

Research Article

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Rice performance following exposure to a sublethal concentration of paraquat applied alone or in mixture with common residual herbicides

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Abstract

In glyphosate-resistant (GR) cropping systems, paraquat applied in mixtures with residual herbicides prior to crop emergence offers an alternative herbicide mode of action (MOA) to aid in GR weed management. Rice is sensitive to off-target herbicide movement; however, severity of injury can vary with herbicide, rate, and formulation. Therefore, research was conducted from 2015 to 2017 in Stoneville, MS, to characterize rice response to a sublethal concentration of paraquat applied at 84 g ai ha⁻¹ in combination with common residual herbicides. Paraquat plus metribuzin injured rice 68% to 69% 14 and 28 d after treatment (DAT), which was 10% to 13% greater than injury following paraquat alone or paraquat plus fomesafen. Pooled across metribuzin and fomesafen treatments, paraquat reduced rough rice yields 23%. Paraquat plus 10 different residual herbicides injured rice ≥51% 28 DAT and reduced rough rice yields ≥21%. These studies indicate a severe negative impact on rice growth and development following exposure to a sublethal concentration of paraquat alone or in mixture with common residual herbicides. Therefore, applications of paraquat plus residual herbicides to fields in proximity to rice should be avoided if conditions are conducive for off-target movement.

Introduction

Rice production in Mississippi occurs in the northwestern portion of Mississippi within the floodplain of the Mississippi and Yazoo rivers because of the region's clay-textured soils, environment, and water availability (Buehring 2008; Miller and Street 2008). In 2018, rice producers harvested 56,275 ha, with production in Bolivar, Sunflower, Tunica, Quitman, and Washington counties accounting for approximately 73% of Mississippi rice hectares (USDA-NASS 2018). In these primary rice-producing counties, land area devoted to rice production makes up only 6.25% of row crop hectareage (USDA-NASS 2018).

Glyphosate-resistant (GR) corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybean [*Glycine max* (L.) Merr.] cropping systems revolutionized weed control after their introduction two decades ago (Edwards 2013; Owen 2000). However, since the introduction of GR cropping technologies, GR weed biotypes have evolved rapidly (Heap 2019). In GR cropping systems, paraquat applied in mixtures with residual herbicides prior to crop emergence offers an alternative herbicide mode of action (MOA) to aid in GR weed management (Bond et al. 2018). Palmer amaranth [*Amaranthus palmeri* (S.) Watts] is the most troublesome weed in corn, cotton, and soybean because of its evolution of resistance to multiple herbicide MOAs, prolific seed production, and genetic diversity (Ward et al. 2013; Webster 2012, 2013). Research has demonstrated that the most effective control methods for GR Palmer amaranth utilize preventative strategies (Culpepper et al. 2010). Residual herbicides are commonly recommended PRE for Palmer amaranth suppression prior to crop emergence (Bond et al. 2018).

Paraquat is a nonselective, broad-spectrum, POST herbicide that inhibits the flow of electrons in photosystem I (PSI) in susceptible plants (Shaner 2014). Paraquat is labeled preplant, PRE, or POST-directed for nonselective weed control in corn, cotton, grain sorghum

Table 1. Coordinates, soil series, soil description, previous crops, soil pH, and soil organic matter (OM) for the paraquat, metribuzin, and fomesafen mixture study and the residual herbicide study in Stoneville, MS, from 2015 to 2017.

Site-year	Coordinates	Soil series	Soil description	Previous crop	pH	OM
2015	33°26.44 N, 90°54.20 W	Sharkey very-fine clay	Very-fine, smectitic, thermic Chromic Epiaquerts	1:1 Rice:fallow	1:2 v:v 7.8	% 2.4
2016A	33°26.34 N, 90°54.12 W	Sharkey very-fine clay	Very-fine, smectitic, thermic Chromic Epiaquerts	Rice:fallow	8.2	2.2
2016B	33°24.23 N, 90°56.80 W	Sharkey very-fine clay	Very-fine, smectitic, thermic Chromic Epiaquerts	Soybean:rice	8.1	2.1
2017A	33°26.26 N, 90°54.11 W	Sharkey very-fine clay	Very-fine, smectitic, thermic Chromic Epiaquerts	Rice:fallow	7.8	2.4
2017B	33°26.19 N, 90°54.25 W	Commerce silty clay loam	Fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquerts	Soybean:rice	7.1	1.7

