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Interactions of clomazone plus pendimethalin mixed with propanil in rice

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Abstract

A study was conducted at the Louisiana State University Agricultural Center's H. Rouse Caffey Rice Research Station in 2017 and 2018 to evaluate the interaction between a prepackage mixture of clomazone plus pendimethalin applied at 0, 760, 1,145, or 1,540 g ai ha^{-1} mixed with propanil at 0, 1,120, 2,240, or 4,485 g ai ha^{-1}. A synergistic response occurred when barnyardgrass was treated with all rates of clomazone plus pendimethalin mixed with either rate of propanil evaluated at 56 d after treatment (DAT). Unlike barnyardgrass, an antagonistic response occurred in yellow nutsedge used as a control when treated with 760 and 1,540 g ha^{-1} of clomazone plus pendimethalin mixed with 1,120 or 22,40 g ha^{-1} of propanil at 28 DAT; however, 1,145 g ha^{-1} of clomazone plus pendimethalin mixed with 4,485 g ha^{-1} of propanil resulted in a neutral interaction. At 28 DAT, rice flatsedge treated with all herbicide mixtures resulted in neutral interactions. The synergism of clomazone plus pendimethalin applied at 1,540 g ha^{-1} mixed with propanil applied at 2,240 or 4,485 g ha^{-1} to control barnyardgrass resulted in an increased rough rice yield compared with 760 or 1,145 g ha^{-1} of clomazone plus pendimethalin mixed with propanil applied at 1,120 or 2,240 g ha^{-1}. These results indicate that if barnyardgrass and rice flatsedge are present in a rice field the prepackage mixture of clomazone plus pendimethalin mixed with propanil can be an option for growers. However, if yellow nutsedge infest the area other herbicides may be needed.

Introduction

Over the past several decades, advances in chemical weed management technology have played an important role in the development of the rice industry, which includes herbicide-resistant rice lines (Carlson et al. 2011; Masson and Webster 2001; Rustom et al. 2018; Webster and Masson 2001). Often, a grower's weed management program will drive the overall production system depending on the presence and pressure of certain weed species (Norsworthy et al. 2007; Webster 2014).

Barnyardgrass is one of the most common and prolific weed species that infests rice in the southern United States (Norsworthy et al. 2013). Populations of barnyardgrass can reduce rice yields by 30%, and high populations can potentially cause complete crop loss if not properly managed (Bagavathiannan et al. 2014; Johnson et al. 1998). Barnyardgrass is highly competitive with rice due to its rapid growth, C_4 photosynthetic pathway, and ability to produce 39,000 seeds plant^{-1} in rice production (Bagavathiannan et al. 2011; Holm et al. 1977; Vengris et al. 1966).

Since the early 1960s, propanil has been a staple in rice herbicide programs for its ability to successfully control barnyardgrass along with other annual grasses and broadleaf weeds that are common in rice production (Carlson et al. 2011; Fish et al. 2015, 2016; Pellerin et al. 2004; Shaner 2014b; Smith 1965). By the 1990s, at least one application of propanil was applied on 98% of the rice acreage in the southern United States (Carey et al. 1995). Propanil-resistant barnyardgrass was identified in Arkansas in the early 1990s, and it was determined that these resistant populations may require 2.5 to 20 times the use rate of propanil in order to achieve control (Baltazar and Smith 1994).

In 2000, clomazone was labeled for use in rice. Clomazone is a 1-deoxy-D-xylulose 5-phosphate–inhibiting herbicide that acts by interfering with chloroplast development and reduces the accumulation of plastid pigments in susceptible weed species (Ferhatoglu and Barrett 2005). Clomazone applied PRE to rice on a course, textured soil controlled barnyardgrass 96% to 97%, and when clomazone was applied POST to barnyardgrass at the one- to two-leaf stage, control was 85% (Willingham et al. 2008). The first confirmation of clomazone-resistant barnyardgrass occurred in Arkansas in 2008 (Norsworthy et al. 2008).

