Weed Technology

www.cambridge.org/wet

Research Article

Cite this article: Norsworthy JK, Arnold CH, Butts TR, Roberts T, Shelton CW (2024) Clomazone and oxyfluorfen combinations in a flooded rice system. Weed Technol. **38**(e95), 1–9. doi: 10.1017/wet.2024.56

Received: 2 July 2024
Revised: 5 August 2024
Accepted: 9 August 2024

Associate Editor:
Jason Bond, Mississippi State University

Nomenclature:
Clomazone; oxyfluorfen; barnyardgrass; *Echinochloa crus-galli* (L.) P. Beauv.; rice; *Oryza sativa* L.

Keywords:
Weed control

Corresponding author:
Jason K. Norsworthy;
Email: jnorswor@uark.edu

Clomazone and oxyfluorfen combinations in a flooded rice system

Jason K. Norsworthy[1], Casey H. Arnold[2], Thomas R. Butts[3], Trenton Roberts[4] and Chad W. Shelton[5]

[1]Distinguished Professor and Elms Farming Chair of Weed Science Department of Crop, Soil, and Environmental Sciences, University of Arkansas, Fayetteville, AR, USA; [2]Former Graduate Research Assistant, Department of Crop, Soil, and Environmental Sciences, University of Arkansas, Fayetteville, AR, USA; [3]Assistant Professor of Weed Science, Purdue University, West Lafayette, Indiana, USA; [4]Professor, Department of Crop, Soil, and Environmental Sciences, University of Arkansas, Fayetteville, AR, USA and [5]Global Innovation Platform Director, Albaugh LLC, Rosalia, WA, USA

Abstract

Rice producers battle herbicide-resistant weeds worldwide while producing rice for ≥50% of the world's population. Oxyfluorfen can provide rice producers with an alternative site of action for barnyardgrass control, as there are no documented cases of grass weeds being resistant to the herbicide in the mid-southern United States. Oxyfluorfen is anticipated to be labeled in the Roxy Rice Production System and may be sold as a clomazone/oxyfluorfen premixture; hence, experiments were conducted in 2021 and 2022 to evaluate preemergence-applied clomazone/oxyfluorfen ratios compared to clomazone alone on silt loam and clay soils. All ratios of the herbicides caused less than 7% injury to rice in two of four site-years on silt loam soils, whereas, in the two other site-years, the mixtures caused 10% to 40% rice injury at all observation timings. All combinations of the two herbicides provided at least 73% barnyardgrass control 5 wk after rice emergence (WAE) in three of the four site-years on silt loam soils. In at least two of four site-years at 1 and 3 WAE, barnyardgrass control was improved when oxyfluorfen was added to clomazone compared to clomazone alone. On clay soil, barnyardgrass control in both site-years was ≥77% at 5 WAE for all clomazone and oxyfluorfen ratios. Injury to rice ranged from 13% to 30% for all treatments containing clomazone and oxyfluorfen in one of two site-years on clay soil at all observation timings. At 7 WAE, contrasts indicated that the 1:3 ratio of clomazone to oxyfluorfen provided greater barnyardgrass control than the 1:1.5 and 1:2 ratios in one of two site-years. Based on these findings, oxyfluorfen would improve the consistency of barnyardgrass control over clomazone alone in some instances. However, there is an increased risk of injury to rice with the addition of oxyfluorfen.

Introduction

Rice producers in the United States are challenged with controlling herbicide-resistant weeds. In Arkansas, barnyardgrass is the most problematic weed that rice producers are challenged with controlling, especially in a flooded rice system (Butts et al. 2022; Norsworthy et al. 2013). Currently, few herbicides are labeled for use in rice that will effectively control barnyardgrass. Barnyardgrass in Arkansas is resistant to the Herbicide Resistance Action Committee (HRAC)/Weed Science Society of America (WSSA) Groups 1, 2, 4, 5, 13, and 29 (Barber et al. 2023; Heap 2023). Barnyardgrass resistance is most prevalent to postemergence herbicides, meaning that residual herbicides are the best chemical control option for controlling herbicide-resistant barnyardgrass.

Rice producers in the mid-southern United States typically use residual herbicides on conventional and herbicide-resistant rice, with clomazone being the most employed for grass control (Norsworthy et al. 2013). For the most effective control with residual herbicides, producers should start with a clean field, apply a residual herbicide, and then make a sequential application 2 to 3 wk later with a residual and postemergence herbicide (Osterholt et al. 2019). Residual herbicides can be mixed with herbicides that have postemergence activity to keep the field weed-free throughout the growing season. Herbicide applications in a rice field containing propanil and a residual herbicide resulted in greater weed control and rice yields than when propanil was applied alone (Crawford and Jordan 1995). In other research, thiobencarb and pendimethalin applied with propanil as an early postemergence herbicide provided greater control of propanil-resistant barnyardgrass than propanil alone (Talbert and Burgos 2007). Hence, there are scenarios in which using residual herbicides, like clomazone, and a postemergence herbicide will provide better grass control than a postemergence herbicide alone.

Residual herbicides vary in the length of time the parent molecule remains intact in the soil, commonly called herbicide persistence (Colquhoun 2006). Residual herbicides can provide

https://doi.org/10.1017/wet.2024.56 Published online by Cambridge University Press

varying levels of weed control depending on soil texture, soil pH, and climatic factors (Colquhoun 2006; Curran 1999; Helling 2005; Radosevich et al. 2007). Weather patterns in an area where residual herbicides have been applied can influence the herbicide's persistence. High temperatures allow residual herbicides to be broken down quickly due to chemical and microbial degradation (Curran 1999; Radosevich et al. 2007). Rainfall or irrigation are common practices for incorporating residual herbicides into the soil; however, excessive rainfall or irrigation may cause herbicide leaching or runoff (Colquhoun 2006; Radosevich et al. 2007). In rice production, residual herbicides exposed to excessive rainfall or irrigation are prone to runoff, as rice is commonly grown in areas where leaching is not an issue.

Oxyfluorfen is a HRAC/WSSA Group 14 herbicide that inhibits protoporphyrinogen IX oxidase (Anonymous 2013). Oxyfluorfen was introduced to control broadleaf and grass weed species when applied in various crops and fallow areas (Anonymous 2013). Because oxyfluorfen can control grass weed species, combinations of clomazone and oxyfluorfen could allow producers to control problematic grass weed species in rice using multiple sites of action (Norsworthy et al. 2012). However, oxyfluorfen is not currently labeled in rice and is typically not used in anaerobic conditions.

Oxyfluorfen-resistant rice has been bred at the California Cooperative Rice Research Foundation, potentially allowing for oxyfluorfen use in season for rice producers (McKenzie et al. 2021). The trait that confers resistance to oxyfluorfen is a mutant allele and was not genetically inserted into the plant (McKenzie et al. 2021). The oxyfluorfen-resistant trait can be bred into new and existing rice varieties so that producers can use a cultivar that best fits the needs of the farm.

