Weed Technology

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Evaluation of Pethoxamid-Containing Weed Control Programs in Drill-seeded Rice (*Oryza sativa* L.)

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Research Article

Cite this article: Godwin J, Norsworthy JK, Scott RC (2018) Evaluation of Pethoxamid-Containing Weed Control Programs in Drill-seeded Rice (*Oryza sativa* L.). Weed Technol 32:544–549. doi: 10.1017/wet.2018.54

Received: 12 February 2018
Revised: 30 May 2018
Accepted: 25 June 2018

Associate Editor:
Daniel Stephenson, Louisana State University

Nomenclature:
Carfentrazone; clomazone; imazethapyr; pethoxamid; propanil; quinclorac; barnyardgrass, *Echinochloa crus-galli* (L.) Beauv.; red rice, *Oryza sativa* var. *sylvatica* L.; rice, *Oryza sativa* L

Key words:
Barnyardgrass control; herbicide resistance; herbicide site of action; rice injury; rice production

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Abstract

Herbicide resistance to several of the most common weed species in US rice production, such as barnyardgrass and red rice, has made weed control extremely difficult with available herbicide options. No very-long-chain fatty acid–inhibiting herbicides are labeled for use in US rice; however, pethoxamid is one such herbicide under development for soil-applied use to control grasses and small-seeded broadleaves in rice and various row crops. Field trials were conducted in 2015 and 2016 near Stuttgart, AR, for rice tolerance and in 2016 near Colt, AR, and Lonoke, AR, for weed control with the use of pethoxamid-containing rice herbicide programs. Pethoxamid was applied alone and in a program at 420 and 560 g ai ha^{-1} with other herbicides labeled in rice including clomazone, quinclorac, propanil, imazethapyr, and carfentrazone POST. Injury less than 10% was seen for all treatments 2 wk after application in 2015 and 2016, except for pethoxamid at 420 g ha^{-1} to clomazone to one-leaf rice. Rice injury dissipated to less than 5% following all treatments by 4 wk after flood establishment. Barnyardgrass was controlled 95% or more near Colt and 93% or more near Lonoke for herbicide programs including clomazone PRE followed by pethoxamid plus quinclorac or imazethapyr at three- to four-leaf stage rice. Considering the minimal injury and high levels of barnyardgrass control associated with pethoxamid-containing weed control programs, pethoxamid provides a unique and effective site of action for use in US rice production.

Introduction

Pethoxamid (FMC Corp., Philadelphia, PA) is a very-long-chain fatty acid (VLCFA)–inhibiting herbicide, which belongs to the chloroacetamide family. Pethoxamid is under development in US rice, with registration anticipated in 2021 (Don Johnson, personal communication). There are no VLCFA-inhibiting herbicides labeled for use in US rice production; therefore, pethoxamid would present a unique site of action (SOA) to combat herbicide-resistant weeds in rice.

Pethoxamid is currently used as a PRE herbicide for European corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] (Schlosser et al. 2016) and is a soil-applied, systemic herbicide with activity on many annual grasses and small-seeded broadleaf weeds, including barnyardgrass and red rice (Anonymous 2016). Pethoxamid, like other VLCFA-inhibiting herbicides, is a root and shoot inhibitor; therefore, it controls germinating seeds (Lingenfelter 2015). Pethoxamid has similar activity to such commonly used herbicides in US row crops as acetochlor, alachlor, and metolachlor.

Previous research has shown that the over-reliance on one particular herbicide or herbicide SOA is the leading cause for the selection of herbicide resistance (Norsworthy et al. 2012). This has led to the selection of barnyardgrass resistance to several of the most commonly used herbicides in rice. In a survey of crop consultants in Arkansas and Mississippi, clomazone was listed as the most often recommended PRE herbicide by 91% of respondents (Norsworthy et al. 2013a). The most commonly used POST herbicides included imazethapyr, quinclorac, fenoxaprop, and propanil (Norsworthy et al. 2012). Barnyardgrass resistance has been confirmed by the University of Arkansas resistance screening program to propanil, quinclorac, imazethapyr, penoxsulam, bispyribac, imazamox, and clomazone; and fenoxaprop and cyhalofop-resistant barnyardgrass populations have been confirmed in Mississippi (Heap 2017; Miller et al. 2015).