Pendimethalin is a dinitroaniline herbicide that acts by disrupting mitotic cellular division by inhibiting microtubule proteins in susceptible weed species (Shaner 2014a). Pendimethalin is a soil-applied herbicide that is absorbed by germinating plant roots and coleoptiles causing highly susceptible weed species not to emerge or die soon after emergence due to lack of root development. Pendimethalin has shown to be active on grass and small seeded broadleaf weeds prior to emergence when applied delayed PRE or POST in rice (Bond et al. 2009; Malik et al. 2010; Stauber et al. 1991).

The potential benefits of applying multiple herbicides in a single mixture include a broadened spectrum of weed control, lower application costs due to a single application versus multiple applications, and the prevention or delay of weed species becoming herbicide resistant (Carlson et al. 2011). Previous research conducted in Louisiana reported that herbicide mixtures used in rice production can broaden the weed control spectrum and increase weed control (Carlson et al. 2011; Fish et al. 2015, 2016; Pellerin et al. 2004; Rustom et al. 2018, 2019). Co-applying herbicides in a timely manner in the early growing season can help protect rice yield and prevent weed competition (Webster et al. 2012).

Multiple herbicides applied in mixture have three possible interactions: additive/neutral, synergistic, or antagonistic (Blouin et al. 2004; Colby 1967; Fish et al. 2015, 2016; Flint et al. 1988; Morse 1978; Rustom et al. 2018, 2019; Streibig et al. 1998). Synergism is when two jointly applied herbicides perform greater than the expected outcome of the herbicides applied alone (Colby 1967). In contrast, an antagonistic response is an interaction of two or more herbicides such that the effect when combined is less than the predicted effect based on the activity of each chemical applied separately. A neutral response occurs when the observed response of two jointly applied herbicides equals the expected response of each herbicide applied alone.

Colby's equation has been the benchmark for determining herbicide mixture interactions due to its simple and straightforwardness and its ability to analyze anything from visual observations, dry/fresh weights, weed counts, etc. (Colby 1967). Colby's equation is a statistical linear model in which the expected response is equal to the percent response of each herbicide applied alone, multiplied by one another, and then divided by 100 (Colby 1967, Flint et al. 1988). However, Blouin et al. (2004) argues that the expected response is defined as a multiplicative, nonlinear function of the means for herbicides when applied alone, and a linear standard model for tests of hypotheses does not directly depict the correct expected response for the herbicide mixture. Thus, Blouin et al. (2004) developed a nonlinear mixed model that is more sensitive than Colby's linear model in detecting significant differences in herbicides responses. Blouin et al. (2010) revised his previous model into an augmented mixed model, which proved to be more versatile than his previous model, and this analysis is often referred to as Blouin's modified Colby's.

Fish et al. (2015) reported a prepackaged mixture of propanil plus thiobencarb co-applied with imazethapyr resulted in a synergistic response for red rice and barnyardgrass control. The same model was used to evaluate the interactions of propanil when mixed with imazamox or imazethapyr, and both synergistic and antagonistic responses occurred (Fish et al. 2016; Webster et al. 2017). Rustom et al. (2018, 2019) also employed Blouin's modified Colby's and reported antagonism when quizalofop was mixed with acetolactate synthase–inhibiting herbicides or broadleaf herbicides with contact activity in rice.

The objective of this research was to evaluate the interaction between various rates of a prepackaged mixture of clomazone plus pendimethalin along with various rates of propanil in order to control barnyardgrass, rice flatsedge (*Cyperus iria* L.), and yellow nutsedge (*Cyperus esculentus* L.). Blouin's modified Colby's equation was used to determine whether each mix is either synergistic, antagonistic, or neutral (Blouin et al. 2010).

Materials and Methods

A study was conducted in 2017 and 2018 at the Louisiana State University Agricultural Center's H. Rouse Caffey Rice Research Station (RRS) near Crowley, LA (30.177147°N, 92.3477430°W) on a Crowley silt loam soil with .4% organic matter, pH 6.4. Field preparation consisted of a fall and spring disking followed by two passes in opposite directions with a two-way bed conditioner consisting of rolling baskets and S-tine harrows set to a 6-cm depth in the study area. A preplant fertilizer of 8-24-24 (N-P-K) was applied at 280 kg ha^{-1} followed by a preflood application of 365 kg ha^{-1} of urea fertilizer, 46-0-0.