There have been limited studies on oxyfluorfen use in rice, especially regarding weed control; therefore, trials were conducted to evaluate weed control and the level of tolerance of oxyfluorfen-resistant rice to preemergence-applied ratios of clomazone plus oxyfluorfen compared to clomazone alone on silt loam and clay soil.

Materials and Methods

General Methodology

Field experiments were conducted in 2021 and 2022 at the Rice Research and Extension Center (RREC) near Stuttgart (Lat. 34.465164; Long. 91.402792), AR, the University of Arkansas Pine Bluff Small Farm Research Center (UAPB) near Lonoke (Lat. 34.845378; Long. 91.881639), AR, and the Northeast Research and Extension Center (NEREC) in Keiser (Lat. 35.666253; Long. 90.081986), AR. Experiments at the RREC were conducted on a Dewitt silt loam soil (Fine, smectitic, thermic Typic Albaqualfs) with 27% sand, 54% silt, 19% clay, 1.75% organic matter, and a pH of 5.6 (USDA-NRCS 2022). Experiments at UAPB were conducted on an Immanuel silt loam soil (Fine-silty, mixed, thermic Oxyaquic Glossudalfs) consisting of 14% sand, 72% silt, 14% clay, and 1.25% organic matter, with a pH of 5.6. Experiments at NEREC were conducted on a Sharkey silty clay with 41% sand, 1% silt, 58% clay, and 2.8% organic matter, with a pH of 5.5. All experiments were planted with an oxyfluorfen-resistant long-grain rice cultivar (Roxy; Albaugh LLC, St Joseph, MO). Rice was planted at 72 seeds m^{-1} of row on May 14, 2021, and April 29, 2022, at the RREC; April 22, 2021, and May 10, 2022, at the NEREC; and May 24, 2021, and May 11, 2022, at UAPB. The experiments were designed as a randomized complete block, with 9 and 12 treatments for the silt loam and clay soil experiments, respectively. Clomazone (Command® 3ME; FMC Corp., Philadelphia, PA) and oxyfluorfen (ALB2023; Albaugh LLC, St. Joseph, MO) were used in the experiments. Clomazone was applied alone at 224 or 336 g ai ha^{-1} on silt loam soil and 448, 560, and 672 g ha^{-1} on clay soil. The amount of oxyfluorfen was determined by using 1:1.5, 1:2, and 1:3 ratios of clomazone to oxyfluorfen. All herbicides were applied preemergence, and a nontreated control was included for comparison. Plots at the RREC and NEREC were 1.8 m wide and 5.2 m long, whereas plots at UAPB were 3.1 m wide and 7.7 m long. The preemergence applications were applied to the soil immediately after planting. Applications at RREC and NEREC were made with a four-nozzle CO_2-pressurized backpack sprayer using AIXR 110015 nozzles at 4.8 kph and 140 L ha^{-1}. Applications at UAPB were made using a tractor-mounted, multi-boom sprayer calibrated to deliver 94 L ha^{-1} at 4.8 kph with AIXR 110015 nozzles. Each treatment at each site was replicated four times. Rice shoot counts were taken in two 1-m sections of a row at either 2 or 3 wk after emergence (WAE). Visible rice injury and barnyardgrass control ratings were recorded 1, 3, and 5 WAE at RREC and UAPB; and 1, 3, 5, and 7 WAE at NEREC. Two 0.25-m^2 quadrants were flagged 1 WAE in each plot. Weed species in the quadrants were counted and pulled weekly until the experiments were flooded. Weed counts were only evaluated at UAPB in 2022. Twenty barnyardgrass panicles were collected from each experiment to estimate seed production at RREC and NEREC in 2021 and all locations in 2022. Two applications of azoxystrobin plus difenoconazole (Amistar Top; Syngenta Crop Protection, Greensboro, NC) were applied to each trial each year to protect the crop from diseases. No maintenance herbicide or insecticide applications were made. Rough rice yields were not collected in 2021 at UAPB as a result of severe lodging in the experiment.

Data Analysis

JMP Pro v. 17.0 (JMP) and SAS v 9.4 (SAS) (SAS Institute Inc, Cary, NC) were used to analyze all data for the experiments. Data were subjected to an ANOVA and means separated using Tukey's honest significant difference test with an alpha value of 0.05 (Gbur et al. 2012). In addition, all experiments had a significant site-year-by-treatment interaction; therefore, all data were analyzed separately by site-year.

All experiments were analyzed using preplanned orthogonal contrasts. Ratios of clomazone to oxyfluorfen were compared to determine if one ratio was superior to others, and ratios were compared to clomazone alone to determine if the addition of oxyfluorfen improved grass weed control.

Results and Discussion

Silt Loam Soil

Weed Control

A contrast indicated that adding oxyfluorfen to clomazone improved barnyardgrass control in two of four site-years at 1 WAE (Table 1). Adding oxyfluorfen to clomazone improved barnyardgrass control in all site-years by 3 WAE. Barnyardgrass control with clomazone alone ranged from 78% to 100% at 1 WAE for the four site-years evaluated.

A previous study has shown that barnyardgrass is susceptible to oxyfluorfen (Lee et al. 1991). Therefore, adding oxyfluorfen to clomazone could benefit areas where clomazone-resistant barnyardgrass is suspected or confirmed. In addition to improved barnyardgrass control, oxyfluorfen plus clomazone provides two

https://doi.org/10.1017/wet.2024.56 Published online by Cambridge University Press

Table 1. Barnyardgrass control following a preemergence application of clomazone and oxyfluorfen on silt loam soil in 2021 and 2022.[a–c]

			Barnyardgrass control											
			1 WAE				3 WAE				5 WAE			
			RREC		UAPB		RREC		UAPB		RREC		UAPB	
Herbicides	Rate	Ratio	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
	g ai ha^{-1}		%											
Clom + oxy	224 + 336	1:1.5	96	99	83	93 AB	90	99	65 C	96	86	93	43 B	88
Clom + oxy	336 + 504	1:1.5	96	98	91	93 AB	93	99	83 ABC	99	93	99	65 AB	81
Clom + oxy	224 + 448	1:2	95	99	89	92 AB	86	98	80 ABC	96	97	99	63 AB	73
Clom + oxy	336 + 672	1:2	95	98	93	92 AB	89	99	89 AB	96	88	100	65 AB	88
Clom + oxy	224 + 672	1:3	96	100	94	96 A	94	100	90 AB	96	97	100	55 AB	90
Clom + oxy	336 + 1,008	1:3	95	100	94	96 A	91	99	94 A	98	96	100	73 A	85
Clom	224	n/a	95	100	78	86 B	79	97	70 BC	95	85	98	48 AB	78
Clom	336	n/a	95	99	78	90 AB	86	98	73 ABC	94	84	100	55 AB	83
Contrasts														
With vs. without oxy			96 vs. 95	99 vs. 100	91 vs. 78*	94 vs. 88*	91 vs. 83*	99 vs. 98*	84 vs. 72*	97 vs. 95*	93 vs. 85	99 vs. 99	61 vs. 52	84 vs. 81
1:1.5 vs. 1:2[d]			96 vs. 95	99 vs. 99	87 vs. 91	93 vs. 92	92 vs. 88	99 vs. 98	74 vs. 85*	98 vs. 96	90 vs. 93	96 vs. 100	54 vs. 64	85 vs. 81
1:1.5 vs. 1:3			96 vs. 96	99 vs. 100	87 vs. 94	93 vs. 96	92 vs. 93	99 vs. 99	74 vs. 92*	98 vs. 97	90 vs. 97	96 vs. 100	54 vs. 64	85 vs. 88
1:2 vs. 1:3			95 vs. 96	99 vs. 100	91 vs. 94	92 vs. 96*	88 vs. 93	98 vs. 99	85 vs. 92	96 vs. 97	93 vs. 97	100 vs. 100	64 vs. 64	81 vs. 88