Targeting the most resistance-prone weeds by rotation, mixing, and sequential applications of differing herbicide SOAs can delay the onset of resistance by reducing selection pressure (Norsworthy et al. 2012). Although yearly herbicide rotations and sequential applications of herbicides with different SOAs can reduce selection on weed species compared to a mono-herbicidal program, there is a possibility that multiple resistance may evolve.

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Mixtures of herbicides with multiple SOAs applies simultaneous selection, reducing the risk for resistance (Diggle et al. 2003). Modeling research has shown that resistance has the lowest risk to evolve when herbicides are applied as mixtures having different SOAs (Diggle et al. 2003). Hence, the integration of a new herbicide SOA in rice production broadens the grower's ability to mix pethoxamid with other rice herbicides to combat herbicide-resistant weed species.

VLCFA-inhibiting herbicides have been used in Asian dry- and water-seeded rice culture as both PRE and POST herbicides. Pretilachlor and butachlor are used in Asian rice production. Butachlor controlled barnyardgrass at least 59% when applied 1, 3, 5, and 7 d after direct seeding sprouted rice seed in India (Mutnal et al. 1998). In a separate study conducted in Sri Lanka, pretilachlor plus pyribenzoxim followed by (fb) MCPA was applied to rice 8 d after sowing in a dry-seeded system, reducing weed densities of barnyardgrass, Chinese sprangletop (*Leptochloa chinensis* L.), and knotgrass (*Paspalum distichum* L.) by 99% (Chauhan 2012).

Preliminary research has been conducted on the tolerance of rice to pethoxamid. Pethoxamid was applied delayed preemergence (DPRE), at spiking, and one- to two-leaf rice stages. Rice treated with pethoxamid was injured no more than 5%, and yield was not reduced compared to the nontreated (Godwin et al. 2016). In other research, rice exhibited tolerance to pethoxamid at 420 and 560 g ai ha^{-1} alone or mixed with clomazone, pendimethalin, or quinclorac when applied to spiking rice, with 80% barnyardgrass and 86% Amazon sprangletop [*Leptichloa panicoides* J. Presl (Hitchcock)] control provided by the 560 g ha^{-1} rate at 66 d after treatment (Doherty et al. 2016).

Many of the commonly used herbicides in US rice production inhibit acetolactate synthase (ALS) and acetyl CoA carboxylase (ACCase). ALS-inhibiting and ACCase-inhibiting herbicides have confirmed resistance in 51 and 15 different weed species, respectively, in the United States alone (Heap 2017). There is lower risk for the selection of weed resistance to VLCFA-inhibiting herbicides compared to many commonly used rice herbicides based on there being only five confirmed resistant species worldwide, and only one in the United States, that being Italian ryegrass (*Lolium multiflorum* Lam.) (Heap 2017).

It is believed that pethoxamid may provide an effective and alternative herbicide SOA for use in US rice production when used in combination with other herbicides. It was hypothesized that rice would display adequate tolerance to pethoxamid applied alone and in combination with other rice herbicides at various application timings, while providing an effective level of weed control. The objective of this research was to evaluate weed control and rice tolerance following pethoxamid-containing programs in drill-seeded rice.

Materials and Methods

Field trials were conducted at the Rice Research and Extension Center near Stuttgart (hereafter referred to as Stuttgart), AR (34 28'23" N, 91 25'05" W), in 2015 and 2016 and at the Pine Tree Research Station near Colt (hereafter referred to as Colt), AR (35 07'23" N, 90 55'46" W), and the University of Arkansas Pine Bluff Lonoke Farm near Lonoke (hereafter referred to as Lonoke), AR, in 2016. Studies located at Stuttgart evaluated only rice tolerance, whereas those at Colt and Lonoke assessed weed control. The soils at Stuttgart, Colt, and Lonoke were a Dewitt silt loam (fine, smectic, thermic typic albaqualf), Calloway silt loam (fine-silty, mixed, active, thermic aquic fraglossudalfs), and Immanuel silt loam (fine-silty, mixed, active, thermic oxyaquic glossudalfs), respectively. Imidazolinone-resistant (Clearfield™, BASF Corp., Research Triangle Park, NC) inbred rice cultivars CL111 (Stuttgart) and CL151 (Colt and Lonoke) were drill-seeded in 18-cm rows at a seeding rate of 72 seeds m^{-1} of row. Plot size was 1.8 by 5.2 m. Rice was planted on May 5, 2015 and April 29, 2016 at Stuttgart, and on May 9 and May18, 2016 at Colt and Lonoke, respectively. Rice fertility programs were based on University of Arkansas Division of Agriculture Research and Extension recommendations (Norman et al. 2013).