The long grain imidazolinone-resistant rice cultivar 'CL 111' and the long grain acetyl CoA carboxylase–resistant rice cultivar 'PVL01' were drill seeded at 84 kg ha^{-1} on 18-cm rows on April 4, 2017, and March 22, 2018, respectively. Plot size was 5.1 by 2.2 m^{-2}. No surface irrigation was applied after planting due to 40 and 20 mm of rainfall occurring within 5 d of planting in 2017 and 2018, respectively. A total of 270 and 150 mm of rainfall was recorded from planting to the establishment of the permanent flood in 2017 and 2018, respectively. An 80-cm permanent flood was established when the rice reached the 1-tiller growth stage and maintained until 3 wk prior to harvest.

The experimental design of the study was a randomized complete block with a factorial arrangement of treatments with four replications. Factor A consisted of a prepackaged mix of clomazone plus pendimethalin applied at 0, 760, 1,145, or 1,540 g ai ha^{-1}, or the equivalent rate of clomazone applied alone at 0, 222, 335, or 450 g ai ha^{-1} and pendimethalin applied alone at 0, 538, 810, or 1,090 g ai ha^{-1}. Factor B consisted of propanil applied at 0, 1,120, 2,240, or 4,485 g ha^{-1}. Sources of materials are listed in Table 1.

Herbicide applications were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} at 190 kPa. The spray boom consisted of five flat-fan 110015 nozzles (Flat Fan AirMix Venturi Nozzle, Greenleaf Technologies, Covington, LA 70434) at 38-cm spacing. All herbicide mixtures were applied when rice reached the one- to two-leaf stage. A crop oil concentrate (COC) at 1% vol/vol was added to the treatment that contained only the prepackaged mixture of clomazone plus pendimethalin (Table 1.). No COC was added to any herbicide mixture containing propanil due to its emulsifiable concentrate formulation. In order to obtain yield data, a standard uniform treatment of halosulfuron was applied at 35 d after treatment (DAT) over the entire area at a rate of 53 g ha^{-1} to control escaped broadleaf and sedge weeds.

The research area had a natural population of barnyardgrass, rice flatsedge, and yellow nutsedge. At the initial POST application timing, barnyardgrass were one- to two-leaf and 3- to 5-cm in height at a density of 30 to 40 plants m^{-2}. Yellow nutsedge had three-leaf and 3- to 5-cm in height at a density of 20 to 25 plants m^{-2}. Rice flatsedge had three-leaf and 2- to 3-cm in height with 5 to 10 plants m^{-2}. An activating 130- and 30-mm rainfall was recorded within 3 d of the initial POST application in 2017 and 2018, respectively.

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Table 1. Source of materials for all products used in the study.

Herbicide	Trade name	g L^{-1}	Manufacturer
Propanil	Stam	480	UPL-USA, King of Prussia, PA; www.upi-usa.com
Clomazone + pendimethalin	RiceOne	130 + 313	UPL-USA, King of Prussia, PA; www.upi-usa.com
Halosulfuron	Permit	-[a]	Gowan Company, Yuma, AZ; www.gowanco.com
Crop oil concentrate	Agri-Dex	-[b]	Helena Agri-Enterprises, Collierville, TN; www.helenaagri.com

[a]The formulation for halosulfuron is a water-dispersible granule that contains 75% ai by weight.
[b]The crop oil concentrate is formulated at 17% nonionic surfactant and 83% unsulfonated oil residue.

Visual evaluations included crop injury, barnyardgrass, rice flatsedge, and yellow nutsedge control on a scale of 0% to 100%, where 0% indicates no injury or control and 100% indicates complete plant death at 14, 28, 42, and 56 DAT. Rice flatsedge and yellow nutsedge were rated only at 14 and 28 DAT due to the uniform standard treatment of halosulfuron applied at 35 DAT. Rice plant height was recorded immediately prior to harvest by measuring four plants in each plot from the ground to the tip of the extended panicle. The center four rows of each plot were harvested utilizing a Mitsubishi VM3 (Mitsubishi Corporation, 3-1, Marunouchi 2-chome, Chiyoda-ky, Tokyo, Japan). Grain moisture was adjusted to 12%.

