprop mixed with propanil plus molinate or bentazon. Blouin et al. (2010) further modified the nonlinear model into the augmented mixed-model, which proved to be more versatile than the Blouin et al. (2004) nonlinear mixed model when observing fenoxaprop mixtures with various rice herbicides.

Research has indicated that herbicides applied sequentially can be more effective at certain timings than the same herbicides applied in a mixture (Burke et al. 2002; Corkern et al. 1998; Crooks et al. 2003; Dernoeden and Fidanza 1994; Myers and Coble 1992). Myers and Coble (1992) evaluated a reduction in imazethapyr activity when mixed with clethodim, fluazifop, quizalofop, or sethoxydim, in comparison to imazethapyr alone on large crabgrass (*Digitaria sanguinalis* L.), fall panicum (*Panicum dichotomiflorum* Michx.), and broadleaf signalgrass. Imazethapyr applied alone at 5 days before or 1 day after each of the graminicides did not decrease grass control when compared with each herbicide applied alone; however, imazethapyr applied 3 or 1 days before and the same day as the graminicides decreased grass weed control. Dernoeden and Fidanza (1994) evaluated sequential applications of 2,4-D plus mecoprop plus dicamba before and after a fenoxaprop application for smooth crabgrass control (*Digitaria ischaemum* Schreb.), concluding fenoxaprop activity was reduced when 2,4-D plus mecoprop plus dicamba was applied less than 14 days before fenoxaprop; however, no significant reduction in control was observed when the same herbicide was applied 21 days before or more than 3 days after the fenoxaprop application.

Herbicide mixtures are an integral part of weed management practices in both conventional and IR rice production. With the potential for ACCase antagonism by broadleaf and/or sedge herbicides, it is imperative to both evaluate and understand the efficacy of quizalofop when applied alone, in mixtures with, or sequentially with various broadleaf and/or sedge herbicides in an ACCase-resistant rice production system. This research will aid in developing beneficial herbicide programs for producers choosing to utilize ACCase-resistant rice production.

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Chapter 2

Interactions of Quizalofop-p-ethyl Mixed with Acetolactate Synthase (ALS) Herbicides used in Rice Production

Introduction

A rising weed management concern in rice (*Oryza sativa* L.) producing areas throughout the world is the management of weedy rice (*O. sativa* L.), more particularly imidazolinone-resistant (IR) weedy rice (Gressel and Valverde 2009). IR commercial rice technology was first commercialized in 2002 under the name Clearfield (CL) (BASF, Research Triangle Park, NC 27709) providing a tool for producers to control red rice with a herbicide during cultivated rice production for the very first time (Croughan 2003). Weedy rice is taxonomically classified as the same species as cultivated rice, but can include different phenotypic characteristics such as various grain color, medium to long grain size, awned and/or awnless seed, light to dark green vegetative color, variable plant height, and pubescent to glabrous leaves (Gressel and Valverde 2009; Rustom et al. 2015). Generally, weedy rice has superior height and tillering capabilities in comparison with cultivated rice; therefore, it 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).

IR hybrid rice seed has a history of dormancy, and can become weedy when allowed to voluntarily establish in succeeding growing seasons (Sudianto et al. 2013). Outcrossing between cultivated rice and its weedy and wild relatives, red rice and *O. rufipogon*, has also been reported (Chen et al. 2004; Majumder et al. 1997; Messegeur et al. 2004; Song et al. 2002; 2003). Research conducted by Rajguru et al. (2005) suggested the technology used in IR rice was transferred by natural outcrossing to produce IR red rice. The term weedy rice will refer to the entire complex of volunteer hybrids, outcrosses, and red rice.

Another weed management issue in rice producing areas throughout the world is barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv.). Barnyardgrass resistant to propanil, quinclorac, imazethapyr, imazamox, penoxsulam, or bispyribac-sodium has become a common issue in rice production throughout the southern United States and the potential exists for the continued spread of resistant biotypes (Riar et al. 2013; Talbert and Burgos 2007). Historically, weed control programs in rice in the southern United States have included propanil for the control of annual grasses such as barnyardgrass (Smith 1965; Smith and Hill 1990).

With rising concerns about IR weedy rice and barnyardgrass resistant to herbicides with several different modes of action, BASF is currently developing a new herbicide resistant rice to be sold under the trade name Provisia®. The herbicide targeted for use is quizalofop, which will also be sold under the trade name Provisia® (BASF, Research Triangle Park, NC 27709). Quizalofop is a Group 1 herbicide, with a mode of action that inhibits acetyl coenzyme A carboxylase (ACCase) (Burton et al. 1989; Focke and Lichtenthaler 1987). Quizalofop provides postemergence (POST) control of annual and perennial grasses, with little to no activity on broadleaf weeds and sedges (Shaner 2014). Quizalofop has been used to substantially reduce weedy rice infestations during soybean production when applied at rates from 35 to 84 g ai ha^{-1} and 84 to 112 g ha^{-1} in non-crop areas for annual or perennial grass control (Askew and Shaw 1998; Minton and Shaw 1989; Shaner 2014). The targeted single quizalofop application rate in ACCase-resistant (ACCase-R) rice production will be 92 to 155 g ha^{-1}, not to exceed 240 g ha^{-1} per year.

Herbicide mixtures have proven to be beneficial for improving efficacy, broadening the weed control spectrum, and maximizing yield and economic returns (Carlson et al. 2011; Pellerin et al. 2003, 2004; Webster et al. 2012). Herbicide mixtures can have one of three responses: synergistic, antagonistic, or neutral (Berenbaum 1981; Blouin 2010; Drury 1980; Fish et al. 2015; 2016; Hatzios and Penner 1985; Morse 1978; Nash 1981; Streibig et al. 1998;). ACCase herbicide activity is often antagonized when applied in mixtures with other herbicides (Barnwell and Cobb 1994). 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.” ACCase antagonism 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 neutral responses (Zhang et al. 2005). Blackshaw et al. (2006) observed quizalofop antagonism by 2,4-D amine on volunteer wheat (*Triticum aestivum* L.) seedlings. Vidrine et al. (1995) determined quizalofop to be least susceptible to antagonism on johnsongrass and barnyardgrass when compared with clethodim, fluazifop, sethoxydim, and fenoxaprop when mixed with lactofen, imazaquin, chlorimuron, or fomesafen.

ACCase-R rice will provide an additional tool for producers to control weedy rice and a broad range of grasses with quizalofop during cultivated rice production. There are many herbicides currently labeled for use in rice production; however, given the history of ACCase antagonism when mixed with other herbicides, it is important to understand which herbicides are antagonistic, synergistic, or neutral when applied in a mixture with quizalofop. These responses will aid in developing weed control programs for rice producers who utilize this new technology. The overall objective of this research was to determine antagonistic, synergistic, or neutral interactions of quizalofop mixtures with acetolactate synthase (ALS) inhibiting herbicides on weedy rice and barnyardgrass in ACCase-R rice production.

Materials and Methods

A study was conducted in 2015 and 2016 at the H. Rouse Caffey Rice Research Station (RRS) near Crowley, Louisiana to evaluate quizalofop activity when applied independently or in a mixture with ALS mode of action herbicides. The soil type at the RRS is a Crowley silt loam (fine smectic, thermic Typic Albaqualfs) with a pH of 6.4 and 1.4% organic matter. Field preparation consisted of a fall and spring disking followed by (FB) two passes in opposite directions with a two-way bed conditioner consisting of rolling baskets and S-tine harrows set at 6 cm depth.

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 'PVL024B' long grain rice, 2 rows of 'CL-111' long grain rice, and 2 rows of 'CLXL-745' long grain rice. Rice was planted at a rate of 67 kg ha^{-1}. Awnless straw-hull red rice was also broadcast in the plot area prior to drill seeding at a rate of 50 kg ha^{-1}. CL rice varieties and red rice were planted to represent a weedy rice population. The research area was naturally infested with barnyardgrass. The area was surface irrigated to a depth of 2.5 cm 24 hours after planting. A permanent 10-cm flood was established when ACCase-R rice reached the five-leaf to one-tiller stage, and was maintained until two weeks prior to harvest. Each herbicide application was applied when ACCase-R rice was at the three- to four-leaf growth stage with a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} with five flat-fan 110015 nozzles spaced at 35 cm. Red rice, CL-111, and CLXL-745 were at the three- to four-leaf growth stage and barnyardgrass was two- to five-leaf with a population of 50 to 100 plants m^2 when applications were applied.

