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Imazamox Plus Propanil Mixtures for Grass Weed Management in Imidazolinone-Resistant Rice

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A study was established to evaluate interactions between imazamox at 0 and 44 g ai ha^{-1} mixed with propanil at 0, 1,120, 2,240, 3,360, and 4,480 g ai ha^{-1} for the control of red rice and barnyardgrass. Blouin's Modified Colby's procedure was used to test for interactions. At 7 d after treatment (DAT), a synergistic response occurred for red rice treated with imazamox at 44 g ha^{-1} mixed with propanil at 3,360 and 4,480 g ha^{-1} by increasing expected control of 62% to an observed control of 67 and 75%, respectively, and the synergistic response continued across all evaluations through 49 DAT. No antagonism occurred for any imazamox plus propanil mixture for red rice control. An antagonistic response was shown for barnyardgrass control with imazamox at 44 g ha^{-1} mixed with any rate of propanil, at 7 DAT. However, imazamox plus propanil at 4,480 g ha^{-1} resulted in a neutral response at 14 through 49 DAT. Rice treated with imazamox plus propanil at 4,480 g ha^{-1} plus imazamox resulted in a yield of 6,640 kg ha^{-1}. The synergistic response observed for red rice control with a mixture of imazamox plus propanil can benefit producers by increasing control of red rice, and this mixture contains two different modes of action that can be part of an overall resistance management strategy.
Nomenclature: Imazethapyr; propanil; barnyardgrass, *Echinochloa crus-galli* (L.) Beauv.; red rice, *Oryza sativa* L.; rice, *Oryza sativa* L.
Key words: Additive interaction, antagonism, neutral interaction.

Se estableció un estudio para evaluar interacciones entre imazamox a 0 y 44 g ai ha^{-1} mezclado con propanil a 0, 1,120, 2,240, 3,360, y 4,480 g ai ha^{-1} para el control de arroz rojo y *Echinochloa crus-galli*. El procedimiento modificado Colby y Blouin fue usado para evaluar las interacciones. A 7 d después del tratamiento (DAT), ocurrió una respuesta sinérgica en el arroz rojo tratado con imazamox a 44 g ha^{-1} mezclado con propanil a 3,360 y 4, 480 g ha^{-1} al incrementarse el control esperado de 62% a un valor observado de 67 a 75%, respectivamente, y la respuesta sinérgica continuó en todas las evaluaciones hasta 49 DAT. No ocurrió antagonismo para ninguno de las mezclas de imazamox más propanil en el control de arroz rojo. Se demostró una respuesta antagónica en el control de *E. crus-galli* con imazamox a 44 g ha^{-1} en mezcla con cualquier dosis de propanil, a 7 DAT. Sin embargo, imazamox más propanil a 4,480 g ha^{-1} resultaron en una respuesta neutral entre 14 y 49 DAT. El arroz tratado con imazamox más propanil a 4,480 g ha^{-1} más imazamox resultó en un rendimiento de 6,640 kg ha^{-1}. La respuesta sinérgica observada para el control de arroz rojo con una mezcla de imazamox más propanil puede beneficiar a los productores al incrementar el control del arroz rojo. Además, esta mezcla contiene dos modos de acción diferente que pueden ser parte de una estrategia general de manejo de resistencia a herbicidas.

Red rice has been recognized as a weed in U.S. rice fields for over 150 yr, and has become increasingly troublesome in cultivated rice fields throughout the southern United States (Craigmiles 1978; Dowler 1997; Khodayari et al. 1987; Smith 1981; Webster 2004). Barnyardgrass is another troublesome weed problem in rice production in temperate and tropical areas (Dowler 1997; Holm et al. 1977) and is capable of reducing rice yields by 80% (Smith 1965). In southern U.S. rice production, weed management decisions prior to the release of imidazolinone-resistant (IR) rice (Clearfield rice, BASF Corporation, Research Triangle Park, NC 27709), were often based on the control of barnyardgrass, because of the lack of herbicides available for red rice control. However, this changed with the development of IR rice (Carlson et al. 2011, 2012; Croughan 1994; Pellerin and Webster 2004; Webster et al. 2012; Webster and Masson 2001).

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IR rice, introduced in the early 2000s, exhibited tolerance to the imidazolinone class of herbicides, which inhibit acetohydroxy acid synthase (EC 2.2.1.6), also known as acetolactate synthase (Stidham and Singh 1991; Stougaard et al. 1990). IR rice was developed in 1993 through seed mutagenesis, allowing IR rice lines to be considered nontransgenic (Croughan 1994). For the first time, red rice could be economically controlled while producing a crop of rice with the use of imidazolinone herbicides (Carlson et al. 2011, 2012; Webster et al. 2012).