Control data 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 (Fish et al. 2015, 2016; Rustom et al. 2018, 2019; Webster et al. 2017). Rough rice yield and plant height data were analyzed using the MIXED procedure of SAS (SAS 2013). Tukey's HSD test was used to separate yield means at the 5% probability level. The fixed effects for all models were the herbicide treatments and evaluation timings. The random effects for the model were year, replication within year, and plot. 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; Rustom et al. 2018). Normality of effects over all DAT was checked using the UNIVARIATE procedure of SAS. Assumptions of normality were met (SAS 2013).

Results and Discussion

At 14 DAT, antagonism occurred for barnyardgrass control when it was treated with clomazone plus pendimethalin applied at 1,145 and 1,540 g ha^{-1} mixed with 1,120 g ha^{-1} of propanil, with an observed control of 79% and 81%, respectively, compared with an expected control of 90% and 93%, respectively (Table 2). However, these same mixtures were synergistic at 56 DAT. A synergistic response occurred when barnyardgrass was treated with 2,240 and 4,485 g ha^{-1} of propanil mixed with any rate of clomazone plus pendimethalin at 42 and 56 DAT. These data suggest that mixing a prepackaged mixture of clomazone plus pendimethalin with propanil will increase barnyardgrass control later in the growing season compared with applying the herbicides individually. This increase in control is likely due to the residual activity of both clomazone and pendimethalin that provides extended suppression of barnyardgrass after the initial application. Similar results of synergism were observed for barnyardgrass control when propanil was mixed with imazethapyr or imazamox (Fish et al. 2016; Webster et al. 2017).

At 14 DAT, antagonism occurred for yellow nutsedge when treated with 760, 1,145, or 1,540 g ha^{-1} of clomazone plus pendimethalin mixed with 1,120 g ha^{-1} of propanil with an observed control of 51%, 54%, and 56%, respectively, compared with the expected control of 59%, 62%, and 67%, respectively (Table 3). An antagonistic response occurred for yellow nutsedge control when treated with clomazone plus pendimethalin applied at 1,145 g ha^{-1} mixed with all rates of propanil. At 28 DAT, antagonism occurred for yellow nutsedge control across all herbicide mixtures except when 1,145 g ha^{-1} of clomazone plus pendimethalin was mixed with the high rate of propanil applied at 4,485 g ha^{-1}, which resulted in a neutral response. In order to control the yellow nutsedge population and obtain yield data, a standard uniform treatment of halosulfuron applied at 53 g ha^{-1} was applied over the entire test area at 35 DAT.

At 14 DAT, synergism occurred for rice flatsedge control when treated with clomazone plus pendimethalin applied at 760 g ha^{-1} mixed with propanil at either 2,240 or 4,485 g ha^{-1}, with an observed control of 69% and 73% compared with an expected control of 57% and 63%, respectively (Table 4.). Synergism also occurred at 14 DAT when clomazone plus pendimethalin applied at 1,540 g ha^{-1} was mixed with propanil applied at either 2,240 or 4,485 g ha^{-1}, with an observed control of 74% and 81% compared with an expected control of 61% and 67%. All other herbicide mixtures produced a neutral interaction at 14 and 28 DAT. At 14 DAT, the synergism that occurred may have been due to the higher rates of propanil causing more necrosis on the rice flatsedge leaves. Those same herbicide mixtures that were synergistic at 14 DAT were neutral at 28 DAT.

At 14 DAT, rice crop injury was 10% to 15% regardless of the herbicide mixture applied, and injury was less than 5% at 28 DAT through 56 DAT (data not shown). A main effect for propanil rate occurred for rice plant height (Table 5). Rice treated with either 1,120, 2,240, or 4,485 g ha^{-1} of propanil resulted in heights of 98, 100, and 100 cm, respectively, which was taller than the nontreated rice at 86 cm.