[a]Abbreviations: Clom, clomazone; n/a, not applicable; oxy, oxyfluorfen; RREC, Rice Research and Extension Center; UAPB, University of Arkansas Pine Bluff Small Farm Research Center; WAE, wk after emergence.
[b]Means within the same column followed by the same letter are not different according to Tukey's honest significant difference ($\alpha = 0.05$); the absence of letters indicates no treatment differences.
[c]* Indicates significant difference ($\alpha = 0.05$).
[d]Ratios indicate clomazone/oxyfluorfen.

effective sites of action, a strategy known to mitigate the evolution of herbicide resistance (Norsworthy et al. 2012).

Contrasts indicated that all ratios of clomazone and oxyfluorfen provided similar levels of barnyardgrass control in three of four site-years at 1 and 3 WAE (Table 1). By 5 WAE, all ratios of oxyfluorfen and clomazone provided similar levels of barnyardgrass control across all site-years. In other research, clomazone at 280 g ha^{-1} provided 90% to 100% barnyardgrass control (Westberg et al. 1989). Effective control should be expected with all ratios that included clomazone at 336 g ha^{-1}, as both herbicides are labeled for barnyardgrass control in crops on silt loam soil (Anonymous 2013).

All clomazone/oxyfluorfen ratios were comparable in the amount of barnyardgrass seed produced (Table 2). Adding oxyfluorfen to soil-applied clomazone reduced barnyardgrass seed production in one of three site-years. Allowing barnyardgrass plants to interfere with rice and reproduce could substantially affect rough rice grain yield (Smith 1968) and lead to greater barnyardgrass infestations due to increases in the soil seedbank. The return of barnyardgrass seeds to the soil seedbank could cause significant ramifications for producers in future growing seasons and lead to the selection of barnyardgrass plants resistant to oxyfluorfen.

Broadleaf signalgrass [*Urochloa phatyphylla* (Wright) Webster] was present for two site-years compared to four site-years for barnyardgrass. For all observations, contrasts indicated no improved control with adding oxyfluorfen to clomazone in either site-year (Table 3). Broadleaf signalgrass control did not differ among any of the clomazone/oxyfluorfen ratios tested.

Clomazone alone can provide control of broadleaf signalgrass when used at similar rates and is labeled for control of the weed at 336 g ha^{-1} (Anonymous 2021; O'Barr et al. 2007). Oxyfluorfen at 1,120 g ha^{-1} has provided 80% control of broadleaf signalgrass 3 WAE (Price et al. 2008). Although research has shown that oxyfluorfen provides some control of broadleaf signalgrass, oxyfluorfen is not labeled for control of the weed (Anonymous 2013). Broadleaf signalgrass control will not be improved by adding oxyfluorfen to clomazone.

Tolerance

The visible rice injury following an application of clomazone plus oxyfluorfen was in the form of bleaching caused by clomazone along with stunting, necrosis, and reduced plant vigor caused by oxyfluorfen based on comparison to clomazone alone treatments. At 1 WAE, visible rice injury for all treatments was ≤7% for two of the four site-years, whereas injury was as much as 40% at RREC in 2022 for clomazone at 336 g ha^{-1} in the 1:3 ratio of clomazone to oxyfluorfen (Table 4). In three of the four site-years, there was less than 5% visible rice injury for all ratios of clomazone and oxyfluorfen at 5 WAE. In general, the rice was able to recover from a preemergence application of clomazone plus oxyfluorfen by 5 WAE; however, in 2022, there was still 23% injury to rice following the 1:3 ratio with clomazone at 336 g ha^{-1} at RREC. The high injury observed in 2022 at RREC could be attributed to the site receiving ≥1.3 cm of rainfall 7 DAT compared to 15 DAT in 2021.

The earlier activating rainfall in 2022 could have made the herbicide available for uptake by germinating seedlings in 2022, leading to greater injury. Oxyfluorfen has demonstrated the ability to cause a greater reduction in biomass when applied to wet soil compared to dry soil (Chon et al. 1997). A study conducted in the greenhouse showed that preemergence applications of oxyfluorfen

Table 2. Cumulative barnyardgrass densities and barnyardgrass seed production following a preemergence application of clomazone and oxyfluorfen on silt loam soil in 2021 and 2022.[a–c]

			Barnyardgrass density							Barnyardgrass seed production		
			2 WAE			3 WAE		4 WAE				
			RREC		UAPB	RREC		RREC		RREC		UAPB
Herbicides	Rate	Ratio	2021	2022	2022	2021	2022	2021	2022	2021	2022	2022
	g ai ha^{-1}		No. plants m^{-2}							Thousand m^{-2}		
Nontreated	n/a	n/a	55 A	181 A	8	61 A	192 A	103 A	197 A	42 A	12	56 A
Clom + oxy	224 + 336	1:1.5	14 B	26 B	1	14 B	27 B	19 B	29 B	3 B	10	21 B
Clom + oxy	336 + 504	1:1.5	17 B	22 B	1	18 B	23 B	25 B	23 B	6 B	7	18 B
Clom + oxy	224 + 448	1:2	18 B	32 B	6	18 B	34 B	26 B	39 B	5 B	9	24 B
Clom + oxy	336 + 672	1:2	13 B	11 B	1	13 B	12 B	20 B	12 B	3 B	9	13 B
Clom + oxy	224 + 672	1:3	14 B	28 B	1	15 B	31 B	32 B	32 B	8 B	8	11 B
Clom + oxy	336 + 1,008	1:3	6 B	7 B	1	6 B	8 B	15 B	8 B	4 B	10	19 B
Clom	224	n/a	13 B	33 B	1	14 B	36 B	24 B	40 B	11 B	12	15 B
Clom	336	n/a	10 B	24 B	0	11 B	26 B	35 B	27 B	17 B	10	19 B
Contrasts												
With vs. without oxy			14 vs. 12	21 vs. 29	2 vs. 1	14 vs. 13	23 vs. 31	24 vs. 30	24 vs. 34	5 vs. 14*	9 vs. 11	18 vs. 17
1:1.5 vs. 1:2[d]			16 vs. 16	24 vs. 22	1 vs. 4	16 vs. 16	25 vs. 23	22 vs. 23	26 vs. 26	5 vs. 4	9 vs. 9	20 vs. 19
1:1.5 vs. 1:3			16 vs. 10	24 vs. 18	1 vs. 1	16 vs. 11	25 vs. 20	23 vs. 24	26 vs. 20	5 vs. 6	9 vs. 9	20 vs. 15
1:2 vs. 1:3			16 vs. 10	22 vs. 18	4 vs. 1	16 vs. 11	23 vs. 20	23 vs. 24	26 vs. 20	4 vs. 6	9 vs. 9	19 vs. 15