Imazamox (Beyond® herbicide label, BASF Corporation, Research Triangle Park, NC 27709) is an imidazolinone herbicide labeled for use in IR rice. Imazamox is labeled at rates of 44 to 53 g ai ha^{-1}, and it is usually applied to rice at the three- to four-leaf stage or as a late-season application on rice at the panicle initiation (PI) stage of growth to 14 d after PI (Webster 2014). Imazamox is a useful tool for late-season application for control of escapes or late-emerging red rice, and because of the lack of residual activity with imazamox (Shaner 2014).

For many years, the weed control program for rice in the southern United States centered on propanil for control of annual grass and broadleaf weeds (Smith 1961, 1965; Smith and Hill 1990). Propanil was commercialized in the early 1960s and became the primary herbicide for control of barnyardgrass. By the early 1990s, 98% of the rice acreage was treated with at least one application of propanil each year (Carey et al. 1995). With the development of IR rice, researchers have reported increased weed control spectrum with the use of propanil-based products mixed with imazethapyr (Carlson et al. 2011; Pellerin et al. 2003, 2004).

Herbicide mixtures have proven to be beneficial in improving efficacy and broadening the weed control spectrum in IR rice (Carlson et al. 2011; Pellerin et al. 2003, 2004; Webster et al. 2012). Research has shown that the addition of propanil, or one of many other herbicides labeled in rice, to imazamox or imazethapyr can increase alligatorweed [*Alternathera philoxeroides* (Mart) Griseb.], barnyardgrass, hemp sesbania [*Sesbania herbacea* (Mill.) McVaugh], red rice, and Texasweed [*Caperonia palustris* (L.) St. Hil.] control in IR rice production (Carlson et al. 2011; Pellerin et al. 2003; Webster et al. 2012). The use of herbicide mixtures is favorable to producers because of increased weed control and reduced application cost (Hydrick and Shaw 1994). Oftentimes, herbicides used in mixture have different modes of action (Blouin et al. 2010; Lanclos et al. 2002; Zhang et al. 2005), and it is understood that herbicide mixtures can have one of these three responses—synergistic, antagonistic, or additive (Berenbaum 1981; Blouin 2010; Drury 1980; Hatzios and Penner 1985; Morse 1978; Nash 1981; Streibig et al. 1998). From this point forward, an additive response will be reported as a neutral response. The use of different modes of action in a single spray mixture can be part of a herbicide resistance management strategy (Norsworthy et al. 2012).

Lanclos et al. (2002) employed the method of Colby (1967) to determine interactions of glufosinate mixtures on glufosinate-resistant rice. Many mixtures were determined to be antagonistic when glufosinate was mixed with various herbicides labeled for use in rice. Zhang et al. (2005) employed the Blouin et al. (2004) nonlinear model to evaluate fenoxaprop mixtures in rice. Fenoxaprop at 75 g ai ha^{-1} mixed with propanil plus molinate or bentazon were neutral for barnyardgrass control, and an antagonistic response occurred with fenoxaprop applied at 89 g ha^{-1}. Webster et al. (2006) employed the Blouin et al. (2004) model to confirm a safening interaction on rice treated with clomazone mixed with halosulfuron or bensulfuron. Blouin et al. (2010) further modified the nonlinear model into the augmented mixed-model methodology and it proved to be more versatile than the Blouin et al. (2004) nonlinear mixed model.

Researchers have demonstrated the importance of incorporating herbicide mixtures to the standard program in IR rice production to maximize weed control (Carlson et al. 2011; Fish et al. 2012, 2013; Pellerin et al. 2003, 2004; Webster et al. 2012). With this in mind, the objective of this research was to evaluate the interactions of imazamox when mixed with various rates of propanil on red rice and barnyardgrass in IR rice production. Blouin et al. (2010) methodology was used to determine if there was a synergistic, antagonistic, or neutral response with each mixture.

Materials and Methods

A field study was conducted at four locations: (1) the Louisiana State University Agricultural Center's Rice Research Station (RRS) near Crowley, Louisiana, in 2011 and 2012 on a Crowley silt loam soil with pH 6.4 and 1.4% organic matter (OM); (2) the Louisiana State University Agricultural Center Northeast Research Station (NERS) near St. Joseph, LA, in 2012 on a Sharky clay with pH 6.1 and 2.1% OM; (3) the Louisiana State University Agricultural Center Macon Ridge Research Station (MRRS) near Winnsboro, LA, in 2012 on a Gigger silt loam with pH 5.8 and 1.3% OM; and (4) the Mississippi State University Delta Research and Extension Station (DREC) near Stoneville, MS in 2012 on a Sharkey clay with a pH of 8.2 and 2.1% OM.