At each location, the experiment was a randomized complete block design with four replications. In total, 12 different herbicide treatments were evaluated along with a nontreated plot. Herbicides and adjuvants evaluated in all studies are shown in Table 1. Treatments evaluated are presented in Table 2. Herbicides were applied with a CO_2-pressurized backpack sprayer through 110015 AIXR (TeeJet, 1801 Business Park Drive, Springfield, IL 62703) nozzles calibrated to deliver 143 L ha^{-1} using a three-nozzle boom at a 51-cm nozzle spacing at 4.83 km h^{-1}.

The trial at Stuttgart was placed in an area of low weed density, and plots were occasionally hand-rogued to remove any weeds not controlled by the treatments. Entire study areas at Colt and Lonoke were tilled prior to planting to destroy existing weed populations. All one-leaf herbicide applications were made with an average of 11 barnyardgrass plants m^{-2} ranging from 2 to 5 cm

Table 1. Description of herbicides and adjuvants used in rice experiments.

Trade name	Common name	Formulation	Rate	Manufacturer	Website
			g ai ha^{-1}		
---[a]	Pethoxamid	EC	420 or 560	FMC Corp., Philadelphia, PA	http://fmc.com/
Aim	Carfentrazone	EC	18	FMC Corp., Philadelphia, PA	http://fmc.com/
Command	Clomazone	ME	336	FMC Corp., Philadelphia, PA	http://fmc.com/
Facet L	Quinclorac	EC	420	BASF Corp., Research Triangle Park, NC	https://www.basf.com/us/en.html
Induce	Nonionic surfactant	---	0.25% vol/vol	Helena Chemical, Collierville, TN	https://www.helenaagri.com/
Newpath	Imazethapyr	EC	71	BASF Corp., Research Triangle Park, NC	https://www.basf.com/us/en.html
Stam M4	Propanil	EC	4,500	RiceCo USA, Memphis, TN	http://www.ricecousa.com/

[a]Pethoxamid is not registered in any crop and thus does not have a trade name.
[b]Abbreviations: EC, emulsifiable concentrate; ME, microencapsulated.

https://doi.org/10.1017/wet.2018.54 Published online by Cambridge University Press

Table 2. Rice injury ratings 2 wk after treatment (WAT) and shoot density at Stuttgart, AR, in 2015 and 2016.[a–c]

Program				Injury 2 WAT		Shoot density	
PRE herbicide	POST herbicide	POST timing	Pethoxamid rate	2015	2016	2015	2016
			g ai ha^{-1}	——%——		—% of nontreated—	
Nontreated				––	––	100abcd	100
	Pethoxamid	1-lf	420	1c	7bc	99abcd	89
	Pethoxamid	1-lf	560	3bc	5cd	104a	93
	Pethoxamid + clomazone	1-lf	420	8ab	8b	102abc	95
	Pethoxamid + clomazone	1-lf	560	13a	11a	104a	89
Clomazone	Pethoxamid + quinclorac	3- to 4-lf	420	3bc	1e	87ef	90
Clomazone	Pethoxamid + quinclorac	3- to 4-lf	560	2c	3de	89ef	89
Clomazone	Pethoxamid + propanil	3- to 4-lf	420	5bc	2de	91def	92
Clomazone	Pethoxamid + propanil	3- to 4-lf	560	4bc	3de	75g	86
Clomazone	Pethoxamid + imazethapyr	3- to 4-lf	420	1c	3de	107a	90
Clomazone	Pethoxamid + imazethapyr	3- to 4-lf	560	1c	2de	95bcde	90
Clomazone	Pethoxamid + carfentrazone	3- to 4-lf	420	1c	2de	82fg	92
Clomazone	Pethoxamid + carfentrazone	3- to 4-lf	560	1c	3de	93cde	89
			P value	0.0033	< 0.0001	< 0.0001	NS

[a]Abbreviations: lf, leaf.
[b]Means within a column followed by the same lowercase letter are not different according to Fisher's protected LSD ($\alpha = 0.05$).
[c]PRE clomazone applied May 6, 2015 and April 29, 2016; one-leaf rice treated May 19, 2015 and May 12, 2016; three- to four-leaf rice treated May 27, 2015 and June 1, 2016.

at Lonoke and 1 barnyardgrass plant m^{-2} ranging from 2 to 4 cm at Colt. The three-leaf applications were applied to an average of 2 barnyardgrass plants m^{-2} ranging from 6 to 9 cm at Lonoke and 4 barnyardgrass plants m^{-2} ranging from 5 to 8 cm at Colt.