This study was a randomized complete block with a factorial arrangement of treatments with four replications. Factor A was quizalofop applied at 120 g ha^{-1} or no quizalofop (Table 2.1). Factor B was penoxsulam at 40 g ai ha^{-1}, penoxsulam plus triclopyr at 352 g ai ha^{-1}, halosulfuron at 53 g ai ha^{-1}, bispyribac at 34 g ai ha^{-1}, orthosulafamuron plus halosulfuron at 94 g ai ha^{-1}, orthosulfamuron plus quinclorac at 491 g ai ha^{-1}, imazosulfuron at 211 g ai ha^{-1}, bensulfuron at 43 g ai ha^{-1}, or no mixture herbicide (Table 2.1). A second quizalofop application was applied to all treatments at a rate of 120 g ha^{-1} at 28 days after (DA) the initial quizalofop treatment (DAIT). The entire research area received an application of halosulfuron applied at of 53 g ha^{-1} at 14 DA the initial herbicide application for maintenance of broadleaf and sedge weeds when ACCase-R rice was at the 5-leaf to one-tiller growth stage. A crop oil concentrate (COC) (Agri-Dex® label, Helena Chemical Company, Collierville, TN) was added to each herbicide application at a rate of 1% v^{-1}.

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 = no injury or control and 100 = complete plant death at 14, 28, and 42 days 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 prior to harvest (data not shown). The center four rows planted in ACCase-R rice were harvested with a Mitsubishi VM3 (Mitsubishi Corporation, 3-1, Marunouchi 2- chome, Chiyoda-ky, Tokyo, Japan) plot combine 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 (release 9.4 SAS Institute, Cary, NC). 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 DAIT was checked with the use of the UNIVARIATE procedure of SAS and significant normality problems were not observed.

Table 2.1. Herbicide information for all products used in experiment[a]

Herbicide common name	Herbicide trade name	Rate	Manufacturer
		g ai ha^{-1}	
Bensulfuron	Londax	43	RiceCo LLC, Memphis, TN
Bispyribac	Regiment	34	Valent U.S.A. Corporation, Walnut Creek, CA
Halosulfuron	Permit	53	Gowan Company, Yuma, AZ
Imazosulfuron	League	211	Valent U.S.A. Corporation, Walnut Creek, CA
Orthosulfamuron + halosulfuron	Strada Pro	94	Nichino America, Inc, Wilmington, DE
Orthosulfamuron + quinclorac	Strada XT	491	Nichino America, Inc, Wilmington, DE
Penoxsulam	Grasp	40	Dow AgroSciences LLC, Indianapolis, IN
Penoxsulam + triclopyr	Grasp Xtra	352	Dow AgroSciences LLC, Indianapolis, IN
Quizalofop	Provisia	120	Dupont Crop Protection, Wilmington, DE

[a]All l treatments contained a crop oil concentrate (Agri-Dex® label, Helena Chemical Company, Collierville, TN)at 1% v^{-1}

Results and Discussion

Antagonistic responses were observed for red rice control at 14 DAIT when quizalofop was mixed with penoxsulam plus triclopyr or bispyribac by reducing an expected control of 92% to an observed control of 79 and 80%, respectively (Table 2.2). All other mixtures resulted in a neutral response on red rice at 14 DAIT. However, at 28 DAIT, all mixture herbicides evaluated antagonized quizalofop for red rice control. Penoxsulam, penoxsulam plus triclopyr, or bispyribac mixtures with quizalofop, reduced the expected control of 97% to an observed control of 64, 59, and 67%, respectively. Halosulfuron, orthosulfamuron plus halosulfuron, orthosulfamuron plus quinclorac, imazosulfuron, or bensulfuron mixtures with quizalofop reduced red rice control to an observed control of to 81 to 88%. A neutral response for red rice control was observed at 42 DAIT for all mixtures, due to the second independent application of quizalofop applied 28 DA the initial treatment. Expected control for red rice, regardless of mixtures, at 42 DAIT was 99% with an observed control of 94 to 99% for all treatments.

Table 2.2. Red rice control with quizalofop applied alone or mixed with various herbicides with activity on the ALS enzyme 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[d]					
None	—	0	—	91	—
Bensulfuron	43	0	92	88	0.3644
Bispyribac	34	0	92	80-	0.0112
Halosulfuron	53	0	92	86	0.1927
Imazosulfuron	211	0	92	86	0.2342
Orthosulfamuron + halosulfuron	94	0	92	88	0.4611
Orthosulfamuron + quinclorac	491	0	92	85	0.1488
Penoxsulam	40	0	92	83	0.0546
Penoxsulam + triclopyr	352	0	92	79-	0.0045

Table 2.2 continued.

Table 2.2 continued.

Mixture Herbicide[a]	Rate	Quizalofop (g ai ha^{-1}) 0 Observed	120 Expected	120 Observed[b]	P value[c]
	g ai ha^{-1}	% of control			
28 DAIT					
None	—	0	—	97	—
Bensulfuron	43	0	97	88-	0.0413
Bispyribac	34	0	97	67-	0.0000
Halosulfuron	53	0	97	86-	0.0188
Imazosulfuron	211	0	97	86-	0.0162
Orthosulfamuron + halosulfuron	94	0	97	86-	0.0109
Orthosulfamuron + quinclorac	491	0	97	81-	0.0004
Penoxsulam	40	0	97	64-	0.0000
Penoxsulam + triclopyr	352	0	97	59-	0.0000
42 DAIT[e]					
None	—	0	—	99	—
Bensulfuron	43	80	99	96	0.2885
Bispyribac	34	79	99	97	0.3658
Halosulfuron	53	76	99	98	0.6575
Imazosulfuron	211	81	99	96	0.2099
Orthosulfamuron + halosulfuron	94	76	99	97	0.4471
Orthosulfamuron + quinclorac	491	78	99	96	0.3205
Penoxsulam	40	78	99	97	0.3714
Penoxsulam + triclopyr	352	79	99	94	0.0917

[a]Evaluation dates for each respective herbicide mixture.
[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 an additive response.
[c]$P < 0.05$ indicates anantagonistic response, $P > 0.05$ indicates an additive response.
[d]DAIT, days after initial treatment.
[e]Control observed for each mixture herbicide with an additional independent application of quizalofop applied 28 days after the initial treatment.

Hybrid CLXL-745 rice was also treated with all mixtures evaluated for red rice control. Similar to red rice responses at 14 DAIT, the addition of bispyribac or penoxsulam plus triclopyr antagonized quizalofop activity; however, the addition of penoxsulam, halosulfuron, and orthosulfamuron plus quinclorac also antagonized quizalofop activity on CLXL-745 (Table 2.3). All mixture herbicides that antagonized quizalofop reduced observed control to 74 to 82%, compared with an expected control

Table 2.3. Hybrid rice CLXL-745 IR rice control with quizalofop applied alone or mixed with various herbicides with activity on the ALS enzyme 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[d]					
None	—	0	—	91	—
Bensulfuron	43	0	90	83	0.0781
Bispyribac	34	0	90	77-	0.0009
Halosulfuron	53	0	90	80-	0.0111
Imazosulfuron	211	0	90	84	0.1084
Orthosulfamuron + halosulfuron	94	0	90	85	0.2076
Orthosulfamuron + quinclorac	491	0	90	82-	0.0476
Penoxsulam	40	0	90	77-	0.0009
Penoxsulam + triclopyr	352	0	90	74-	0.0000
28 DAIT					
None	—	0	—	97	—
Bensulfuron	43	0	96	87-	0.0213
Bispyribac	34	0	96	66-	0.0000
Halosulfuron	53	0	96	87-	0.0140
Imazosulfuron	211	8	96	84-	0.0028
Orthosulfamuron + halosulfuron	94	0	96	85-	0.0056
Orthosulfamuron + quinclorac	491	0	96	78-	0.0000
Penoxsulam	40	0	96	61-	0.0000
Penoxsulam + triclopyr	352	0	96	57-	0.0000
42 DAIT[e]					
None	—	0	—	99	—
Bensulfuron	43	78	99	96	0.2492
Bispyribac	34	76	99	98	0.5464
Halosulfuron	53	79	99	98	0.6131
Imazosulfuron	211	79	99	94	0.0621
Orthosulfamuron + halosulfuron	94	74	99	97	0.4047
Orthosulfamuron + quinclorac	491	77	99	96	0.3155
Penoxsulam	40	77	99	97	0.3353
Penoxsulam + triclopyr	352	77	99	96	0.1762

[a]Evaluation dates for each respective herbicide mixture.

[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 an additive response.

[c]$P < 0.05$ indicates anantagonistic response, $P > 0.05$ indicates an additive response.

[d]DAIT, days after initial treatment.

[e]Control observed for each mixture herbicide with an additional independent application of quizalofop applied 28 days after the initial treatment.

of 90%. Similar to red rice, all ALS herbicides mixed with quizalofop proved to antagonize quizalofop activity on CLXL-745 at 28 DAIT. However, a second independent application of quizalofop 28 DAIT overcame the antagonism observed at 14 or 28 DAIT, with observed control of 94 to 98%, similar to observed control of red rice at 42 DAIT.