[a]Abbreviations: Clom, clomazone; n/a, not applicable; oxy, oxyfluorfen; RREC, Rice Research and Extension Center; UAPB, University of Arkansas Pine Bluff Small Farm Research Center; WAE, wk after emergence.
[b]Means within the same column followed by the same letter are not different according to Tukey's honest significant difference (α = 0.05); the absence of letters indicates no treatment differences.
[c]* Indicates significant difference (α = 0.05).
[d]Ratios indicate clomazone/oxyfluorfen

Table 3. Broadleaf signalgrass control following a preemergence application of clomazone and oxyfluorfen on silt loam soil in 2021 and 2022 at the Rice Research and Extension Center near Stuttgart, AR.[a–c]

			Broadleaf signalgrass control					
			1 WAE		3 WAE		5 WAE	
Herbicides	Rate	Ratio	2021	2022	2021	2022	2021	2022
	g ai ha^{-1}		%					
Clom + oxy	224 + 336	1:1.5	95	96	89	92	97	61
Clom + oxy	336 + 504	1:1.5	94	97	94	96	96	78
Clom + oxy	224 + 448	1:2	93	97	92	91	98	59
Clom + oxy	336 + 672	1:2	95	97	94	96	95	59
Clom + oxy	224 + 672	1:3	94	97	94	93	98	64
Clom + oxy	336 + 1,008	1:3	94	98	91	97	96	82
Clom	224	n/a	95	96	91	89	96	83
Clom	336	n/a	93	97	90	94	95	65
Contrasts								
With vs. without oxy			94 vs. 94	97 vs. 97	92 vs. 91	94 vs. 92	97 vs. 96	67 vs. 74
1:1.5 vs. 1:2[d]			95 vs. 94	97 vs. 97	92 vs. 93	94 vs. 94	97 vs. 97	70 vs. 59
1:1.5 vs. 1:3			95 vs. 94	97 vs. 98	92 vs. 93	94 vs. 95	97 vs. 97	70 vs. 73
1:2 vs. 1:3			94 vs. 94	97 vs. 98	93 vs. 93	94 vs. 95	97 vs. 97	59 vs. 73

[a]Abbreviations: Clom, clomazone; oxy, oxyfluorfen; n/a, not applicable; WAE, wk after emergence.
[b]Means within the same column followed by the same letter are not different according to Tukey's honest significant difference (α = 0.05); the absence of letters indicates no treatment differences.
[c]*Indicates significant difference (α = 0.05).
[d]Ratios indicate clomazone/oxyfluorfen.

resulted in the most injury when the soil was maintained at 100% saturation (C. Arnold, unpublished data), indicating that increased injury could be observed if the soil in the field was at 100% saturation.

Contrasts revealed that oxyfluorfen addition to clomazone can increase the risk for rice injury over clomazone alone (Table 4). Oxyfluorfen applied preemergence in combination with clomazone caused greater injury in two of the four site-years 1 WAE than clomazone alone, albeit, in one of the significant site-years, the difference was not likely of biological significance. By 5 WAE, visible rice injury was greater in one of four site-years when comparing rice treated with and without oxyfluorfen, potentially a result of the rainfall received before the rice emerged. Excessive water in the experiment could have caused greater injury because of the herbicide being available for uptake by the plant early in the growing season (Paiman, 2019).

Contrasts revealed that a 1:1.5 ratio of clomazone to oxyfluorfen caused less injury to rice than the 1:3 ratio for one of the four site-years at 1 WAE (Table 4). The 1:3 ratio resulted in greater levels of rice injury when contrasted with the 1:2 ratio in two of four site-years. The 1:3 ratio would be expected to have more injury than the 1:1.5 or 1:2 ratio due to the higher rate of oxyfluorfen applied and

https://doi.org/10.1017/wet.2024.56 Published online by Cambridge University Press

Table 4. Rice injury following a preemergence application of clomazone and oxyfluorfen on silt loam soil in 2021 and 2022.[a–c]

Herbicides	Rate	Ratio	Injury											
			1 WAE				3 WAE				5 WAE			
			RREC		UAPB		RREC		UAPB		RREC		UAPB	
			2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
	g ai ha^{-1}							%						
Clom + oxy	224 + 336	1:1.5	5	20 ABC	1 A	10 B	4	7 BC	0	0	2	6 AB	0	0
Clom + oxy	336 + 504	1:1.5	5	30 AB	4 A	24 A	4	16 AB	0	0	1	14 AB	0	0
Clom + oxy	224 + 448	1:2	5	25 ABC	0 A	17 AB	4	6 BC	0	0	1	2 B	0	0
Clom + oxy	336 + 672	1:2	7	30 AB	3 A	13 AB	3	11 ABC	0	0	1	11 AB	0	0
Clom + oxy	224 + 672	1:3	3	28 ABC	4 A	21 AB	3	8 ABC	0	0	0	4 B	0	0
Clom + oxy	336 + 1,008	1:3	6	40 A	4 A	26 A	3	17 A	0	0	2	23 A	0	0
Clom	224	n/a	4	9 BC	0 A	13 AB	3	7 BC	0	0	1	3 B	0	0
Clom	336	n/a	5	10 C	1 A	22 AB	3	6 C	0	0	1	4 B	0	0
Contrasts														
With vs. without oxy			5 vs. 5	29 vs. 10*	3 vs. 1*	19 vs. 18	4 vs. 3	11 vs. 7*	0 vs. 0	0 vs. 0	1 vs. 1	10 vs. 4*	0 vs. 0	0 vs. 0
1:1.5 vs. 1:2[d]			5 vs. 6	25 vs. 28	3 vs. 2	17 vs. 15	4 vs. 4	12 vs. 9	0 vs. 0	0 vs. 0	2 vs. 1	10 vs. 7	0 vs. 0	0 vs. 0
1:1.5 vs. 1:3			5 vs. 5	25 vs. 34	3 vs. 4	17 vs. 24*	4 vs. 3	12 vs. 13	0 vs. 0	0 vs. 0	2 vs. 1	10 vs. 14	0 vs. 0	0 vs. 0
1:2 vs. 1:3			6 vs. 5	28 vs. 34	2 vs. 4*	15 vs. 24*	4 vs. 3	9 vs. 13	0 vs. 0	0 vs. 0	1 vs. 1	7 vs. 14	0 vs. 0	0 vs. 0

[a]Abbreviations: Clom, clomazone; n/a, not applicable; oxy, oxyfluorfen; RREC, Rice Research and Extension Center; UAPB, University of Arkansas Pine Bluff Small Farm Research Center; WAE, wk after emergence.
[b]Means within the same column followed by the same letter are not different according to Tukey's honest significant difference ($\alpha = 0.05$); the absence of letters indicates no treatment differences.
[c]* Indicates significant difference ($\alpha = 0.05$).
[d]Ratios indicate clomazone/oxyfluorfen.

hence greater herbicide availability for the rice plants. By 3 WAE, contrasts indicated no differences in injury among the ratios of clomazone to oxyfluorfen evaluated, and all ratios resulted in ≤13% injury of oxyfluorfen-resistant rice averaged over clomazone rates.