[*Sorghum bicolor* (L.) Moench], peanut (*Arachis hypogaea* L.), soybean, and numerous vegetable and fruit crops (Anonymous 2019; Shaner 2014). However, paraquat is only labeled preplant or PRE in rice (Anonymous 2019; Bond et al. 2018).

Early-season rice stressors can consist of factors such as pests feeding, suboptimal temperatures, and herbicide drift (Walker et al. 2008). In Mississippi, rice is ideally seeded between April 1 and May 20, with emergence soon thereafter, and these dates often coincide with preplant and/or PRE herbicide applications to corn, cotton, and soybean (Buehring 2008). Visible injury symptoms from off-target herbicide movement may vary based on herbicide MOA and may not always be indicative of total damage to rice (Davis et al. 2011; Ellis et al. 2003; Kurtz and Street 2003). Severe negative implications on rice growth and development following off-target movement of imazethapyr, imazethapyr plus imazapyr, imazamox, glufosinate, or glyphosate have been reported (Bond et al. 2006; Davis et al. 2011; Ellis et al. 2003; Hensley et al. 2012; Kurtz and Street 2003; Webster et al. 2015, 2016). However, severity of injury can vary with herbicide rate, formulation, and carrier volume (Bond et al. 2006; Davis et al. 2011; Hensley et al. 2012; Webster et al. 2015). Webster et al. (2015) reported the greatest rice injury from a sublethal rate of glufosinate applied during late reproductive development was 24% 7 DAT. Glufosinate applied to rice at 31 and 62 g ha⁻¹ during late reproductive development reduced yield more than with any other application timing (Webster et al. 2015). Kurtz and Street (2003) reported that glyphosate applied at 140 g ae ha⁻¹ during late reproductive development injured rice ≤5%; however, yield was reduced ≥63% in 3 of 4 yr.

Two techniques for evaluating the effects of off-target herbicide movement are use of various or constant carrier volume (Banks and Schroeder 2002; Davis et al. 2011; Ellis et al. 2002; Roider et al. 2008; Webster et al. 2015). When off-target movement is tested utilizing various carrier volumes, the herbicide rate is reduced in proportion to a specified spray volume; alternately, when testing with a constant carrier volume, a series of reduced herbicide rates are applied in a single carrier volume (Davis et al. 2011; Hensley et al. 2012). Both techniques are accepted to test the effects off-target herbicide movement to sensitive plant species, but inconsistent results are possible (Ellis et al. 2002; Roider et al. 2008). Injury to wheat (*Triticum aestivum* L.) was 23% less when a systemic herbicide was applied in constant carrier volume compared with proportional carrier volume (Roider et al. 2008). Other research suggests no difference between techniques regardless of herbicide type when applied to soybean (Ellis et al. 2002).

Extensive university research has documented the effects on rice growth and development from glyphosate, glufosinate, and acetolactate synthase-inhibiting herbicides applied at sublethal rates (Bond et al. 2006; Davis et al. 2011; Ellis et al. 2003; Hensley et al. 2012; Webster et al. 2015, 2016). However, no data have been published on rice response following exposure to a sublethal concentration of paraquat alone or in combination with residual herbicides representing different MOAs. Therefore, research was conducted to characterize rice response to a sublethal concentration of paraquat in combination with common residual herbicides.

Materials and Methods

Two separate herbicide mixture studies (paraquat, fomesafen, and metribuzin mixture study and residual herbicide mixture study) to characterize rice response to a sublethal concentration of paraquat applied alone or in combination with common residual herbicides were conducted from 2015 to 2017 at the Mississippi State University Delta Research and Extension Center in Stoneville, MS. Global positioning system coordinates, soil series, soil description, previous crop history, soil pH, and soil organic matter (OM) for both studies are provided in Table 1.