Antagonistic responses were observed at 14 DAIT for CL-111 when treated with quizalofop plus any ALS herbicide except bensulfuron, which indicated a neutral response at 14 DAIT (Table 2.4). All other ALS herbicides antagonized quizalofop, with an observed control 70 to 82%, compared with an expected control of 90%. Bensulfuron was the only ALS herbicide that did not antagonize quizalofop activity on red rice, CLXL-745, or CL-111 evaluated at 14 DAIT, and this may indicate the potential as a mixture herbicide with quizalofop early in the growing season when weedy rice is present. However, by 28 DAIT, antagonism was observed for all mixtures evaluated. Bensulfuron was slightly antagonistic to quizalofop activity by decreasing observed control to 88%, compared with an expected control of 96%, with a P-value of 0.0213. As with red rice and CLXL-745, the addition of a follow up application of quizalofop resulted in a neutral response for all ALS herbicide mixtures evaluated.

Table 2.4. CL-111 IR rice control with quizalofop applied alone or mixed with various herbicides with activity on the ALS enzyme 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[d]					
None	—	0	—	91	—
Bensulfuron	43	0	90	83	0.0779
Bispyribac	34	0	90	71-	0.0000
Halosulfuron	53	0	90	75-	0.0003
Imazosulfuron	211	0	90	79-	0.0077
Orthosulfamuron + halosulfuron	94	0	90	82-	0.0409

Table 2.4 continued.

Table 2.4 continued.

		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[d]					
Orthosulfamuron + quinclorac	491	0	90	79-	0.0064
Penoxsulam	40	0	90	77-	0.0010
Penoxsulam + triclopyr	352	0	90	70-	0.0000
28 DAIT					
None	—	0	—	97	—
Bensulfuron	43	0	96	88-	0.0213
Bispyribac	34	0	96	67-	0.0000
Halosulfuron	53	0	96	86-	0.0140
Imazosulfuron	211	8	96	85-	0.0028
Orthosulfamuron + halosulfuron	94	0	96	83-	0.0056
Orthosulfamuron + quinclorac	491	0	96	80-	0.0000
Penoxsulam	40	0	96	63-	0.0000
Penoxsulam + triclopyr	352	0	96	56-	0.0000
42 DAIT[e]					
None	—	0	—	99	—
Bensulfuron	43	77	99	96	0.2492
Bispyribac	34	75	99	98	0.5464
Halosulfuron	53	72	99	97	0.6131
Imazosulfuron	211	78	99	96	0.0621
Orthosulfamuron + halosulfuron	94	72	99	98	0.4047
Orthosulfamuron + quinclorac	491	76	99	96	0.3155
Penoxsulam	40	75	99	96	0.3353
Penoxsulam + triclopyr	352	76	99	95	0.1762

[a]Evaluation dates for each respective herbicide mixture.

[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 an additive response.

[c]$P < 0.05$ indicates anantagonistic response, $P > 0.05$ indicates an additive response.

[d]DAIT, days after initial treatment.

[e]Control observed for each mixture herbicide with an additional independent application of quizalofop applied 28 days after the initial treatment.

Barnyardgrass was evaluated each year of the study. Penoxsulam plus triclopyr and bispyribac antagonized quizalofop at 14 DAIT, as with red rice, CLXL-745, and CL-111 (Table 2.5). In addition, penoxsulam, orthosulfamuron plus halosulfuron, and orthosulfamuron plus quinclorac were also found to be antagonistic for barnyardgrass control when mixed with quizalofop. However, barnyardgrass treated with quizalofop plus imazosulfuron indicated a neutral response, even at 28 DAIT. As with red rice, CL-111, and CLXL-745, any antagonism observed at 14 and 28 DAIT was overcome with a second application of quizalofop, except with penoxsulam containing herbicides. These data indicate that penoxsulam may need to be avoided in an ACCase-R rice production system.

Table 2.5. Barnyardgrass control with quizalofop with quizalofop mixed with various herbicides with activity on the ALS enzyme 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[d]					
None	—	0	—	91	—
Bensulfuron	43	0	89	84	0.3377
Bispyribac	34	22	91	60-	0.0000
Halosulfuron	53	0	89	85	0.3910
Imazosulfuron	211	21	91	86	0.2228
Orthosulfamuron + halosulfuron	94	18	91	80-	0.0208
Orthosulfamuron + quinclorac	491	53	93	73-	0.0000
Penoxsulam	40	34	91	58-	0.0000
Penoxsulam + triclopyr	352	32	92	61-	0.0000
28 DAIT					
None	—	0	—	97	—
Bensulfuron	43	0	97	87-	0.0405
Bispyribac	34	9	97	34-	0.0000
Halosulfuron	53	0	97	85-	0.0188
Imazosulfuron	211	8	97	88	0.0663
Orthosulfamuron + halosulfuron	94	9	97	83-	0.0038
Orthosulfamuron + quinclorac	491	17	97	75-	0.0000
Penoxsulam	40	10	97	38-	0.0000
Penoxsulam + triclopyr	352	13	97	33-	0.0000
42 DAIT[e]					
None	—	0	—	99	—
Bensulfuron	43	79	99	96	0.4521
Bispyribac	34	78	99	92	0.1571
Halosulfuron	53	71	99	94	0.3223
Imazosulfuron	211	75	99	93	0.2274
Orthosulfamuron + halosulfuron	94	76	99	96	0.5402
Orthosulfamuron + quinclorac	491	79	99	91	0.0951

Table 2.5 continued.

Table 2.5 continued.

		Quizalofop (g ai ha⁻¹)			
		0	120		
Mixture Herbicide[a]	Rate	Observed	Expected	Observed[b]	P value[c]
	g ai ha^{-1}	% of control			
42 DAIT[e]					
Penoxsulam	40	78	99	88-	0.0226
Penoxsulam + triclopyr	352	78	99	87-	0.0091

[a]Evaluation dates for each respective herbicide mixture.

[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 an additive response.

[c]P < 0.05 indicates anantagonistic response, P > 0.05 indicates an additive response.

[d]DAIT, days after initial treatment.

[e]Control observed for each mixture herbicide with an additional independent application of quizalofop applied 28 days after the initial treatment.

Crop injury was less than 10% across all evaluations (data not shown). ACCase-R rough rice yield was 6300 kg ha^{-1} when treated with quizalofop applied alone (Table 2.6). ACCase-R rice yield was reduced to 1350 to 2750 kg ha^{-1} when treated with quizalofop mixed with penoxsulam, penoxsulam plus triclopyr, or bispyribac. These three mixtures also consistently antagonized quizalofop activity on red rice, CLXL-745, CL-111, and barnyardgrass. ACCase-R rice treated with quizalofop mixed with halosulfuron, orthosulfamuron plus halosulfuron, orthosulfamuron plus quinclorac imazosulfuron, or bensulfuron resulted in a yield of 4510 to 5410 kg ha^{-1}. These mixtures were also antagonistic on red rice, CLXL-745, CL-111, and barnyardgrass. These yield data indicate antagonism of quizalofop by ALS inhibiting herbicides on weedy rice and barnyardgrass result in corresponding yield reductions of ACCase-R rice.

Table 2.6. 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}	kg ha^{-1}
None	—	2300 h	6300 a
Bispyribac	34	2240 h	1350 i
Bensulfuron	43	2750 fg	4510 e
Halosulfuron	53	2850 fg	5410 bc
Imazosulfuron	211	3020 f	4970 cd
Orthosulfamuron + halosulfuron	94	2970 f	4690 de
Orthosulfamuron + quinclorac	491	2920 f	5740 b
Penoxsulam	40	2590 fgh	2580 fgh
Penoxsulam + triclopyr	352	2410 gh	2750 fg

[a]Respective herbicide mixtures

[b]Means followed by a common letter are not significantly different at P = 0.05 with the use of Fisher's protected LSD

In conclusion, it is important to understand the compatibility between quizalofop and ALS inhibiting herbicides before developing a herbicide program for ACCase-R rice. These data suggest applying quizalofop mixed with common ALS herbicides used in rice production can result in an antagonistic response resulting in a yield reduction, thus reducing economic returns. All mixtures evaluated indicated an antagonistic response on either barnyardgrass or weedy rice at either 14 or 28 DAIT. By 28 DAIT, penoxsulam containing compounds and bispyribac were least compatible with quizalofop for barnyardgrass and weedy rice control, thus resulting in greatest ACCase-R rice yield loss. ACCase-R rice treated with penoxsulam containing herbicides indicated similar yields when applied alone or mixed with quizalofop. ACCase-R rice treated with bispyribac resulted in lower yields when applied in a mixture with quizalofop, compared with bispyribac applied alone, and this may indicate quizalofop may also antagonize bispyribac. Zhang et al. (2005) reported similar antagonistic responses with ALS inhibiting herbicides halosulfuron or bensulfuron mixed with the ACCase herbicide fenoxaprop. Another ACCase herbicide, cyhalofop, has also been reported to be antagonized when mixed with halosulfuron (Scherder et al. 2005). These data indicate a second application of quizalofop alone applied 28 DAIT can result in a neutral response for weedy rice and barnyardgrass control, except where quizalofop was previously applied mixed with penoxsulam containing herbicides on barnyardgrass. Though these data indicate neutral responses from a second quizalofop application for barnyardgrass and weedy rice, initially antagonized weeds can still compete with ACCase-R rice, resulting in yield reductions. When comparing weedy rice or barnyardgrass control and ACCAse-R rice yield, independent applications of quizalofop are more beneficial than mixing quizalofop with ALS inhibiting herbicides; however, ALS herbicides can be applied 28 days prior to quizalofop in ACCase-R rice production to avoid antagonism of quizalofop activity.