A clomazone plus pendimethalin rate by propanil rate interaction occurred for rice yield. Rough rice yield was 4,560, 5,360, and 5,350 kg ha^{-1} when treated with 1,540 g ha^{-1} of clomazone plus pendimethalin mixed with 1,120, 2,240, and 4,485 g ha^{-1} of propanil, respectively (Table 5.). Similarly, rice treated with 760 and 1,145 g ha^{-1} of clomazone plus pendimethalin mixed with the high rate of propanil applied at 4,485 g ha^{-1} yielded 4,660 and 4,800 kg ha^{-1}, respectively. These mixtures were also neutral or synergistic at each visual evaluation for barnyardgrass control compared with the herbicides applied alone (Table 2.). The rough rice yield data indicate that the synergism at 42 DAT and 56 DAT of clomazone plus pendimethalin mixed with propanil in a postemergence timing on barnyardgrass resulted in the corresponding rough rice yield increase.

In conclusion, the addition of a prepackaged mixture of clomazone plus pendimethalin mixed with propanil is synergistic for

Table 2. Barnyardgrass control and interactions with various rates of a prepackaged mixture of clomazone plus pendimethalin mixed with various rates of propanil using Blouin's modified Colby's analysis, 2017 and 2018.[b,c]

		Clomazone plus Pendimethalin ($g\ ha^{-1}$)									
		0	760			1,145			1,540		
Herbicide mixture[a]	Rate	Observed	Expected	Observed	P value	Expected	Observed	P value	Expected	Observed	P value
	$g\ ha^{-1}$	% control									
14 DAT[d]											
Propanil	0	0	–	73	–	–	80	–	–	85	–
Propanil	1,120	52	88	78	0.0528	90	79–	0.0230	93	81–	0.0179
Propanil	2,240	61	90	80	0.0606	92	84	0.1229	94	6	0.1460
Propanil	4,485	65	91	85	0.2867	93	87	0.3193	95	93	0.7898
28 DAT											
Propanil	0	0	–	66	–	–	70	–	–	72	–
Propanil	1,120	37	79	73	0.1929	81	77	0.2931	82	78	0.2636
Propanil	2,240	38	79	65–	0.0023	82	78	0.3118	83	79	0.4403
Propanil	4,485	37	78	75	0.4767	81	84	0.5841	82	84	0.8228
42 DAT											
Propanil	0	0	–	36	–	–	49	–	–	52	–
Propanil	1,120	14	45	55+	0.0482	56	66+	0.0297	59	66	0.1273
Propanil	2,240	14	45	60+	0.0031	56	70+	0.0032	59	73+	0.0026
Propanil	4,485	16	46	71+	0.0001	57	76+	0.0001	60	84+	0.0001
56 DAT											
Propanil	0	0	–	27	–	–	38	–	–	44	–
Propanil	1,120	7	32	47+	0.0054	43	56+	0.0091	49	72+	0.0001
Propanil	2,240	11	35	61+	0.0001	45	70+	0.0001	50	77+	0.0001
Propanil	4,485	12	36	62+	0.0000	45	71+	0.0001	51	82+	0.0001

[a]Evaluation dates for each respective herbicide mixture.
[b]Observed means followed by a plus (+) are significantly different from Blouin's modified Colby's expected responses at the 5% level indicating a synergistic response. A minus (–) indicates an antagonistic response. No sign indicates a neutral response.
[c]$P < 0.05$ indicates antagonistic or synergistic response, $P > 0.05$ indicates an additive response.
[d]Abbreviation: DAT, days after treatment.

Table 3. Yellow nutsedge control and interactions with various rates of a prepackaged mixture of clomazone and pendimethalin mixed with various rates of propanil using Blouin's modified Colby's analysis, 2017 and 2018.[b,c]

		Clomazone plus Pendimethalin ($g\ ha^{-1}$)									
		0	760			1,145			1,540		
Herbicide mixture[a]	Rate	Observed	Expected	Observed	P-value	Expected	Observed	P-value	Expected	Observed	P-value
	$g\ ha^{-1}$	% control									
14 DAT[d]											
Propanil	0	0	–	39	–	–	44	–	–	51	–
Propanil	1,120	32	59	51–	0.0309	62	54–	0.0137	67	56-	0.0015
Propanil	2,240	32	59	55	0.3689	62	53–	0.0082	67	69	0.4268
Propanil	4,485	37	62	55	0.0694	65	57–	0.0253	69	69	0.8807
28 DAT											
Propanil	0	0	–	39	–	–	41	–	–	46	–
Propanil	1,120	17	49	31–	0.0001	52	35-	0.0001	55	41–	0.0001
Propanil	2,240	24	54	38–	0.0001	56	42-	0.0003	59	42–	0.0001
Propanil	4,485	35	60	45–	0.0001	61	55	0.0562	64	51–	0.0001