Glyphosate (Roundup PowerMax 4.5 L, 1,120 g ha⁻¹; Monsanto Co., St. Louis, MO), paraquat (Gramoxone 2.0 SL, 560 g ha⁻¹; Syngenta Crop Protection, Greensboro, NC), and/or 2,4-D (2,4-D Amine 3.8 SL, 560 g ae ha⁻¹; Agri Star, Ankeny, IA) were applied in late March to early April each site-year to control emerged vegetation. Clomazone (Command 3 ME, 498 g ai ha⁻¹; FMC Corp., Philadelphia, PA) plus saflufenacil (Sharpen 2.85 SC, 4.5 g ai ha⁻¹; BASF Crop Protection, Research Triangle Park, NC) was applied PRE each site-year for residual weed control. Fenoxaprop-p-ethyl (Ricestar HT 0.58 EC, 1,949 g ai ha⁻¹; Bayer CropScience, Research Triangle Park, NC) plus quinclorac (Facet 1.50 SL, 375 g ai ha⁻¹; BASF Crop Protection, Research Triangle Park, NC) plus halosulfuron (Permit 75 DF, 12 g ai ha⁻¹; Gowan Company, Yuma, AZ) plus petroleum oil surfactant (Herbimax, 83% petroleum oil; Loveland Products, Greeley, CO) at 1% (v/v) was applied at two- to three-leaf rice early POST (EPOST) to maintain experimental sites weed free.

Rice was drill-seeded on June 9, 2015, on May 11 and 17, 2016, and on May 9 and 18, 2017 to a depth of 2 cm using a small-plot grain drill (Great Plains 1520; Great Plains Mfg., Inc., Salina, KS). Rice cultivar, 'CL151' (HorizonAg, Memphis, TN) was seeded at 83 kg ha⁻¹ (356 seed m⁻²) all site-years. Treated plots contained eight rows of rice spaced 20 cm apart and were 4.6 m in length. Treated plots were bordered on either end by a 1.5-m fallow alley

Table 2. Herbicide common and trade names, application concentration, and herbicide manufacturer information for treatments in the residual herbicide study conducted at Stoneville, MS, from 2015 to 2017.

Common name	Rate	Trade name	Manufacturer
	g ai ha ⁻¹		
Paraquat	84	Gramoxone SL 2.0	Syngenta Crop Protection, P.O. Box 18300, Greensboro, NC 27409
Sulfentrazone plus metribuzin	23 plus 34	Authority MTZ 45 DF	FMC Corp., 1735 Market Street, Philadelphia, PA 19103
S-metolachlor plus metribuzin	183 plus 43	Boundary 6.5 EC	Syngenta Crop Protection, P.O. Box 18300, Greensboro, NC 27409
S-metolachlor plus fomesafen	120 plus 26	Prefix 5.29 EC	Syngenta Crop Protection, P.O. Box 18300, Greensboro, NC 27409
Sulfentrazone plus cloransulam-methyl	28 plus 3.5	Sonic 70 DF	Dow AgroSciences, 9330 Zion Road, Indianapolis, IN 46268
Flumioxazin plus pyroxasulfone	8.6 plus 11	Fierce 76 DG	Valent U.S.A, P.O. Box 8025, Walnut Creek, CA 94596
Chlorimuron-ethyl plus flumioxazin plus thifensulfuron-methyl	2.55 plus 8 plus 0.77	Envive 41.3 DG	DuPont, 1007 North Market Street, Wilmington, DE 19898
Metribuzin plus chlorimuron	27 plus 45	Canopy 75 DF	DuPont, 1007 North Market Street, Wilmington, DE 19898
S-metolachlor plus mesotrione plus atrazine	145 plus 19 plus 145	Lexar EZ 3.7 EC	Syngenta Crop Protection, P.O. Box 18300, Greensboro, NC 27409
Thiencarbazone-methyl plus isoxaflutole	3.5 plus 9.1	Corvus 2.63 EC	Bayer CropScience, 2 T.W. Alexander Drive, Research Triangle Park, NC 27709
Fluometuron	111	Cotoran 4 L	DuPont, 1007 North Market Street, Wilmington, DE 19898