At Stuttgart, visual assessment of crop injury using a scale of 0 to 100% with 0 being no injury and 100% being crop death, was evaluated every 2 wk following the first application until physiological maturity. Visible-injury assessments included reduction in crop density, height, and overall plant vigor. Shoot density (number of shoots m^{-1} of row) was recorded 5 wk after planting. Crop heights were recorded 8 wk after planting by measuring height in three random locations with each plot. Also collected were days to 50% heading relative to the nontreated and rough rice yield (kg ha^{-1}), adjusted to 12.5% moisture. Shoot density and crop height were normalized for each site-year by converting them to a percentage of the nontreated plot. At Colt and Lonoke, a visual assessment of barnyardgrass control (0 to 100%) compared to the nontreated plot was assessed every 2 wk following the first herbicide application until physiological maturity.

Data were analyzed in JMP Pro 12 (SAS Institute Inc., Cary, NC). Data were analyzed separately by site-year with block (replication) included as a random effect. The nontreated data were removed from the analysis for the rice tolerance and barnyardgrass control assessments. All means were separated using Fisher's protected LSD ($\alpha = 0.05$). To determine the effect of pethoxamid rate, the use of a PRE herbicide, and the use of an additional herbicide with pethoxamid on barnyardgrass control, contrasts were conducted for the rate of pethoxamid applied (420 g ha^{-1} vs. 560 g ha^{-1}); the use of a PRE herbicide compared to no PRE; and pethoxamid plus clomazone, pethoxamid plus quinclorac, pethoxamid plus propanil, pethoxamid plus imazethapyr, or pethoxamid plus carfentrazone compared to pethoxamid applied alone for barnyardgrass control 3 wk after pethoxamid treatment (WAT) and 4 wk after rice flooding (WAF) at Colt and Lonoke.

Results and Discussion

Rice injury ratings at Stuttgart were less than 10% for all treatments, except for pethoxamid at 560 g ha^{-1} plus clomazone applied to one-leaf rice 2 WAT in both 2015 and 2016 (Table 2). By 4 WAF, rice injury had dissipated to less than 5% following all treatments (data not shown), indicating that pethoxamid can be safely applied at either one-leaf or three- to four-leaf rice stages alone or in combination with other rice herbicides. These results coincide with previous research on a silty clay soil where a higher rate of pethoxamid applied at 840 g ha^{-1} at DPRE, spiking, and one- to two-leaf rice caused less than 5% injury 3 WAT (Godwin et al. 2016).

Even though injury was no more than 13% and no height reduction occurred for any treatment in 2015 or 2016 (data not shown), differences in shoot density occurred at Stuttgart in 2015 as a result of herbicide treatment. In 2015, clomazone fb pethoxamid at 420 g ha^{-1} plus carfentrazone or clomazone fb pethoxamid at 560 g ha^{-1} plus propanil applied to three- to four-leaf rice had shoot densities less than the nontreated (Table 2). The reduced

https://doi.org/10.1017/wet.2018.54 Published online by Cambridge University Press

Table 3. Rough rice yield at Stuttgart, AR, in 2015 and 2016.[a–c]

PRE herbicide	POST herbicide	POST timing	Pethoxamid rate	Yield	
				2015	2016
			g ai ha^{-1}	——kg ha^{-1}——	
Nontreated				8,289efg	7,080def
	Pethoxamid	1-lf	420	7,680g	6,370f
	Pethoxamid	1-lf	560	9,810a	6,870def
	Pethoxamid + clomazone	1-lf	420	8,640cdefg	6,420ef
	Pethoxamid + clomazone	1-lf	560	8,540defg	7,280cdef
Clomazone	Pethoxamid + quinclorac	3-4 lf	420	9,550abcd	8,290ab
Clomazone	Pethoxamid + quinclorac	3- to 4-lf	560	9,090abcde	7,330cd
Clomazone	Pethoxamid + propanil	3- to 4-lf	420	9,350abcd	8,740a
Clomazone	Pethoxamid + propanil	3- to 4-lf	560	8,790bcdef	7,990abc
Clomazone	Pethoxamid + imazethapyr	3- to 4-lf	420	7,730fg	7,680bcd
Clomazone	Pethoxamid + imazethapyr	3- to 4-lf	560	9,600abc	7,730bcd
Clomazone	Pethoxamid + carfentrazone	3- to 4-lf	420	9,700ab	8,340ab
Clomazone	Pethoxamid + carfentrazone	3- to 4-lf	560	9,650abc	8,090abc
			P value	0.0001	< 0.0001