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Chapter 3

Interactions of Quizalofop-p-ethyl Mixed with Contact Herbicides used in Rice Production

Introduction

Imidazolinone-resistant (IR) rice (*Oryza sativa* L.), sold under the name Clearfield® (BASF, Research Triangle Park, NC 27709) is resistant to imidazolinone herbicides (Croughan 2003). This herbicide resistant technology was commercialized in 2002, and for the first time rice producers were able to control red rice (*O. sativa* L.) with a herbicide during cultivated rice production. IR hybrid rice was introduced in 2003 (RiceTec, Inc. Houston, TX).

Crops are often associated with their respective weedy forms and for over 150 years, red rice has been a troublesome, conspecific pest of cultivated rice (Craigmiles 1978; De Wet and Harlan 1975; Gealy et al. 2003). Another conspecific pest to cultivated rice is volunteer hybrid IR rice. Hybrid rice seed has a history of dormancy and becomes weedy when allowed to establish in succeeding growing seasons (Sudianto et al. 2013). From this point forward, the entire complex of conspecific rice pests to rice will be referred to as weedy rice. Research has suggested IR technology can be transfered by outcrossing to produce IR red rice (Rajguru et al. 2005). A major issue with weedy rice is the ability to outcross with inbred and hybrid IR rice, causing the development of IR weedy rice.

Weedy rice, more specifically IR weedy rice, has become a major weed management concern in cultivated rice production (Gressel and Valverde 2009). Weedy rice is taxonomically classified as the same species as cultivated rice; however, the two can often differ phenotypically with regards to plant height, grain color, grain size, presence of awns, vegetative color, and pubescence (Rustom et al. 2015). 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 one red plant per m^2 can reduce yield by 219 kg ha $^{-1}$ after season long competition.

Another weed management issue in rice production throughout the world is barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv.) resistant to propanil, quinclorac, penoxsulam, bispyribac, and imidazolinone herbicides. Historically, weed control programs in rice across the southern United States have included propanil to control barnyardgrass (Smith 1965; Smith and Hill 1990). Reports in 1995 indicated 98% of Arkansas rice fields receive at least one application of propanil per year to control weeds such as barnyardgrass (Carey et al. 1995). In 2010, Malik et al. reported significant propanil or quinclorac resistant barnyardgrass populations in the state of Arkansas.

With rising concerns about IR weedy rice and barnyardgrass resistant to several herbicides with different modes of action, BASF is currently developing a new herbicide resistant rice. This rice was developed 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). ACCase-resistant rice (ACCase-R) will allow the use of quizalofop applied postemergence to control many annual and perennial grasses including the weedy rice complex (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} per year. Quizalofop has been used to substantially reduce red rice infestations during soybean production applied at rates from 35 to 84 g ai ha^{-1} and 84 to 112 g ha^{-1} in non-crop areas for annual or perennial grass control.

Herbicide mixtures have proven to be beneficial for improving efficacy, broadening the weed control spectrum, and maximizing yield and economic returns (Carlson et al. 2011; Pellerin et al. 2003, 2004; Webster et al. 2012). Herbicide mixtures can have one of three responses: synergistic, antagonistic, or neutral (Berenbaum 1981; Blouin 2010; Drury 1980; Fish et al. 2015; 2016; Hatzios and Penner 1985; Morse 1978; Nash 1981; Streibig et al. 1998). ACCase inhibiting herbicide activity is often antagonized when applied in mixtures with other herbicides (Barnwell and Cobb 1994; Blackshaw et al. 2006; 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." 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).

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 weeds; however, given the history of ACCase antagonism when mixed with 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 utilize this new technology. The objective of this research was to evaluate potential antagonistic, synergistic, or neutral interactions of quizalofop mixtures with herbicides that have primarily contact activity when used in an ACCase-R rice production system.

Materials and Methods

A study was conducted in 2015 and 2016 at the H. Rouse Caffey Rice Research Station (RRS) near Crowley, Louisiana to evaluate quizalofop activity when applied independently or in a mixture with contact herbicides. The soil type at the RRS is a Crowley silt loam (fine smectic, thermic Typic Albaqualfs) with a pH of 6.4 and 1.4%

organic matter. Field preparation consisted of a fall and spring disking followed by (FB) two passes in opposite directions with a two-way bed conditioner consisting of rolling baskets and S-tine harrows set at 6 cm depth.

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 'PVL024B' 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 prior to drill seeding at a rate of 50 kg ha^{-1}. IR rice varieties and red rice were planted to represent a weedy rice population. The research area was naturally infested with barnyardgrass. The area was surface irrigated to a depth of 2.5 cm 24 hours after planting. A permanent 10-cm flood was established when ACCase-R rice reached the five-leaf to one-tiller stage, and was maintained until two weeks prior to harvest. Each herbicide application was applied when ACCase-R rice was at the three- to four-leaf growth stage with a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} with five flat-fan 110015 nozzles (Greenleaf Technologies, Covington LA, 70433) spaced 35 cm apart. Red rice, CL-111, and CLXL-745 were at the three- to four-leaf growth stage and barnyardgrass was two- to five-leaf with a population of 50 to 100 plants m^2 when applications were applied.

The study was a randomized complete block with a factorial arrangement of treatments with four replications. Factor A was quizalofop applied at 120 g ha^{-1} or no quizalofop (Table 3.1). Factor B was bentazon at 1050 g ai ha^{-1}, carfentrazone at 18 g ai ha^{-1}, propanil at 3360 g ai ha^{-1}, saflufenacil at 25 g ai ha^{-1}, thiobencarb at 3360 g ai ha^{-1}, or no mixture herbicide (Table 3.1). A second quizalofop application was applied to all treatments at a rate of 120 g ha^{-1} at 28 days after (DA) the initial quizalofop treatment (DAIT). The entire research area was treated with halosulfuron applied at a rate of 53 g ai ha^{-1} at 14 DAIT for maintenance of broadleaf and sedge weeds. A crop oil concentrate (COC) (Agri-Dex® label, Helena

Chemical Company, Collierville, TN) was added to each herbicide application at a rate of 1% v^{-1}, except treatments containing thiobencarb or propanil.

Table 3.1. Herbicide information for all products used in the study[a]

Herbicide common name	Herbicide trade name	Rate	Manufacturer
		g ai ha^{-1}	
Bentazon	Basagran	1050	BASF Corporation, Research Triangle Park, NC
Carfentrazone	Aim	18	Bayer Crop Protection LLC, Greensboro, NC
Propanil	Stam M4	3360	RiceCo LLC, Memphis, TN
Quizalofop	Provisia	120	Dupont Crop Protection, Wilmington, DE
Saflufenacil	Sharpen	25	BASF Corporation, Research Triangle Park, NC
Thiobencarb	Bolero	3360	Valent U.S.A. Corporation, Walnut Creek, CA

[a]All treatments contained a crop oil concentrate (Agri-Dex® label, Helena Chemical Company, Collierville, TN)at 1% v/v, except propanil and thiobencarb.

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 = no injury or control and 100 = 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 prior to harvest (data not shown). The center four rows planted in ACCase-R rice were harvested with a Mitsubishi VM3 (Mitsubishi Corporation, 3-1, Marunouchi 2- chome, Chiyoda-ky, Tokyo, Japan) plot combine 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. 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 DAIT was checked with the use of the UNIVARIATE procedure of SAS and significant normality problems were not observed.

Results and Discussion

Antagonistic responses were observed for red rice control when quizalofop was mixed with propanil at 14, 28, and 42 DAIT (Table 3.2). At 14 and 28 DAIT, expected control was 95 and 94%, respectively compared with an observed control of 75 and 71%, respectively. At 42 DAIT, a slight antagonistic response was observed, P-value 0.0479, on red rice treated with quizalofop plus propanil with an observed control of 94%, compared with an expected control of 99% with a P-value of 0.0479. All other contact herbicides mixed with quizalofop resulted in a neutral response for red rice control at all evaluation timings, and indicate the potential for mixtures with quizalofop in ACCase-R rice production.

Table 3.2. 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[d]					
None	—	0	—	95	—
Bentazon	1050	0	95	89	0.1434
Carfentrazone	18	0	95	90	0.1853
Propanil	3360	0	95	75^{-}	0.0000
Saflufenacil	25	0	95	88	0.0882
Thiobencarb	3360	0	95	91	0.2795

Table 3.2 continued

Table 3.2 continued.