The experimental design was a two-factor factorial in a randomized complete block with four replications. Long grain 'CL 161' IR rice was planted in 2011 and long grain 'CL 111' IR rice was planted in 2012 at the RRS, NERS, and the MRRS; and long grain 'CL 151' IR rice was planted in 2012 at the DREC. The Clearfield rice lines used in this research are very similar, and each line contains CL-161 in the pedigree (Steven D. Linscombe, personal communication, Louisiana State University Agricultural Center Rice Breeder). The growth characteristics are similar across each line used in this research and other long grain rice lines released from the LSU Agricultural Center rice breeding program. Factor A was imazamox applied at 0 and 44 g ha^{-1}, and factor B was propanil (RiceShot® herbicide label, RiceCo LLC, Memphis, TN 38137) applied at 0, 1,120, 2,240, 3,360, and 4,480 g ha^{-1}. Preliminary research indicated the potential of synergism with a mixture of imazamox plus propanil applied at labeled rates of 3,360, and 4,480 g ha^{-1}. The range of propanil rates were selected to determine if a synergistic interaction may occur below the labeled use rates of 3,360 and 4,480 g ha^{-1}.

Herbicide applications at all locations were made with the use of a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} solution at 190 kPa. The spray boom consisted of five flat-fan 110015 nozzles (Flat Fan Airmix® Venturi Nozzle, Greenleaf Technologies, Covington, LA 70434) with a 38-cm spacing. A COC at 1% v v^{-1}(Agri-Dex adjuvant label, Helena Chemical Company, Collierville, TN 38017) was added to imazamox when applied alone; however, no COC was added to any mixture that contained propanil. The propanil formulation used in this research is an EC formulation and requires no adjuvant when mixed with imazamox. The initial treatment containing herbicide mixtures was applied on one- to three-leaf rice. In order to follow the IR rice stewardship program, the entire area at all locations received a second application of imazethapyr at 70 g ha^{-1} applied alone 14 d later to rice in the four- to five-leaf stage.

Data obtained from the studies include weed control and injury on a scale of 0 to 100, with 0 being no weed control or crop injury and 100 being complete weed control or crop death. Rice plant height was recorded from the ground to the tip of the extended panicle immediately prior to harvest (data not shown). A small plot combine was used to harvest rice from the center four rows of each plot, and grain yield was adjusted to 12% moisture.

Treatments were applied at the RRS in 2011 on one- to three-leaf, or 2- to 8-cm, red rice; one- to four-leaf, or 1- to 8-cm, barnyardgrass; and in 2012 on two- to three-leaf, or 5- to 10-cm, red rice; and on two- to three-leaf, or 5- to 10-cm, barnyardgrass. In 2012, at the NERS, applications were made on two-leaf to one-tiller, or 1- to 8-cm, barnyardgrass. In 2012, at the MRRS, applications were made on two- to four-leaf, or 3- to 5-cm, barnyardgrass. In 2012, at the DREC, applications were made on one- to four-leaf, or 5- to 8-cm, red rice; and one- to three-leaf, or 3- to 5-cm, barnyardgrass. Natural populations of each weed existed at each location with additional overseeding, and densities of red rice and barnyardgrass were 20 to 40 plants sq m^{-1} for each species. Visual weed control observations were made at the RRS at 7, 14, 21, 35, and 49 d after treatment (DAT), at the NERS at 14, 28, and 49 DAT, at the MRRS at 28 and 49 DAT, and at DREC at 7 and 14 DAT.

Interaction for control data were analyzed under the guidelines described in detail by Blouin et al. (2010), and rough rice-yield data were analyzed with the use of the MIXED procedure of SAS (SAS 2008). The fixed effects for all models were the treatment mixtures from the two rates of imazamox in combination with the five rates of propanil. The random effects for the model were location by year and reps within location by year, and treatment-by-

Table 1. Red rice control with imazamox and propanil mixtures in 2011 and 2012 at the RRS[a] and DREC.