In some instances, the visible injury was related to a reduced rice stand (Table 5). The number of shoots per meter row of rice was reduced when a 1:3 ratio of clomazone to oxyfluorfen was used, compared to a 1:2 ratio in one of three site-years. The 1:3 ratios decreased the shoot counts compared to the 1:1.5 ratios in two of three site-years. The 1:2 clomazone plus oxyfluorfen ratios had increased rice shoots in one of three site-years. Using oxyfluorfen in oxyfluorfen-resistant rice can cause reduced shoot density by thinning rice via the death of emerging plants. In general, rice shoot densities appear to be consistently reduced when the ratio of clomazone to oxyfluorfen increases.

Rough rice yields were influenced by the ratio of clomazone plus oxyfluorfen used and the addition of oxyfluorfen to clomazone in one of three site-years (Table 5). When oxyfluorfen was applied with clomazone, rough rice yield was increased compared to clomazone alone at UAPB in 2022. A 1:3 ratio of clomazone plus oxyfluorfen resulted in higher rough rice yields than a 1:2 ratio at UAPB in 2022. At RREC in 2022, there was lodging in the trial resulting in extreme yield variability.

Yield at UAPB in 2022 increased as barnyardgrass control numerically increased. However, there did not appear to be a relationship between oxyfluorfen-resistant rice injury and rough rice yield. A severe reduction in rice yields can be observed when barnyardgrass competes with rice for the growing season (Smith 1968, 1974). There could have been other factors that influenced rice yield; however, these factors would have likely been uniform throughout the trial.

Clay Soil

Weed Control

Contrasts indicated that all ratios of clomazone and oxyfluorfen evaluated on clay soil provided comparable barnyardgrass control through 3 WAE in both site-years (Table 6). By 5 WAE, the 1:3 ratio of clomazone to oxyfluorfen provided greater barnyardgrass control than the 1:1.5 ratio in one of two site-years. Additional control as the oxyfluorfen rate increased equates with the fact that oxyfluorfen alone is labeled for barnyardgrass control in several crops (Anonymous 2013). The same trend was apparent 7 WAE; however, contrasts indicated that barnyardgrass control had decreased to 75% to 86% for all clomazone plus oxyfluorfen ratios. Based on the contrasts conducted, the 1:2 and 1:3 ratios of clomazone to oxyfluorfen would be better suited for barnyardgrass control than the 1:1.5 ratio in drill-seeded rice across varying soil types.

Clomazone is a widely used preemergence herbicide for grass weed control in mid-southern U.S. rice production (Norsworthy et al. 2013). Contrasts revealed that oxyfluorfen addition to clomazone improved barnyardgrass control in one of two site-years at 1 WAE on clay soil (Table 6). At 3 and 5 WAE, there was improved barnyardgrass control when oxyfluorfen was included with clomazone in both site-years. Adding oxyfluorfen to clomazone reduced the number of barnyardgrass plants that had emerged by 3 and 4 WAE compared to clomazone alone in both site-years (Table 7). The clomazone plus oxyfluorfen ratios evaluated had no influence on the number of emerging barnyardgrass plants up to 3 WAE in both site-years. Using

Table 5. Rice shoot counts and rough rice yield following a preemergence application of clomazone and oxyfluorfen on silt loam soil in 2021 and 2022.[a–c]

			Shoot density			Yield		
			RREC		UAPB	RREC		UAPB
Herbicides	Rate	Ratio	2021	2022	2022	2021	2022	2022
	g ai ha^{-1}		No. shoots m^{-1} row			kg ha^{-1}		
Nontreated	n/a	n/a	25	42	60 A	4,890	550 B	70 C
Clom + oxy	224 + 336	1:1.5	22	41	47 AB	4,200	2,470 AB	3940 AB
Clom + oxy	336 + 504	1:1.5	20	45	40 B	4,330	4,110 A	4620 AB
Clom + oxy	224 + 448	1:2	19	39	44 AB	4,670	1,290 AB	4250 AB
Clom + oxy	336 + 672	1:2	18	41	42 B	5,830	3,320 AB	4180 AB
Clom + oxy	224 + 672	1:3	15	41	33 B	4,840	2,480 AB	4780 A
Clom + oxy	336 + 1,008	1:3	17	33	36 B	5,000	4,110 A	4670 A
Clom	224	n/a	16	47	40 B	4,570	3,000 AB	3630 B
Clom	336	n/a	15	47	38 B	4,370	3,440 AB	4420 AB
Contrasts								
With vs. without oxy			19 vs. 16	40 vs. 47*	40 vs. 39	4,810 vs. 4,470	2970 vs. 3220	4,410 vs. 4,030*
1:1.5 vs. 1:2[d]			21 vs. 19	43 vs. 40	44 vs. 43	4,260 vs. 5,250*	3300 vs. 2300	4,280 vs. 4,210
1:1.5 vs. 1:3			21 vs. 16*	43 vs. 37	44 vs. 35*	4,260 vs. 4,920	3300 vs. 3300	4,280 vs. 4,730
1:2 vs. 1:3			19 vs. 16	40 vs. 37	43 vs. 35*	5,250 vs. 4,920	2300 vs. 3300	4,210 vs. 4,730*

[a]Abbreviations: Clom, clomazone; n/a, not applicable; oxy, oxyfluorfen; RREC, Rice Research and Extension Center; UAPB, University of Arkansas Pine Bluff Small Farm Research Center; WAE, wk after emergence.
[b]Means within the same column followed by the same letter are not different according to Tukey's honest significant difference (α = 0.05); the absence of letters indicates no treatment differences.
[c]*Indicates significant difference (α = 0.05).
[d]Ratios indicate clomazone/oxyfluorfen.