[a]Evaluation dates for each respective herbicide mixture.
[b]Observed means followed by a plus (+) are significantly different from Blouin's modified Colby's expected responses at the 5% level indicating a synergistic response. A minus (–) indicates an antagonistic response. No sign indicates a neutral response.
[c]$P < 0.05$ indicates antagonistic or synergistic response, $P > 0.05$ indicates an additive response.
[d]Abbreviation: DAT, days after treatment–

control of barnyardgrass. These results are similar to reports by other researchers who noted increased control of barnyardgrass with propanil-containing herbicides mixed with other residual herbicides labeled for use in rice (Carlson et al. 2011, 2012; Fish et al. 2015, 2016; Pellerin et al. 2003; Webster et al 2017) Applying residual herbicides like clomazone plus pendimethalin along with the POST herbicide propanil offers producers the ability to control small emerged grasses while providing extended control later in the growing season with the residual combination. If a second POST application is needed later in the season, the synergistic control from the prepackaged mixture of clomazone plus pendimethalin mixed with propanil could potentially decrease the weed pressure present at the second POST application. An added benefit of applying multiple herbicide modes of action per individual application will help prevent or reduce the development of herbicide-resistant weeds, which can be part of an overall herbicide resistance management strategy (Norsworthy et al. 2012).

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Table 4. Rice flatsedge control and interactions with various rates of a prepackaged mixture of clomazone and pendimethalin mixed with various rates of propanil using Blouin's modified Colby's analysis, 2017 and 2018.[b,c]

		Clomazone plus Pendimethalin (g ha^{-1})									
		0	760			1145			1540		
Herbicide mixture[a]	Rate	Observed	Expected	Observed	P-value	Expected	Observed	P-value	Expected	Observed	P-value
	g ha^{-1}	% control									
14 DAT[d]											
Propanil	0	0	–	44	–	–	43	–	–	50	–
Propanil	1,120	29	61	66	0.2119	60	69	0.0252	65	66	0.6835
Propanil	2,240	22	57	9+	0.0025	56	69	0.0012	61	74+	0.0012
Propanil	4,485	37	63	73+	0.0083	62	62	0.8901	67	81+	0.0003
28 DAT											
Propanil	0	0	–	38	–	–	42	–	–	48	–
Propanil	1,120	23	52	47	0.1422	56	56	0.9035	60	61	0.7604
Propanil	2,240	24	53	59	0.1149	56	66	0.0211	60	61	0.9638
Propanil	4,485	25	54	57	0.3429	57	70	0.0015	61	69	0.0539

[a]Evaluation dates for each respective herbicide mixture.
[b]Observed means followed by a plus (+) are significantly different from Blouin's modified Colby's expected responses at the 5% level indicating a synergistic response. A minus (–) indicates an antagonistic response. No sign indicates a neutral response.
[c]$P < 0.05$ indicates antagonistic or synergistic response, $P > 0.05$ indicates an additive response.
[d]Abbreviation: DAT, days after treatment

Table 5. Rough rice yield when treated with different rates of clomazone plus pendimethalin mixed with different rates of propanil and rice plant height when treated with different rates of propanil, 2017 and 2018.[b,c]

		Clomazone plus pendimethalin (g ha^{-1})				
Herbicide mixture[a]	Rate	0	760	1,145	1,540	Plant height
	g ha^{-1}	kg ha^{-1}				cm
Propanil	0	0 g	3,490 c–f	3,210 def	3,420 c–f	86 b
Propanil	1,120	2,870 f	3,960 b–e	4,040 b–e	4,560 ab	98 a
Propanil	2,240	3,090 ef	4,220 bcd	4,240 bcd	5,360 a	100 a
Propanil	4,485	3,360 c–f	4,660 ab	4,800 ab	5,350 a	101 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.
[c]Plant height with propanil rate main effect, data averaged over clomazone plus pendimethalin rate.

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