Mixture Herbicide[a]	Rate	Quizalofop (g ai ha^{-1}) 0 Observed	120 Expected	120 Observed[b]	P value[c]
28 DAIT					
None	—	0	—	94	—
Bentazon	1050	0	94	89	0.1743
Carfentrazone	18	0	94	95	0.7799
Propanil	3360	0	94	71⁻	0.0000
Saflufenacil	25	0	94	94	0.9721
Thiobencarb	3360	0	94	95	0.4851
42 DAIT[e]					
None	—	0	—	99	—
Bentazon	1050	79	99	97	0.4032
Carfentrazone	18	82	99	97	0.2778
Propanil	3360	79	99	94⁻	0.0479
Saflufenacil	25	82	99	98	0.6112
Thiobencarb	3360	76	99	98	0.5312

[a]Evaluation dates for each respective herbicide mixture.
[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 an additive response.
[c]P < 0.05 indicates anantagonistic response, P > 0.05 indicates an additive response.
[d]DAIT, days after initial treatment.
[e]Control observed for each mixture herbicide with an additional independent application of quizalofop applied 28 days after the initial treatment.

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 75 and 69%, respectively, compared with an expected control of 94 and 92%, respectively (Table 3.3). The same treatment at 42 DAIT was still antagonistic with an additional treatment of quizalofop applied alone at 28 DAIT according to Blouin's modified Colby's analysis. In addition, bentazon or saflufenacil slightly antagonized quizalofop activity on CLXL-745 14 DAIT, indicating an observed control of 88 to 89% with P-values of 0.0427 and 0.0048, respectively. However, quizalofop plus bentazon or saflufenacil indicated neutral responses at 28 DAIT, similar to what was observed with red rice.

Table 3.3. Hybrid CLXL-745 IR 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[d]					
None	—	0	—	94	—
Bentazon	1050	0	94	89^{-}	0.0427
Carfentrazone	18	0	94	90	0.0765
Propanil	3360	0	94	75^{-}	0.0000
Saflufenacil	25	0	94	88^{-}	0.0048
Thiobencarb	3360	0	94	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[e]					
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.
[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 an additive response.

[c]P < 0.05 indicates anantagonistic response, P > 0.05 indicates an additive response.
[d]DAIT, days after initial treatment.
[e]Control observed for each mixture herbicide with an additional independent application of quizalofop applied 28 days after the initial treatment.

CL-111 responses were similar to CLXL-745, except a neutral response was observed for quizalofop mixed with saflufenacil at 14 DAIT (Table 3.4). Neutral responses were observed for red rice, CLXL-745, CL-111, and barnyardgrass at all evaluation dates when quizalofop was mixed with carfentrazone or thiobencarb, and this may indicate the potential for use as a mixture herbicide with quizalofop in an ACCase-R rice production system. As with red rice, the only antagonism of quizalofop activity was observed with propanil mixtures at all evaluation dates 14, 28, and 42 DAIT. The addition of a second quizalofop application was not sufficient enough to overcome the antagonism observed at 14 and 28 DAIT when quizalofop was applied mixed with propanil.

Table 3.4. CL-111 IR 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[d]					
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

Table 3.4 continued.

Table 3.4 continued.

		Quizalofop (g ai ha^{-1})			
		0	120		
Mixture Herbicide[a]	Rate	Observed	Expected	Observed[b]	P value[c]
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[e]					
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.

[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 an additive response.

[c]P < 0.05 indicates anantagonistic response, P > 0.05 indicates an additive response.

[d]DAIT, days after initial treatment.

[e]Control observed for each mixture herbicide with an additional independent application of quizalofop applied 28 days after the initial treatment.

Barnyardgrass was 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 3.5). By 42 DAIT, the second quizalofop application at 28 DAIT could not overcome the antagonism observed at earlier evaluations 14 and 28 DAIT, with an observed control of 83% compared with an expected control of 99%. These data indicate propanil should be avoided in an ACCase-R rice production system. In addition, quizalofop activity on barnyardgrass was antagonized by saflufenacil at 14 DAIT. However, by 28 DAIT, the same mixture indicated a neutral response for activity of quizalofop barnyardgrass.

Table 3.5. 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[d]					
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[e]					
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.

[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 an additive response.

[c]P < 0.05 indicates anantagonistic response, P > 0.05 indicates an additive response.
[d]DAIT, days after initial treatment.
[e]Control observed for each mixture herbicide with an additional independent application of quizalofop applied 28 days after the initial treatment.

ACCase-R rice injury was less than 10% across all evaluations (data not shown). ACCase-R rice treated with two independent applications of quizalofop resulted in a rough rice yield of 5450 kg ha^{-1}. ACCase-R rice treated with quizalofop plus propanil resulted in a rough yield of 1970 kg ha^{-1}, and this yield did not differ compared with the nontreated rice (Table 3.6). However, rice treated with an independent application of propanil at 3360 g ha^{-1} resulted in a yield of 3610 kg ha^{-1}. These yield reductions are a result of antagonism observed when quizalofop was mixed with propanil on red rice, CLXL-745, CL-111, and barnyardgrass. ACCase-R rice treated with quizalofop plus carfentrazone or thiobencarb yielded 5070 to 5250 kg ha^{-1}, with no differences compared with ACCase-R rice treated with two independent applications of quizalofop. Yields for ACCase-R rice treated with quizalofop plus bentazon or saflufenacil were reduced to 4110 and 4570 g ai ha^{-1}, respectively, and these yield reductions are likely a result of the antagonism observed at 14 DAIT on CLXL-745, CL-111, and barnyardgrass. This indicates early season antagonism of red rice, CLXL-745, CL-111, and barnyardgrass can negatively impact ACCase-R rice yield.

Table 3.6. Rough rice yields of ACCase-resistant rice treated with quizalofop and each respective mixture in 2015 and 2016.

		Quizalofop (g ai ha^{-1})	
	Rate	0	120
	g ai ha^{-1}	kg ha^{-1}	kg ha^{-1}
None	—	1980 f	5450 a
Bentazon	1050	2900 e	4110 c
Carfentrazone	18	2850 e	5250 a
Propanil	3360	3610 d	1970 f
Saflufenacil	25	2650 e	4570 b
Thiobencarb	3360	2950 e	5070 a

[a]Respective herbicide mixtures
[b]Means followed by a common letter are not significantly different at P = 0.05 with the use of Fisher’s protected LSD

In conclusion, it is essential to understand the compatibility between quizalofop and contact herbicides before developing a herbicide program for ACCase-R rice production. When comparing all contact herbicides evaluated, these data suggest propanil is least compatible in a mixture with quizalofop on red rice, CLXL-745, CL-111, and barnyardgrass, thus resulting in reduced yield and a negative impact on economic returns. Quizalofop activity can be antagonized when applied on red rice, CLXL-745, CL-111, or barnyardgrass when mixed with propanil, even with a follow up treatment of quizalofop applied alone 28 DAIT. These data contradict Zhang et al. (2005) reporting 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 ACCase-R rice treated with quizalofop plus bentazon or saflufenacil indicated neutral responses at 28 DAIT, antagonized red rice, CLXL-745, CL-111, and barnyardgrass at 14 DAIT can still compete with ACCase-R rice early in the growing season, resulting 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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Chapter 4

Evaluation of Sequential Applications of Quizalofop and Propanil plus Thiobencarb in ACCase-resistant Rice

Introduction

Imidazolinone-resistant (IR) rice (BASF, Research Triangle Park, NC 27709) (*Oryza sativa* L.) was introduced for commercial use in 2002, allowing producers to manage red rice (*O. sativa* L.) populations with imidazolinone herbicides during cultivated rice production for the very first time (Croughan 2003). IR hybrid rice was introduced in 2003 (RiceTec, Inc. Houston, TX 77059). For over 150 years, red rice has been recognized as one of the most troublesome weeds in rice production in the southern United States (Craigmiles 1978; De Wet and Harlan 1975; Gealy et al. 2003; Fish 2015; 2016). Research has suggested the technology used in IR rice production can outcross to red rice, resulting in IR red rice (Chen et al. 2004; Majumder et al. 1997; Messegeur et al. 2004; Rajguru et al. 2005; Song et al. 2002; 2003;). Hybrid rice seed can remain dormant and become weedy in succeeding growing seasons, and when the rice is IR, the emergence of this rice in the following years can have weedy characteristics (Sudianto et al. 2013). From this point forward, the complex of red rice, outcrosses, and volunteer hybrid rice will be referred to as weedy rice.

A rising weed concern in rice producing areas throughout the southern United States is the management of weedy rice, more specifically IR weedy rice (Gressel and Valverde 2009). Although taxonomically classified as the same species as cultivated rice, weedy rice can include a broad range of different phenotypic characteristics including various grain color and size, presence or lack of awns, dark to light green vegetation, variable plant height, and glabrous to pubescent leaves (Gressel and Valverde 2009; Rustom et al. 2015). Red rice, a variation of weedy rice, has been reported to have superior growth capabilities in comparison with cultivated rice; therefore, it competes 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 one red rice plant m^{-2} can reduce yield by 219 kg ha^{-1}, and red rice infestations can reduce cultivated rice yield by up to 80% and after season long competition.