Table 6. Barnyardgrass control following a preemergence application of clomazone and oxyfluorfen on clay soil in 2021 and 2022 at the Northeast Research and Extension Center in Keiser, AR.[a–c]

			Barnyardgrass control							
			1 WAE		3 WAE		5 WAE		7 WAE	
Herbicides	Rate	Ratio	2021	2022	2021	2022	2021	2022	2021	2022
	g ai ha^{-1}		%							
Clom + oxy	448 + 672	1:1.5	99	95	96	95 A	78 AB	86 AB	71 B	79 ABC
Clom + oxy	560+ 840	1:1.5	99	92	97	96 A	81 AB	80 AB	78 AB	68 ABC
Clom + oxy	672 + 1,008	1:1.5	99	96	97	96 A	83 AB	89 A	80 AB	79 ABC
Clom + oxy	448 + 896	1:2	100	91	96	89 AB	78 AB	77 AB	74 AB	60 BC
Clom + oxy	560 + 1,120	1:2	100	97	98	96 A	83 AB	88 AB	75 AB	83 A
Clom + oxy	672 + 1,344	1:2	100	98	97	98 A	93 A	92 A	91 A	89 A
Clom + oxy	448 + 1,344	1:3	100	93	98	89 AB	85 AB	79 AB	81 AB	72 ABC
Clom + oxy	560 + 1,680	1:3	98	98	99	96 A	94 A	91 A	90 A	82 AB
Clom	448	n/a	100	87	71	82 B	73 B	72 B	70 B	60 C
Clom	560	n/a	98	88	94	91 AB	76 AB	79 AB	69 B	61 BC
Clom	672	n/a	100	95	96	95 A	84 AB	89 A	80 AB	85 A
Contrasts										
With vs. without oxy			99 vs. 99	95 vs. 90*	97 vs. 87*	94 vs. 89*	84 vs. 78*	85 vs. 80*	80 vs. 73*	77 vs. 69*
1:1.5 vs. 1:2[d]			99 vs. 100	94 vs. 95	97 vs. 97	96 vs. 94	81 vs. 85	85 vs. 86	76 vs. 80	75 vs. 77
1:1.5 vs. 1:3			99 vs. 99	94 vs. 96	97 vs. 99	96 vs. 93	81 vs. 90*	85 vs. 85	76 vs. 86*	75 vs. 77
1:2 vs. 1:3			100 vs. 99	95 vs. 96	97 vs. 99	94 vs. 93	85 vs. 90	86 vs. 85	80 vs. 86	77 vs. 77

[a]Abbreviations: Clom, clomazone; n/a, not applicable; oxy, oxyfluorfen; WAE, wk after emergence.
[b]Means within the same column followed by the same letter are not different according to Tukey's honest significant difference (α = 0.05); the absence of letters indicates no treatment differences.
[c]*Indicates significant difference (α = 0.05).
[d]Ratios indicate clomazone/oxyfluorfen.

multiple sites of action would allow producers to achieve effective barnyardgrass control and contribute to the sustainability of the Roxy Rice Production System (Green 2014).

The number of barnyardgrass seeds produced by plants on an area basis was not reduced by adding oxyfluorfen to clomazone (Table 7). However, the 1:3 ratio of clomazone to oxyfluorfen decreased barnyardgrass seed production compared to the 1:1.5 and 1:2 ratios in one of the two site-years. The seed production observed could result from the barnyardgrass control and emergence observed earlier in the growing season. The seed returned to the soil seedbank can potentially cause herbicide control failures in the future or select weeds resistant to oxyfluorfen (Schwartz-Lazaro and Copes 2019).

Tolerance

Adding oxyfluorfen to clomazone increased injury levels to oxyfluorfen-resistant rice in both site-years at 1 WAE (Table 8). At 3 WAE, there was no difference in the level of injury observed in both site-years. However, at 5 and 7 WAE, there was greater injury

Table 7. Cumulative barnyardgrass densities and barnyardgrass seeds produced following a preemergence application of clomazone and oxyfluorfen on clay soil in 2021 and 2022 at the Northeast Research and Extension Center in Keiser, AR.[a–c]

			Barnyardgrass density						Barnyardgrass seed production	
			2 WAE		3 WAE		4 WAE			
Herbicides	Rate	Ratio	2021	2022	2021	2022	2021	2022	2021	2022
	g ai ha^{-1}		No. plants m^{-2}						Thousand m^{-2}	
Nontreated	n/a	n/a	19 A	1230 A	137 A	1434 A	203 A	1824 A	21 A	82 A
Clom + oxy	448 + 672	1:1.5	1 B	10 B	11 B	10 B	19 B	252 B	15 AB	28 BC
Clom + oxy	560+ 840	1:1.5	1 B	30 B	3 B	34 B	6 B	291 B	11 AB	20 BC
Clom + oxy	672 + 1,008	1:1.5	0 B	4 B	4 B	4 B	5 B	182 B	11 AB	19 BC
Clom + oxy	448 + 896	1:2	0 B	35 B	2 B	45 B	4 B	332 B	11 AB	38 B
Clom + oxy	560 + 1,120	1:2	1 B	8 B	3 B	9 B	5 B	243 B	8 AB	20 BC
Clom + oxy	672 + 1,344	1:2	0 B	4 B	2 B	4 B	3 B	137 B	8 AB	12 C
Clom + oxy	448 + 1,344	1:3	0 B	28 B	6 B	32 B	7 B	294 B	3 B	30 BC
Clom + oxy	560 + 1,680	1:3	4 B	8 B	8 B	8 B	8 B	163 B	5 AB	18 BC
Clom	448	n/a	0 B	51 B	56 B	67 B	98 AB	464 B	14 AB	24 BC
Clom	560	n/a	4 B	29 B	32 B	56 B	69 B	720 B	15 AB	32 BC
Clom	672	n/a	1 B	8 B	13 B	17 B	32 B	249 B	7 AB	15 C
Contrasts										
With vs. without oxy			1 vs. 2	16 vs. 29	5 vs. 34*	18 vs. 47*	7 vs. 66*	237 vs. 478*	9 vs. 12	23 vs. 24
1:1.5 vs. 1:2[d]			1 vs. 0	15 vs. 16	6 vs. 2	16 vs. 19	10 vs. 4	242 vs. 237	12 vs. 9	22 vs. 23
1:1.5 vs. 1:3			1 vs. 2	16 vs. 18	6 vs. 7	16 vs. 20	10 vs. 8	242 vs. 229	12 vs. 4*	22 vs. 24
1:2 vs. 1:3			0 vs. 2*	15 vs. 18	2 vs. 7	19 vs. 20	4 vs. 8	237 vs. 229	9 vs. 4	23 vs. 24

[a]Abbreviations: Clom, clomazone; n/a, not applicable; oxy, oxyfluorfen; WAE, wk after emergence.
[b]Means within the same column followed by the same letter are not different according to Tukey's honest significant difference ($\alpha = 0.05$); the absence of letters indicates no treatment differences.
[c]* Indicates significant difference ($\alpha = 0.05$).
[d]Ratios indicate clomazone/oxyfluorfen.