[a]Abbreviation: lf, leaf.
[b]Means within a column followed by the same lowercase letter are not different according to Fisher's protected LSD ($\alpha = 0.05$).
[c]PRE clomazone applied May 6, 2015 and April 29, 2016; one-leaf rice treated May 19, 2015 and May 12, 2016; and three- to four-leaf rice treated May 27, 2015 and June 1, 2016.

shoot density may be a result of two emulsifiable concentrate formulations being applied as a mixture; however, it should be noted that there are no known published reports of carfentrazone or propanil alone reducing rice shoot density. Observed rice injury from both of these treatments was less than 5% in both 2015 and 2016. Even though a reduction in shoot density was observed, there was no delay in heading (data not shown), and yield was not reduced relative to the nontreated (Table 3).

Barnyardgrass was controlled 97% or more up to 4 WAF at Colt with PRE-applied clomazone-containing herbicide programs that were fb pethoxamid plus another herbicide to three- to four-leaf rice (Table 4). At Lonoke, barnyardgrass was controlled 93% or more 3 WAT and 4 WAF following applications of clomazone PRE fb pethoxamid plus quinclorac or imazethapyr. The reduction in control with propanil-containing programs was attributed to the population of barnyardgrass at Lonoke being confirmed resistant to propanil. Propanil resistance is a common problem in Arkansas. From 2006 to 2012, nearly 50% of barnyardgrass samples submitted to the University of Arkansas herbicide resistance screening program were documented as resistant to propanil (Norsworthy et al. 2013b). The low barnyardgrass control (78% to 87%) when pethoxamid plus carfentrazone was applied to three- to four-leaf rice following PRE-applied clomazone is probably a result of emerged barnyardgrass at the time of application. Pethoxamid only provides residual control, and carfentrazone is only used for POST control of broadleaf weeds (Scott et al. 2016).

Contrasts revealed differences in barnyardgrass control between the rate of pethoxamid used, the use of pethoxamid in combination with other rice herbicides vs. the use of pethoxamid alone, and the use of a PRE vs. the absence of a PRE (Table 5). At Lonoke, barnyardgrass control was improved with pethoxamid at 560 g ha^{-1} compared to 420 g ha^{-1} at both 3 WAT and 4 WAF (Table 5). Also, pethoxamid in combination with all herbicides evaluated, except propanil or carfentrazone at Lonoke, enhanced barnyardgrass control 4 WAF (Table 5). Likewise, the use of a PRE herbicide resulted in higher levels of barnyardgrass control at Colt, 3 WAT and 4 WAF, when compared to treatments without a PRE. Hence, for season-long barnyardgrass control, it is imperative that pethoxamid be used in an herbicide program rather than applied alone to one-leaf rice.

All treatments at Colt and Lonoke containing clomazone PRE fb pethoxamid in a mixture with another herbicide applied to three- to four-leaf rice provided three different herbicide sites of action, including a diterpene biosynthesis inhibitor (clomazone), a VLCFA inhibitor (pethoxamid), and the corresponding site of action for the herbicide added to pethoxamid. The three effective herbicide sites of action at Colt resulted in an increase in weed control both 3 WAT and 4 WAF when compared to pethoxamid applied alone (Table 4). Hence, pethoxamid in a program can provide residual control until permanent flood is established, resulting in season-long barnyardgrass control.