Barnyardgrass is another troublesome weed throughout rice producing areas in the southern United States, and is capable of reducing rice yields by 80% (Smith 1965). Weed control programs throughout rice producing areas in the southern United States often included propanil for barnyardgrass management, and by the early 1990s a reported 98% of Arkansas rice acreage included at least one propanil application (Carey et al. 1995; Smith 1965; Smith and Hill 1990). However, barnyardgrass resistance to propanil, quinclorac, penoxsulam, bispyribac, and imidazolinone herbicides has become an issue in many rice producing areas (Croughan 1999; Riar et al. 2013; Talbert and Burgos 2007).

BASF is currently developing a new herbicide resistant rice, which will be sold under the trade name Provisia® (BASF, Research Triangle Park, NC 27709). Quizalofop is a Group 1 aryloxyphenoxypropionate herbicide that inhibits acetyl coenzyme A carboxylase (ACCase), and is the herbicide targeted for use in this new system. Quizalofop will also be sold under the trade name Provisia® (BASF, Research Triangle Park, NC 27709). Quizalofop has historically been used for weedy rice management in soybean production (Askew and Shaw 1998; Minton and Shaw 1989). ACCase-resistant (ACCase-R) rice will provide a new tool for postemergence management of a broad range of annual and perennial grasses, including the weedy rice complex (Shaner 2014). The targeted quizalofop application rate in ACCase-R production will be 92 to 155 g ai ha^{-1}, not to exceed 240 g ha^{-1} per year.

Herbicides applied in mixtures can have both positive and negative impacts with regards to herbicide activity, crop yield, and overall economic returns (Blackshaw et al. 2006; Carlson et al. 2011; Pellerin et al. 2003, 2004; Webster et al. 2012; Zhang et al. 2005). Mixtures can have one of three responses: synergistic, antagonistic, or neutral (Fish et al. 2015; 2016). ACCase inhibiting herbicide activity has been antagonized when co-applied with other herbicides (Barnwell and Cobb 1994; Blackshaw et al. 2006; Vidrine et al. 1995; Zhang et al. 2005). Herbicide antagonism is defined 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" (Beste 1983). In Louisiana rice production, ACCase herbicide activity has been reduced when fenoxaprop was applied in mixtures with halosulfuron, bensulfuron, or carfentrazone; however, other herbicides such as bentazon or molinate resulted in neutral responses when applied with fenoxaprop (Zhang et al. 2005). Reductions in quizalofop activity when mixed with 2,4-D amine have been suggested; however reports have also indicated quizalofop to be the least susceptible to antagonism when applied in mixtures with lactofen, imazaquin, chlorimuron, or fomesafen (Blackshaw et al. 2006; Vidrine et al. 1995).

Research has indicated that herbicides applied sequentially can be more effective at certain timings than the same herbicides applied in a mixture (Burke et al. 2002; Corkern et al. 1998; Crooks et al. 2003; Dernoeden and Fidanza 1994; Myers and Coble 1992). Myers and Coble (1992) evaluated a reduction in imazethapyr activity when mixed with clethodim, fluazifop, quizalofop, or sethoxydim, in comparison to imazethapyr alone on large crabgrass (*Digitaria sanguinalis* L.), fall panicum (*Panicum dichotomiflorum* Michx.), and broadleaf signalgrass (*Urochloa platyphylla* Munro ex C. Wright). Imazethapyr applied alone at five days before or one day after each of the ACCase herbicides resulted in an additive or neutral response when compared to each herbicide applied alone; however, imazethapyr applied three or one days before and the same day as the ACCase herbicides resulted in an antagonoistic response. Dernoeden and Fidanza (1994) evaluated sequential applications of 2,4-D plus mecoprop plus dicamba before and after a fenoxaprop application for smooth crabgrass control (*Digitaria ischaemum* Schreb.), concluding fenoxaprop activity was antagonized when 2,4-D plus mecoprop plus dicamba was applied less than 14 days before fenoxaprop. However, an additive/neutral response was observed when the same herbicide was applied 21 days before or more than three days after the fenoxaprop application.

Herbicide mixtures are an integral part of weed management strategies in both conventional and IR rice production. Mixtures can be beneficial in ACCase-R rice production; however, given the history of antagonism of ACCase herbicides applied in mixtures or sequentially with other herbicides, it is imperative to understand which herbicides are antagonistic, synergistic, or neutral when applied in a mixture or sequentially with quizalofop. These potential interactions will have an important role when developing herbicide programs for ACCase-R rice production. The objective of this research was to compare the activity of quizalofop when applied independently, in a mixture with propanil plus thiobencarb, or sequentially before or after a propanil plus thiobencarb application.

Materials and Methods

A field study was conducted in 2015 and 2016 at the H. Rouse Caffey Rice Research Station (RRS) near Crowley, Louisiana to evaluate quizalofop activity when applied independently, in a mixture with propanil plus thiobencarb, or sequentially with propanil plus thiobencarb. The soil type at the RRS is a Crowley silt loam (fine smectic, thermic Typic Albaqualfs) with a pH of 6.4 and 1.4% organic matter. Field preparation consisted of a fall and spring disking followed by (FB) two passes in opposite directions with a two-way bed conditioner consisting of rolling baskets and S-tine harrows set at 6 cm depth.

The experimental design was a randomized complete block replicated four times. 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 'PVL024B' long grain rice, 2 rows of 'CL-111' long grain IR rice, and 2 rows of 'CLXL-745' hybrid long grain IR rice. Rice lines were planted at a rate of 67 kg ha^{-1}. Awnless red rice was also broadcast in the plot area prior to drill seeding at a rate of 50 kg ha^{-1}. IR rice varieties and red rice were planted to represent a weedy rice population. The research area was naturally infested with barnyardgrass. The area was surface irrigated to a depth of 5 cm 24 hours after planting. A permanent 10-cm flood was established when ACCase-R rice reached the five-leaf to one-tiller stage, and was maintained until two weeks prior to harvest.

Each herbicide application was applied with a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} with five flat-fan 110015 nozzles spaced 35 cm apart. A pre-package mixture of propanil plus thiobencarb (RiceBeaux, RiceCo LLC, Memphis, Tn 38137) was applied at a rate of 6720 g ai ha^{-1} for each timing treatment when red rice, CL-111, CLXL-745, and PVL024B rice were at the two- to three-leaf growth stage and barnyardgrass was two- to four-leaf with a population of 50 to 100 plants m^{-2}. Quizalofop was applied at 120 g ai ha^{-1} at timings of 7, 3, and 1 days prior to and following the propanil plus thiobencarb application. In addition, quizalofop was applied alone and in a mixture with propanil plus thiobencarb the same day propanil plus thiobencarb was applied for the timing treatments (day 0). A nontreated was added for comparison.

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 = no injury or control and 100 = complete plant death at 14, 28, and 42 days after the propanil plus thiobencarb treatment (DAT). 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 prior to harvest (data not shown). The center four rows planted in PVL024B rice were harvested with a Mitsubishi VM3 (Mitsubishi Corporation, 3-1, Marunouchi 2- chome, Chiyoda-ky, Tokyo, Japan) plot combine and grain yield was adjusted to 12% moisture.

All data were arranged as repeated measures and subject to the mix procedure of SAS (release 9.4, SAS Institute, Cary, NC). Years, replications (nested within treatments), and all interactions containing any of these effects were considered random effects. 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). Herbicide treatment and evaluation timing were considered fixed effects. Visual injury and control, PVL024B rice height, and rough rice yield were considered repeated measures. Type III statistics were used to test possible interactions of fixed effects using the UNIVARIATE procedure of SAS and significant normality problems were not observed. Tukey's test was used to separate means at the 5% probability level ($p \leq 0.05$).

Results and Discussion

A herbicide application timing interaction occurred for red rice control (Table 4.1); therefore, data were averaged over 14, 28, and 42 DAT evaluation timings. Red rice control was 87 and 91% when treated with quizalofop 3 or 1 days before propanil plus thiobencarb (DBPT), respectfully, similar to control for red rice treated with quizalofop at day 0. However, quizalofop activity on red rice was reduced to 70% when applied in a mixture with propanil plus thiobencarb at day 0. Similar reductions in red rice control were observed when quizalofop was applied 1 and 3 DAPT with an observed control of 76 and 65%, respectfully. These data indicate quizalofop can be applied prior to propanil plus thiobencarb as early as 1 DBPT; however, if a quizalofop application follows propanil plus thiobencarb, the application should be applied at least 7 DAPT for red rice control.

A herbicide application timing interaction occurred for CLXL-745 (Table 4.1); therefore, data were averaged over 14, 28, and 42 DAT evaluation timings. CLXL-745 control was 91% when treated with quizalofop at day 0, similar control of CLXL-745 was observed when quizalofop was applied 1, 3, and 7 DBPT. In comparison, control for CLXL-745 was reduced to 73% when treated with quizalofop mixed with propanil plus thiobencarb at day 0 or quizalofop applied 1 DAPT. Additionally, quizalofop activity was reduced to 57% when applied 3 DAPT. These data indicate quizalofop should not be applied 0 to 3 DAPT to avoid reductions in quizalofop activity on CLXL-745.