Table 8. Rice injury following a preemergence application of clomazone and oxyfluorfen on clay soil in 2021 and 2022 at the Northeast Research and Extension Center in Keiser, AR.[a–c]

			Injury							
			1 WAE		3 WAE		5 WAE		7 WAE	
Herbicides	Rate	Ratio	2021	2022	2001	2002	2001	2002	2001	2002
	g ai ha^{-1}		%							
Clom + oxy	448 + 672	1:1.5	6 B	50	0	30	13	10	9	8
Clom + oxy	560 + 840	1:1.5	8 B	44	0	28	19	8	11	4
Clom + oxy	672 + 1,008	1:1.5	5 B	50	2	28	18	12	12	7
Clom + oxy	448 + 896	1:2	10 B	42	1	23	16	8	12	4
Clom + oxy	560 + 1,120	1:2	9 B	43	1	25	18	8	11	3
Clom + oxy	672 + 1,344	1:2	10 B	51	2	35	18	12	10	5
Clom + oxy	448 + 1,344	1:3	14 AB	51	1	33	19	10	15	4
Clom + oxy	560 + 1,680	1:3	25 A	45	2	17	30	8	17	2
Clom	448	n/a	5 B	38	1	26	23	7	6	3
Clom	560	n/a	3 B	35	0	15	6	8	7	3
Clom	672	n/a	4 B	42	1	21	13	5	6	2
Contrasts										
With vs. without oxy			10 vs. 4*	47 vs. 38*	1 vs. 1	27 vs. 21	18 vs. 14	10 vs. 7*	12 vs. 6*	5 vs. 3
1:1.5 vs. 1:2[d]			6 vs.10	48 vs. 45	1 vs. 1	29 vs. 28	17 vs. 17	10 vs. 9	11 vs. 11	6 vs. 4
1:1.5 vs. 1:3			6 vs. 20*	48 vs. 48	1 vs. 2	29 vs. 25	17 vs. 25	10 vs. 9	11 vs. 16*	6 vs. 3
1:2 vs. 1:3			10 vs. 20*	45 vs. 48	1 vs. 2	28 vs. 25	17 vs. 25	9 vs. 9	11 vs. 16*	4 vs. 3

[a]Abbreviations: Clom, clomazone; n/a, not applicable; oxy, oxyfluorfen; WAE, wk after emergence.
[b]Means within the same column followed by the same letter are not different according to Tukey's honest significant difference ($\alpha = 0.05$); the absence of letters indicates no treatment differences.
[c]* Indicates significant difference ($\alpha = 0.05$).
[d]Ratios indicate clomazone/oxyfluorfen.

with the addition of oxyfluorfen to clomazone in one of the two site-years.

Clomazone alone does not commonly cause severe injury ($\geq$20%) when applied at a similar rate preemergence in rice (Camargo et al. 2011; Scherder et al. 2004). However, oxyfluorfen is not labeled for use in rice, possibly because of the potential for crop injury (Anonymous 2013). Using multiple sites of action in-crop will often lead to greater weed control; however, multiple sites of action could potentially lead to greater injury to rice because of the plant being targeted at multiple sites.

Table 9. Rice shoot counts and rough rice yield following a preemergence application of clomazone and oxyfluorfen on clay soil in 2021 and 2022.[a–c]

Herbicides	Rate	Ratio	Shoot density 2021	Shoot density 2022	Yield 2021	Yield 2022
	g ai ha^{-1}		—No. shoots m^{-1} row—		——kg ha^{-1}——	
Nontreated	n/a	n/a	23	38	5,300 B	540 C
Clom + oxy	448 + 672	1:1.5	24	27	8,960 A	4,860 AB
Clom + oxy	560 + 840	1:1.5	21	37	8,620 A	4,511 AB
Clom + oxy	672 + 1008	1:1.5	27	30	8,510 A	4,910 AB
Clom + oxy	448 + 896	1:2	22	41	8,700 A	3,700 B
Clom + oxy	560 + 1,120	1:2	22	31	8,700 A	4,830 AB
Clom + oxy	672 + 1,344	1:2	23	35	9,030 A	5,370 A
Clom + oxy	448 + 1.344	1:3	22	34	8,920 A	4,030 AB
Clom + oxy	560 + 1,680	1:3	22	40	8,760 A	4,730 AB
Clom	448	n/a	23	36	7,850 A	3,730 B
Clom	560	n/a	22	36	8,520 A	3,840 B
Clom	672	n/a	23	38	8,680 A	4,440 AB
Contrasts						
With vs. without oxy	23 vs 23		34 vs. 37		8,760 vs. 8,450	4,600 vs. 4,000*
1:1.5 vs. 1:2[d]	24 vs. 22		31 vs. 35		8,720 vs. 8,800	4,760 vs. 4,630
1:1.5 vs. 1:3	24 vs. 22		31 vs. 37*		8,720 vs. 8,840	4,760 vs. 4,380
1:2 vs. 1:3	22 vs. 22		35 vs. 37		8,800 vs. 8,840	4,630 vs. 4,380

[a]Abbreviations: Clom, clomazone; n/a, not applicable; oxy, oxyfluorfen.
[b]Means within the same column followed by the same letter are not different according to Tukey's honest significant difference ($\alpha = 0.05$); the absence of letters indicates no treatment differences.
[c]* Indicates significant difference ($\alpha = 0.05$).
[d]Ratios indicate clomazone/oxyfluorfen.

The 1:3 ratio of clomazone to oxyfluorfen caused greater injury than the 1:1.5 and 1:2 ratios of clomazone to oxyfluorfen at 1 WAE in 2021 (Table 8). No difference was observed between clomazone and oxyfluorfen ratios at 3 and 5 WAE in both years. Again at 7 WAE, the 1:3 clomazone to oxyfluorfen ratio caused greater injury than the 1:1.5 and 1:2 ratios. The amount of injury observed with an application containing oxyfluorfen in oxyfluorfen-resistant rice cannot be attributed to differing lines. Even though the seed used in 2021 was harvested in Arkansas in 2020 and shipped for cleaning before planting in 2021, and the 2022 seed was shipped directly from California, the line evaluated in trials in both years was the same.

On clay soil, adding oxyfluorfen to clomazone resulted in greater rough rice yields than clomazone alone in 2022 (Table 9). Rough rice yield data comparing oxyfluorfen plus clomazone to clomazone alone followed the same trend as barnyardgrass control 7 WAE in 2022. Barnyardgrass left uncontrolled following the 7 WAE observation could potentially cause a 35% to 43% reduction in rough rice yields (Smith 1968). The lower barnyardgrass control observed with clomazone alone would significantly reduce rough rice yields than oxyfluorfen plus clomazone (Smith 1968).