Practical Implications

The minimal rice injury or reduction in yield shows that rice can tolerate pethoxamid POST at the rates evaluated on a silt loam soil. Chloroacetamides, such as pethoxamid, have activity on weeds prior to emergence and inhibit early seedling growth

https://doi.org/10.1017/wet.2018.54 Published online by Cambridge University Press

Table 4. Barnyardgrass control 3 wk after treatment (WAT) and 4 wk after permanent flood (WAF) at Colt and Lonoke, AR in 2016.[a–c]

				Barnyardgrass control			
				3 WAT		4 WAF	
PRE herbicide	POST herbicide	POST timing	Pethoxmid rate	Colt	Lonoke	Colt	Lonoke
			g ai ha^{-1}	----------%----------			
Nontreated				--	--	--	--
	Pethoxamid	1-lf	420	94c	84d	81d	71c
	Pethoxamid	1-lf	560	94c	94ab	88c	90a
	Pethoxamid + clomazone	1-lf	420	97abc	91abc	90c	91a
	Pethoxamid + clomazone	1-lf	560	95bc	95a	93bc	93a
Clomazone	Pethoxamid + quinclorac	3- to 4-lf	420	100a	94ab	100a	94a
Clomazone	Pethoxamid + quinclorac	3- to 4-lf	560	100a	96a	98ab	93a
Clomazone	Pethoxamid + propanil	3- to 4-lf	420	100a	90abcd	100a	79b
Clomazone	Pethoxamid + propanil	3- to 4-lf	560	100a	91abc	99a	81b
Clomazone	Pethoxamid + imazethapyr	3- to 4-lf	420	97ab	93abc	100a	93a
Clomazone	Pethoxamid + imazethapyr	3- to 4-lf	560	100a	94ab	100a	93a
Clomazone	Pethoxamid + carfentrazone	3- to 4-lf	420	100a	86cd	98ab	78bc
Clomazone	Pethoxamid + carfentrazone	3- to 4-lf	560	100a	87bcd	100a	78bc
			P value	0.0005	0.0297	< 0.0001	< 0.0001

[a]Abbreviation: lf, leaf
[b]Means within a column followed by the same lowercase letter are not different according to Fisher's protected LSD ($\alpha = 0.05$).
[c]At Colt, PRE clomazone applied May 10, 2016; one-leaf rice treated May 25, 2016; and three- to four-lear rice treated June 2, 2016. At Lonoke, PRE clomazone applied May 19, 2016; one-leaf rice treated May 31, 2016; and three- to four-leaf rice treated June 13, 2016.

Table 5. Contrasts for percentage barnyardgrass control 3 WAT and 4 WAF at Colt and Lonoke, AR in 2016.[a,b]

	Barnyardgrass control			
	3 WAT		4 WAF	
Contrast	Colt	Lonoke	Colt	Lonoke
	----------P value ----------			
420 vs. 560 g ha^{-1}	NS	0.0339	NS	0.0105
PRE vs. no PRE	< 0.0001	NS	< 0.0001	NS
Peth + clom vs. peth	NS	NS	0.0008	< 0.0001
Peth + quin vs. peth	< 0.0001	0.0136	< 0.0001	< 0.0001
Peth + prop vs. peth	< 0.0001	NS	< 0.0001	NS
Peth + imazeth vs. peth	0.0003	NS	< 0.0001	< 0.0001
Peth + carf vs. peth	< 0.0001	NS	<0.0001	NS

[a]Abbreviations: Carf, carfentrazone; clom, clomazone; imazeth, imazethapyr; peth, pethoxamid; prop, propanil; quin, quinclorac; WAF, wk after permanent rice flood; WAT, wk after treatment.
[b]At Colt, PRE clomazone applied May 10, 2016; one-leaf rice treated May 25, 2016; and three- to four-leaf rice treated June 2, 2016. At Lonoke, PRE clomazone applied May 19, 2016; one-leaf rice treated May 31, 2016; and three- to four-leaf rice treated June 13, 2016.

(Fuerst 1987); therefore, pethoxamid would only control weeds that germinate after the herbicide application. If pethoxamid is to be used POST in rice, it is necessary to mix pethoxamid with a rice herbicide that has activity on weeds that have already emerged. Chloroacetamides are considered relatively low-risk herbicides for the selection of weed resistance (Powles and Shaner 2001); therefore, pethoxamid used in a herbicide program offers an alternative and effective herbicide site of action to control many of the resistant weed species found in rice, such as barnyardgrass. Considering the tolerance of rice and high levels of barnyardgrass control associated with the use of pethoxamid-containing rice herbicide programs, an early POST application of pethoxamid provides a unique site of action and aids residual weed control until the permanent rice flood is established.

Acknowledgments. Funding for this research was provided by the Arkansas Rice Research and Promotion Board. The authors have no conflicts of interest to report.

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https://doi.org/10.1017/wet.2018.54 Published online by Cambridge University Press