A herbicide application timing interaction occurred for CL-111 (Table 4.1); therefore, data were averaged over 14, 28, and 42 DAT evaluation timings (Table 4.1). Quizalofop applied 7, 3, or 1 DBPT controlled CL-111 92 to 93%, similar to quizalofop applied alone at day 0. Quizalofop activity was reduced on CL-111 to 76% when applied in a mixture with propanil plus thiobencarb at day 0. Similarly, quizalofop applied 1 and 3 DAPT decreased CL-111 control to 84 and 73%, respectively. These data indicate quizalofop can be applied prior to propanil plus thiobencarb with no reduction in activity on CL-111; however, if propanil plus thiobencarb is applied prior to quizalofop, a 7 day delay should be followed before quizalofop is applied.

Table 4.1. Control of red rice, CLXL-745, and CL-111 when treated with quizalofop applied 1 to 7 days before and after a pre-package mixture of propanil plus thiobencarb application, averaged over evaluation date 14, 28, and 42 DAT.[abcd]

Quizalofop Application	Red Rice	CLXL 745	CL 111
		% of control[e]	
7 DBPT[d]	88 a	84 ab	92 a
3 DBPT	90 a	90 a	93 a
1 DBPT	87 a	87 ab	92 a
0 DBPT[e]	91 a	91 a	94 a
0 DBPT + propanil + thiobencarb[e]	70 bc	73 b	76 cd
1 DAPT[d]	76 bc	73 b	84 bc
3 DAPT	65 c	57 c	73 d
7 DAPT	81 ab	81 ab	86 ab

[a]Means followed by a common letter do not significantly differ at P=0.05 using Tukey's test within columns.
[b]CLXL 745, IR-hybrid rice; CL 111, IR rice.
[c]Rates: Quizalofop at 120 g ai ha^{-1}; propanil + thiobencarb at 6720 g ai ha^{-1}.
[d]Abbreviations: DBPT, days before propanil + thiobencarb; DAPT, days after propanil + thiobencarb; DAT, days after treatments applied 0 DBPT.
[e]Quizalofop applied alone and in a mixture with propanil + thiobencarb at day 0, between 1 DBPT and 1 DAPT.
[f]Control was measured using a scale of 0 = no control and 100= complete plant death based on visual symptoms.

A herbicide application timing by evaluation timing interaction occurred for barnyardgrass control (Table 4.2). Quizalofop applied 1, 3, or 7 DBPT controlled barnyardgrass 87 to 95% across all evaluation dates with no differences observed, similar to control observed when barnyardgrass was treated with quizalofop at day 0. However, barnyardgrass control was reduced to 45% when quizalofop was applied in a mixture with propanil plus thiobencarb at day 0. In addtion, at 14 DAT, barnyardgrass control was reduced to 54 to 61% when applied 1, 3, or 7 DAPT, and this is similar to control observed when quizalofop was applied in a mixture with propanil plus thiobencarb at day 0. At 28 DAT, barnyardgrass control was reduced to 66% when quizalofop was applied 1 DAPT, and this is similar to barnyardgrass control observed when quizalofop was applied 3 DAPT. At 42 DAT, quizalofop activity on barnyardgrass was similar to control observed at 28 DAT for each respective treatment. These data indicate quizalofop should not be applied 0 to 3 DAPT for barnyardgrass control; however, quizalofop can be applied as soon as 1 DBBT or 7 DAPT to avoid reductions in barnyardgrass activity.

Table 4.2. Barnyardgrass control when treated with quizalofop applied 1 to 7 days before and after a pre-package mixture of propanil plus thiobencarb application.[ab]

	Barnyardgrass control[e]		
Quizalofop Application	14 DAT[c]	28 DAT	42 DAT
	%		
7 DBPT[c]	87 ab	92 ab	92 ab
3 DBPT	88 ab	92 ab	95 a
1 DBPT	87 ab	92 ab	94 a
0 DBPT[d]	88 ab	88 ab	97 a
0 DBPT + propanil + thiobencarb[d]	53 gh	45 h	48 gh
1 DAPT[c]	54 gh	66 efg	73 def
3 DAPT	64 fg	73 def	74 c-f
7 DAPT	61 fgh	82 b-e	90 ab

[a]Means followed by a common letter do not significantly differ at P=0.05 using Tukey’s test within and across columns

[b]Rates: Quizalofop at 120 g ai ha^{-1}; propanil + thiobencarb at 6720 g ai ha^{-1}.

[c]Abbreviations: DBPT, days before propanil + thiobencarb; DAPT, days after propanil + thiobencarb; DAT, days after treatments applied 0 DBPT.

[d]Quizalofop applied alone and in a mixture with propanil + thiobencarb at day 0, between 1 DBPT and 1 DAPT

[e]Control was measured using a scale of 0 = no control and 100= complete plant death based on visual symptoms.

PVL024B rice injury was less than 10% across all evaluations (data not shown). PVL024B rice treated with quizalofop at 7, 3, or 1 DBPT resulted in rough rice yields of 4260, 4350, and 3890 kg ha^{-1}, respectfully, and these yields are similar to PVL024B rice treated with quizalofop alone at day 0 (Table 4.3). Similarly, PVL024B rice treated with quizalofop 7 DAPT yielded 3840 kg ha^{-1}. However, PVL024B rice yield was reduced to 3180 kg ha^{-1} when treated with propanil plus thiobencarb at day 0, similar to PVL024B rice treated with quizalofop 1 or 3 DAPT. These data suggest PVL024B rough rice yield can be reduced when treated with quizalofop applied 0 to 3 DAPT.

Table 4.3. Acetyl coenzyme A-resistant rough rice yield treated with quizalofop alone, quizalofop mixed with propanil plus thiobencarb, and quizalofop applied sequentially with propanil plus thiobencarb in 2015 and 2016.[ab]

Quizalofop Application	Rough Rice Yield
	kg ha^{-1}
Nontreated	2380 d
7 DBPT[c]	4260 a
3 DBPT	4350 a
1 DBPT	3890 ab
0 DBPT[d]	4060 a
+ propanil + thiobencarb[d]	3180 c
1 DAPT[c]	3040 cd
3 DAPT	3310 bc
7 DAPT	3840 ab

[a]Means followed by a common letter do not significantly differ at P=0.05.
[b]Rates: Quizalofop at 120 g ai ha^{-1}; propanil + thiobencarb at 6720 g ai ha^{-1}.
[c]Abbreviations: DBPT, days before propanil + thiobencarb; DAPT, days after propanil + thiobencarb.
[d]Quizalofop applied alone and in a mixture with propanil + thiobencarb at day 0, between 1 DBPT and 1 DAPT.

In conclusion, it is important to understand the compatibility between quizalofop and propanil plus thiobencarb before developing a herbicide program for ACCase-R rice production. These data suggest that quizalofop should be applied 1 to 7 DBPT or no earlier than 7 to maximize weed control. Quizalofop applied 0 to 3 DAPT can result in reduced quizalofop activity on weedy rice and barnyardgrass, and this control is similar to control of weeds when treated with quizalofop applied in a mixture with propanil plus thiobencarb at day 0. Furthermore, reductions in quizalofop activity will result in corresponding yield reductions. This is similar to the findings of Myers and Coble (1992), indicating ACCase herbicides applied the same day as or 1 to 3 days following an imazethapyr application resulted in a reduction in ACCase herbicide activity. These data are also similar to the findings of Dernoeden and Fidanza (1994) reporting a reduction in fenoxaprop activity when applied following a 2,4-D plus mecoprop plus dicamba application. In order to maximize weedy rice and barnyardgrass control, ACCase-R rice yield potential, and economic returns, quizalofop applications from 0 to 3 DAPT should be avoided in an ACCAse-R rice production system.

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Chapter 5

Summary

Weedy rice (*Oryza sativa* L.) and barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv.) are two of the most troublesome weeds in rice production across the southern United States, and these weeds are capable of reducing cultivated rice yield by up to 80% (Gressel and Valverde 2009; Smith 1965; 1988). Imidazolinone-resistant (IR) weedy rice and barnyardgrass resistant to several different modes of action has been reported in multiple studies, and these herbicide-resistant weed populations can potentially spread throughout the southern United States (Croughan 1999; Gressel and Valverde 2009; Riar et al. 2013; Talbert and Burgos 2007).

The development of ACCase-resistant (ACCase-R) rice (BASF, Research Triangle Park, NC 27709) will provide a new tool for producers to control IR weedy rice and barnyardgrass resistant to several different modes of action (Shaner 2014) with quizalofop, an ACCase inhibiting herbicide, during cultivated rice production. Given the history of ACCase herbicide antagonism by other herbicides (Barnwell and Cobb 1994; Blackshaw et al. 2006; Vidrine et al. 1995; Zhang et al. 2005), this research was conducted to evaluate quizalofop activity when applied mixtures or sequentially with other herbicides used in rice production. Results from this research can be used to develop efficient weed management programs for ACCase-R rice production.