Practical Implications

Oxyfluorfen use in oxyfluorfen-resistant rice will provide producers an alternative option for controlling herbicide-resistant barnyardgrass and reducing the risk of target-site herbicide resistance. On silt loam and clay soils, a 1:2 or 1:3 ratio of clomazone to oxyfluorfen should be used to provide the highest levels of barnyardgrass control throughout the growing season. The 1:3 ratio of clomazone to oxyfluorfen will increase the risk of injury to rice compared to the 1:2 ratio on silt loam and clay soils. By applying a 1:2 ratio of clomazone to oxyfluorfen, the labeled recommended rate of clomazone at 336 g ha^{-1} on a silt loam soil would result in oxyfluorfen being applied at 672 g ha^{-1} as the herbicides were co-applied as a mixture. The maximum annual use rate of oxyfluorfen in rice is anticipated to be 1,680 g ha^{-1}, which would result in there being an additional 1,008 g ha^{-1} of the herbicide available for a postemergence application (Chad Shelton, personal communication). If clomazone were applied at 672 g ha^{-1} on clay soil, the oxyfluorfen rate would be 1,344 g ha^{-1} at a 1:2 ratio. Under this scenario, it is unlikely that sufficient oxyfluorfen would be available to make a postemergence application as a a result of annual rate limitations on the herbicide. It is also important to note that these recommendations are solely based on barnyardgrass on both soil textures. Other weeds could be present within a field for which oxyfluorfen may or may not effectively control, resulting in different results from those observed here.

Acknowledgments. Assistance with plot establishment and maintenance by the staff at the Rice Research and Extension Center and the University of Arkansas Pine Bluff Small Farm Research Center is appreciated.

Funding. Partial funding for this research was provided by the Arkansas Rice Promotion Board and Albaugh LLC.

Competing interests. Chad Shelton is an employee of Albaugh LLC.

References

Anonymous (2013) Goal 2XL herbicide product label. DOW Publication No. 62179-424. Indianapolis, IN: DOW Agrosciences LLC. 32 p

Anonymous (2021) Command 3ME herbicide product label. FMC Publication No. 279-3158. Philadelphia, PA: FMC Corp. 27 p

Butts TR, Kouame KB-J, Norsworthy JK, Barber LT (2022) Arkansas rice: herbicide resistance concerns, production practices, and weed management costs. Front Agron 4:881667

Camargo ER, Senseman SA, McCauley GN, Guice JB (2011) Rice tolerance to saflufenacil in clomazone weed control program. Int J Agron 2011:1–8

Chon SU, Guh JO, Han SU, Lee EK, Shin CS (1997) Morphological and anatomical response of rice and barnyard-grass to oxyfluorfen under various growing conditions. Kor J Weed Sci 17:281–287

Colquhoun J (2006) Herbicide persistence and carryover. University of Wisconsin – Extension, Cooperative Extension. http://corn.agronomy.wisc.edu/Management/pdfs/A3819.pdf. Accessed: September 20, 2022

Crawford SH, Jordan DL (1995) Comparison of single and multiple applications of propanil and residual herbicides in dry-seeded rice (*Oryza sativa*). Weed Technol 9:153–157

Curran WS (1999) Persistence of herbicides in soil. Penn State Extension. https://extension.psu.edu/persistence-of-herbicides-in-soil. Accessed: September 20, 2022

Gbur EE, Stroup WW, McCarter KS, Durham S, Young LJ, Christman M, West M, Kramer M (2012) Analysis of generalized linear mixed models in the agricultural and natural resources sciences. Madison, WI: American Society of Agronomy, Soil Science Society of America, and Crop Science of America

Green JM (2014) Current state of herbicide-resistant crops. Pest Manag Sci 70:1351–1357

Heap I (2023) International Herbicide-Resistant Weed Database. https://www.weedscience.org/Pages/Species.aspx. Accessed: January 10, 2023

Helling CS (2005) The science of soil residual herbicides. Pages 3–22 *in* Van Acker RC, ed. Soil Residual Herbicides: Science and Management. Lacomb, AB, Canada: Canadian Weed Science Society

Lee JJ, Matsumoto H, Pyon JY, Ishizuka K (1991) Mechanism of selectivity of diphenyl ether herbicides oxyfluorfen and chlomethoxynil in several plants. Weed Res (Japan) 36:162–170

McKenzie KS, Andaya CB, Andaya VC, De Leon TB (inventors); California Cooperative Rice Research Foundation Inc, assignee (2021) November 23. International patent 2021,052593,A1

Moldenhauer K, Counce P, Hardke J, eds. (2021) Rice growth and development. Pages 9–20 *in* Rice Production Handbook. University of Arkansas System Division of Agriculture Research and Extension

Norsworthy JK, Bond J, Scott RC (2013) Weed management practices and needs in Arkansas and Mississippi rice. Weed Technol 27:623–630

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60 (SP I):31–62

O'Barr JH, McCauley GN, Bovey RW, Senseman SA, Chandler JM (2007) Rice response to clomazone as influenced by application rate, soil type, and planting date. Weed Technol 21:199–205

Osterholt MJ, Webster EP, Blouin DC, McKnight BM (2019) Overlay of residual herbicides in rice for improved weed management. Weed Technol 33: 426–430

Paiman, Effendy I (2019) The effect of soil water content and biochar on rice cultivation in polybag. Open Agriculture 5:117–125

Price AJ, Koger CH, Wilcut JW, Miller D, van Santen E (2008) Efficacy of residual and non-residual herbicides used in cotton production systems when applied with glyphosate, glufosinate, or MSMA. Weed Technol 22:459–466

Radosevich SR, Holt JS, Ghersa CM (2007) Ecology of Weeds and Invasive Plants. 3rd edn. Hoboken, NJ: John Wiley and Sons, Inc. Pp 307–348

Scherder EF, Talbert RE, Clark SD (2004) Rice (*Oryza sativa*) cultivar tolerance to clomazone. Weed Technol 18:140–144

Schwartz-Lazaro LM, Copes JT (2019) A review of the soil seedbank from a weed scientist's perspective. Agron J 9:369

Smith RJ (1968) Weed competition in rice. Weed Sci 16:252–255

Smith RJ (1974) Competition of barnyardgrass with rice cultivars. Weed Sci 5:423–426

Talbert RE, Burgos NR (2007) History and management of herbicide-resistant barnyardgrass (*Echinochloa crus-galli*) in Arkansas rice. Weed Technol 21:324–331

[USDA] US Department of Agriculture (2024) Agricultural Research Service, Dale Bumpers National Rice Research Center: Stuttgart, AR. https://www.ars.usda.gov/southeast-area/stuttgart-ar/dale-bumpers-national-rice-research-center/docs/weather-station-data/. Accessed: October 25, 2024

[USDA] US Department of Agriculture (2022) Natural Resources Conservation Service, National Water and Climate Center. https://wcc.sc.egov.usda.gov/nwcc/site?sitenum=2030. Accessed: February 13, 2023

Westberg DE, Oliver LR, Frans RE (1989) Weed control with clomazone alone and with other herbicides. Weed Technol 3:678–685

https://doi.org/10.1017/wet.2024.56 Published online by Cambridge University Press