Mixture herbicide[b]	Rate	Imazamox (g ai ha^{-1}) 0 Observed	44 Expected	44 Observed[c]	P value
	g ai ha^{-1}	—% of control—			
7 DAT					
None	–	0	–	62	–
Propanil	1,120	0	63	64	0.4473
Propanil	2,240	0	62	66+	0.0285
Propanil	3,360	0	62	67+	0.0047
Propanil	4,480	4	62	75+	0.0000
14 DAT					
None	–	0	–	83	–
Propanil	1,120	0	83	84	0.6261
Propanil	2,240	0	83	86	0.3312
Propanil	3,360	0	83	89+	0.0247
Propanil	4,480	1	83	91+	0.0038
21 DAT					
None	–	0	–	81	–
Propanil	1,120	0	81	81	NS
Propanil	2,240	0	81	84	0.2174
Propanil	3,360	4	81	90+	0.0009
Propanil	4,480	0	81	89+	0.0009
28 DAT					
None	–	0	–	74	–
Propanil	1,120	0	74	80+	0.0031
Propanil	2,240	0	74	81+	0.0006
Propanil	3,360	0	74	83+	0.0000
Propanil	4,480	0	74	90+	0.0000
35 DAT					
None	–	0	–	77	–
Propanil	1,120	2	79	84	0.0508
Propanil	2,240	5	78	85+	0.0173
Propanil	3,360	6	78	90+	0.0001
Propanil	4,480	7	77	95+	0.0000
49 DAT					
None	–	0	–	73	–
Propanil	1,120	0	73	80+	0.0201
Propanil	2,240	0	73	84+	0.0005
Propanil	3,360	0	73	82+	0.0018
Propanil	4,480	0	73	84+	0.0005

[a] RRS, Louisiana State University AgCenter Rice Research Station near Crowley, LA; DREC, Mississippi State University Delta Research and Extension Center near Stoneville, MS.

[b] Evaluation date and respective herbicide mixture.

[c] Observed means followed by a plus (+) or a minus (–) are significantly different from Blouin's modified Colby's expected responses at the 5% level indicating a synergistic or an antagonistic response. No (+) or (–) indicates a neutral response.

rep interactions. The formulation of the model was detailed by Blouin et al. (2011). The dependent variables in separate analyses were red rice control, barnyardgrass control, and rough rice yield. The analyses for control were by DAT. The analysis for yield used the Fisher's protected LSD to compare treatment means. Normality of plot effects over all DAT was checked with the use of the UNIVARIATE procedure of SAS (SAS 2011). Significant normality problems were not observed.

Results and Discussion

At 7 DAT, a synergistic response was observed for red rice treated with imazamox at 44 g ha^{-1} mixed with propanil at 3,360 and 4,480 g ha^{-1} by increasing control from an expected control of 62% to an observed control of 67 and 75%, respectively (Table 1). This synergistic response continued across all evaluations through 49 DAT. The positive aspect of this mixture was that no antagonism occurred for any mixture regardless of propanil rate. Propanil at 1,120, 2,240, and 3,360 g ha^{-1} mixed with imazamox resulted in a synergistic response at the later evaluation dates, 28 through 49 DAT.

At 7 DAT, an antagonistic response was shown for barnyardgrass control with imazamox at 44 g ha^{-1} mixed with propanil at 1,120, 2,240, 3,360, and 4,480 g ha^{-1} by decreasing control from an expected control of 96, 96, 98, and 98% to an observed control of 87, 92, 93, and 94%, respectively (Table 2). Propanil has long been used for control of barnyardgrass, and the antagonistic responses at 7, 14, 28, and 42 DAT were probably due to imazamox not adding additional activity to the mix for barnyardgrass control. However, the high rate of propanil plus imazamox resulted in a neutral response across all evaluations except 7 DAT.

Crop injury was less than 10% across all evaluations (data not shown). Rice treated with propanil at 4,480 g ha^{-1} plus imazamox at 44 g ha^{-1} resulted in a yield of 6,640 kg ha^{-1} (Table 3), and the yield was higher than rice treated with propanil alone or propanil at 1,120 or 2,240 g ha^{-1} mixed with imazamox. Data suggests a yield increase from rice treated with imazamox plus propanil applied at 3,360 and 4,480 g ha^{-1}

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Table 2. Barnyardgrass control with imazamox and propanil mixtures in 2011 at the RRS[a] and 2012 at the RRS, NERS, MRRS, and DREC.