Research was conducted in 2015 and 2016 in a field study at the LSU AgCenter H. Rouse Caffey Rice Research Station near Crowley, Louisiana to evaluate quizalofop herbicide mixture interactions with common acetolactate synthase (ALS) inhibiting herbicides used in rice production. This study was conducted two times. Herbicide applications were applied when ACCase-R rice was at the three- to four-leaf growth stage. Red rice, CLXL-745, and CL-111 were also planted in the plot area to represent a weedy rice population, and control was evaluated for these and barnyardgrass at 14, 28, and 42 days after the initial treatment (DAIT). Additionally, a second

application of quizalofop was applied to all treatments 28 days after the initial mixture application (DAIT). ACCase-R rough rice yield was also recorded.

At 14 and 28 DAIT, quizalofop activity was severely antagonized when applied in a mixture with penoxsulam, penoxsulam plus triclopyr, or bispyribac, with observed control not exceeding 38%, compared with an expected control of 91 to 97%. At 42 DAIT, the second application of quizalofop applied 28 DAIT could not overcome the barnyardgrass antagonism previously evaluated at 14 and 28 DAIT when quizalofop was applied in a mixture with penoxsulam or penoxsulam plus triclopyr. In addition, all ALS-inhibiting herbicides reduced quizalofop on red rice, CL-111, CLXL-745, or barnyardgrass at either 14 or 28 DAIT. ACCase-R rough rice yield was reduced to 2580, 2570, and 1350 kg ha^{-1} when treated with quizalofop mixed with penoxsulam, penoxsulam plus triclopyr, or bispyribac, respectively, compared with an ACCase-R rice yield of 6300 kg ha^{-1} when treated with quizalofop alone. Additionally, ACCase-R rice yield was also reduced to 4510 to 5740 kg ha^{-1} when treated with any ALS herbicide applied in a mixture with quizalofop. These yield reductions are likely due to competition among antagonized weeds and ACCase-R rice.

A study was conducted at the RRS in 2015 and 2016 to evaluate herbicide mixture interactions of quizalofop and common contact herbicides used in rice production. This study was conducted two times. Herbicide applications were applied when ACCase-R rice was at the three- to four-leaf growth stage. Red rice, CLXL-745, and CL-111 were also planted in the plot area to represent a weedy rice population, and control was evaluated for these and barnyardgrass at 14, 28, and 42 days after the initial quizalofop treatment (DAIT). Additionally, a second application of quizalofop was applied to all treatments 28 days after the initial mixture application (DAIT). ACCase-R rough rice yield was also recorded.

Propanil consistently antagonized quizalofop activity on all weeds evaluated at all evaluation dates. At 14 and 28 DAIT, red rice observed control was 75 and 71%, respectively, compared to an expected control of 95 and 94%, respectively. At 42

DAIT, red rice observed control was 94%, compared with an expected control of 99%. This response was considered antagonistic according to Blouin's (2010) modified Colby's analysis with a p-value of 0.0479. CLXL-745 and CL-111 treated with quizalofop plus propanil indicated similar responses to red rice. Quizalofop activity was reduced most when applied in a mixture with propanil on barnyardgrass. At 14 and 28 DAIT, barnyardgrass observed control was 38 and 16%, respectively, compared with an expected control of 92 and 94%, respectively. At 42 DAIT, a second quizalofop application applied 28 DA propanil plus thiobencarb was not able to overcome the barnyardgrass antagonism observed at 14 and 28 DAIT, with an observed control of 83%, compared with an expected control of 99%. These data indicate propanil may need to be avoided in an ACCase-R rice production system.

A field study was conducted at the RRS in 2015 and 2016 to evaluate quizalofop herbicide activity when applied independently, in a mixture with propanil plus thiobencarb, or sequentially with propanil plus thiobencarb. Quizalofop was applied at 120 g ha^{-1} at 7, 3, and 1 days before a propanil plus thiobencarb treatment (DBPT) or after (DAPT) a propanil plus thiobencarb treatment at 6720 g ai ha^{-1}. In addition, quizalofop was applied alone and in a mixture with propanil plus thiobencarb at day 0, when ACCase-R rice was at the two- to three-leaf growth stage. Red rice, CLXL-745, and CL-111 were also planted in the plot area to represent a weedy rice population, and control was evaluated for these and barnyardgrass at 14, 28, and 42 days after day 0 (DAT). ACCase-R rough rice yield was also recorded.

A herbicide application timing interaction occurred for red rice control; therefore, data were averaged over 14, 28, and 42 DAT evaluation timings. Quizalofop applied alone at day 0 controlled red rice 91%, and was reduced to 70% when applied in a mixture with propanil plus thiobencarb at day 0, similar to red rice control when quizalofop was applied 1 and 3 DAPT. However, red rice control was 91% when quizalofop was applied alone at day 0, similar to quizalofop applied 7, 3, or 1 DBPT.

A herbicide application timing by evaluation timing interaction occurred for barnyardgrass control. At 14 DAT, quizalofop applied alone at day 0 controlled barnyardgrass 88%, similar to quizalofop applied 7, 3, and 1 DBPT. However, quizalofop activity was reduced to 53% on barnyardgrass when applied in a mixture with propanil plus thiobencarb, and this is similar control observed when quizalofop was applied 1, 3, or 7 DAPT. In addition, at 28 and 42 DAT, quizalofop applied 7 DAPT controlled barnyardgrass 82 and 90%, respectively, and this is similar to control observed when quizalofop was applied alone at day 0 at 28 and 42 DAT. These data indicate quizalofop applied in a mixture with propanil plus thiobencarb or 1 to 3 DAPT should be avoided in an ACCAse-R rice production system. Mixtures of quizalofop and propanil plus thiobencarb should also be avoided.

In conclusion, ACCase-R rice (BASF, Research Triangle Park, NC 27709) will be a beneficial tool allowing producers to control grass weeds, specifically IR weedy rice barnyardgrass, with quizalofop during cultivated rice production. Rotating crops and herbicide mode of action has proven to be a beneficial practice for weed management, and ACCase-R rice will provide an additional tool that will improve rotational flexibility (Ball 1992; Martin and Felton 1993). Rustom et al. (2015) reported weedy rice populations were reduced from 251,000 plants m^{-2} in 2013 to 0 plants m^{-2} in 2015 after a yearly rotational system consisting of glyphosate-resistant soybeans in 2013, ACCase-R rice in 2014, and glyphosate-resistant soybeans in 2016. Research conducted by Bergeron et al. (2015) indicated additional benefits of ACCase-R rice, reporting 99% control of Nealley's sprangletop (*Leptochloa nealleyi* Vasey), a troublesome grass weed that has recently adapted to inundated rice growing environments in south Louisiana, when treated with quizalofop applied at 120 g ai ha^{-1}.

Although herbicide mixtures have proven to be beneficial, ACCase-inhibiting herbicides have a history of antagonism by other herbicides; therefore, caution should be taken when considering a mixture with quizalofop in an ACCase-R rice production system (Carlson et al. 2011; Pellerin et al. 2003, 2004; Vidrine et al.

1995; Webster et al. 2012; Zhang et al. 2005). ALS-inhibiting herbicides, especially penoxsulam and bispyribac, should be avoided when considering a mixture with quizalofop to prevent antagonistic interactions on weedy rice and barnyardgrass. In addition to ALS-inhibiting herbicides, contact herbicides such as propanil, bentazon, or saflufenacil mixed with quizalofop should also be avoided.

Research has been reported that herbicides applied in a mixture can result in reduced activity; however, the same herbicides applied sequentially at certain timings can be more effective (Burke et al. 2002; Corkern et al. 1998; Crooks et al. 2003; Dernoeden and Fidanza 1994; Myers and Coble 1992). Propanil is a widely used herbicide in rice production throughout the southern United States to control a broad range of weeds, and reports have suggested 98% of Arkansas rice fields in Arkansas receive at least one propanil application each year (Carey et al. 1995; Smith 1965, Smith and Hill 1990). However, Rustom et al. (2016) reports severe reductions in quizalofop activity on weedy rice and barnyardgrass when quizalofop is applied mixed with a prepackage mixture of propanil plus thiobencarb. Similarly, quizalofop applied 1 to 3 DAPT can result in reduced quizalofop activity on weedy rice and barnyardgrass, compared with quizalofop applied alone. However, quizalofop applied 7 to 1 DBPT or 7 DAPT can result in control similar to an application of quizalofop applied alone for weedy rice and barnyardgrass control.

Employing effective strategies for weed management in ACCase-R rice is important not only from a weed management and overall economic perspective, but also for preserving ACCase-R rice technology. As seen with IR technology, the potential exists for ACCase-R technology outcrossing to rice varieties currently susceptible to ACCase herbicides, such as red rice. Preserving ACCase-R rice technology must include an aggressive stewardship program to remove all weedy rice plants to prevent this technology from outcrossing to currently susceptible rice. This data will play an essential role in developing effective herbicide programs for ACCase-R rice production, which will aid in the preservation of ACCase-R rice technology.

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Vita

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