		Imazamox (g ai ha^{-1})			
		0	44		
Mixture herbicide[b]	Rate	Observed	Expected	Observed[c]	P value
	g ai ha^{-1}	——% of control——			
7 DAT[d]					
None	–	0	–	82	–
Propanil	1,120	76	96	87–	0.0000
Propanil	2,240	79	96	92–	0.0134
Propanil	3,360	87	98	93–	0.0155
Propanil	4,480	88	98	94–	0.0365
14 DAT					
None	–	0	–	81	–
Propanil	1,120	60	93	85–	0.0137
Propanil	2,240	67	94	90	0.2486
Propanil	3,360	75	95	92	0.3712
Propanil	4,480	79	96	95	0.7220
21 DAT					
None	–	0	–	73	–
Propanil	1,120	37	83	79	0.4034
Propanil	2,240	47	86	84	0.6593
Propanil	3,360	62	90	88	0.7244
Propanil	4,480	74	93	90	0.6446
28 DAT					
None	–	0	–	75	–
Propanil	1,120	67	92	78–	0.0001
Propanil	2,240	71	93	84–	0.0053
Propanil	3,360	76	94	84–	0.0015
Propanil	4,480	80	95	92	0.4143
35 DAT					
None	–	0	–	74	–
Propanil	1,120	16	79	74	0.5151
Propanil	2,240	28	81	79	0.6590
Propanil	3,360	35	83	84	0.8600
Propanil	4,480	46	86	91	0.3928
42 DAT					
None	–	0	–	62	–
Propanil	1,120	70	89	77–	0.0252
Propanil	2,240	72	90	79–	0.0282
Propanil	3,360	77	92	84	0.1053
Propanil	4,480	87	95	89	0.2155
49 DAT					
None	–	0	–	65	–
Propanil	1,120	33	77	70	0.3226
Propanil	2,240	38	78	75	0.6522
Propanil	3,360	43	80	83	0.5727
Propanil	4,480	47	82	90	0.2092

[a] RRS, Louisiana State University AgCenter Rice Research Station near Crowley, LA; NERS, Louisiana State University AgCenter Northeast Research Station near St. Joseph, LA; MERS, Louisiana State University AgCenter Macon Ridge Research Station near Winnsboro, LA; and DREC, Mississippi State University Delta Research and Extension Center near Stoneville, MS.

[b] Evaluation date and respective herbicide mixture.

[c] Observed means followed by a plus (+) or a minus (–) are significantly different from Blouin's modified Colby's expected responses at the 5% level indicating a synergistic or an antagonistic response. No (+) or (–) indicates a neutral response.

[d] DAT, days after treatment.

Table 3. Rough rice yields of rice treated with imazamox mixed with propanil at the RRS[a] in 2011 and 2012. Standard error = 1,240.

		Imazamox (g ai ha^{-1})	
Mixture herbicide[b]	Rate	0	44
	g ai ha^{-1}	kg ha^{-1}	kg ha^{-1}
None	–	2,350 f[c]	5,270 cd
Propanil	1,120	3,700 e	5,620 bcd
Propanil	2,240	4,850 d	5,830 bc
Propanil	3,360	5,100 cd	6,310 ab
Propanil	4,480	5,420 cd	6,640 a

[a] RRS, Louisiana State University AgCenter Rice Research Station near Crowley, LA.

[b] Evaluation date and respective herbicide mixture.

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

compared with rice treated with a single application of propanil or imazamox.

In conclusion, the addition of propanil in a mixture with an imazethapyr increases control of alligatorweed, barnyardgrass, hemp sesbania, red rice, and Texasweed (Carlson et al. 2011; Pellerin et al. 2003, 2004; Webster et al. 2012), and this research proves a mixture of imazamox plus propanil can be synergistic when applied to red rice. This increased control of red rice may aid in a resistance management strategy based on a synergistic interaction. Increased weed control by applying herbicide mixtures with multiple modes of action can be used as a management tool for herbicide resistance by reducing the number of plants present and/or by reducing seed set (Neve et al. 2011; Norsworthy et al. 2007, 2012). The synergistic response observed in this research reduced the red rice population size; therefore, the use of an imazamox plus propanil mixture can be used in a red rice resistance management

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strategy in IR rice production. Previous research has shown that herbicide programs containing coapplication or mixture of an imidazolinone herbicide plus propanil resulted in higher rough rice yields than programs including a single herbicide application in IR rice (Carlson et al. 2011; Webster et al. 2012). Increased weed pressure, even over a short period of time, can decrease rough rice yield (Carlson et al. 2012; Zhang et al. 2003). Therefore, it is recommended that producers be aggressive early in the growing season with herbicide mixtures in an IR system and should consider applying imazamox plus propanil to broaden the weed control spectrum and increase yields and profits (Carlson et al. 2011; Webster et al. 2012).

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