that contained no rice and on each side by identically sized buffer plots included to minimize treatment contamination. In all studies, nitrogen (N) fertilizer was applied at 168 kg ha⁻¹ as urea (Urea 46-00-00, SouthernGRO Fertilizer, 46-0-0; J&J Bagging, Yazoo City, MS) immediately prior to flood establishment (Norman et al. 2013). Plots were flooded to an approximate depth of 6 to 10 cm when rice reached the one- to two-tiller stage. Rice in all studies was managed throughout the growing season to optimize yield (Buehring 2008).

All herbicide treatments in the paraquat, fomesafen, and metribuzin mixture study, and in the residual herbicide mixture study were applied at a sublethal concentration of 10% of their suggested use rate in Mississippi (Al-Khatib and Peterson 1999; Bond et al. 2018) using a CO₂-pressurized backpack sprayer equipped with flat-fan nozzles (AIRMIX 11002; Greenleaf Technologies, Covington, LA) set to deliver 140 L ha⁻¹ at 206 kPa using water as a carrier. All herbicide treatments included NIS (Activator 90, 90% non-ionic surfactant; Loveland Products, Greeley, CO) at 0.5% (v/v) and ammonium sulfate water-conditioning agent (Class Act NG, 50% nitrogen fertilizer; WinField Solutions, St. Paul, MN) at 2.5% (v/v).

Paraquat, Fomesafen, and Metribuzin Mixture Study

A study conducted from 2015 to 2017 in Stoneville, MS, evaluated rice performance following exposure to a sublethal concentration of paraquat applied alone or in mixture with a sublethal concentration of metribuzin or fomesafen. Treatments were arranged as a two-factor factorial within a randomized complete block design with four replications. Factor A was paraquat rate and consisted of paraquat at 0 and 84 g ha⁻¹. Factor B was companion herbicide and consisted of no companion herbicide, metribuzin (Tricor 75DF, herbicide; United Phosphorus Inc., King of Prussia, PA) at 42 g ai ha⁻¹, and fomesafen (Reflex 2L, herbicide; Syngenta Crop Protection, Greensboro, NC) at 39 g ai ha⁻¹. Herbicide treatments were applied to rice in the two- to three-leaf stage (EPOST). Visible estimates of aboveground rice injury were recorded 3, 21, and 28 DAT on a scale of 0 to 100% where 0 indicated no visible effect of herbicides and 100 indicated complete plant death. Plant heights were determined 14 DAT by measuring from the soil surface to the uppermost extended leaf and calculating the mean height of five randomly selected plants in each plot. Rice density 14 DAT was determined by counting all emerged plants in two 1-m² quadrats in each plot. The number of days to 50%

heading was recorded as an indication of rice maturity by calculating the time from seedling emergence until 50% of rice plants in an individual plot had visible panicles. Rice dry weight at maturity was determined by hand-harvesting a randomly selected area measuring 1 m from rows 2 or 7 in each plot to determine rice dry weight. Hand-harvested samples were greenhouse-dried at 32 to 49 (± 5) C for 2 wk. Samples were then weighed to determine rice dry weight, and weights were converted to g m⁻².

The remaining area in each plot was harvested with a small-plot combine (Wintersteiger Delta; Wintersteiger, Inc., Salt Lake City, UT) at a moisture content of approximately 20% to determine rough rice yield after all subsamples had been collected. Grain weights and moisture contents were recorded, and rough rice yield was adjusted to a uniform moisture content of 12% for statistical analysis. Whole and total milled rice yield were determined from cleaned 120-g subsamples of rough rice using the procedure outlined by Adair et al. (1972). Rice was mechanically hulled and milled in a Grainman No. 2 miller (Grain Machinery Manufacturing Corp., Miami, FL) for 30 s and size-separated with a No. 12 4.76-mm screen.

All data were subjected to ANOVA using the PROC MIXED procedure in SAS (Statistical software release 9.3; SAS Institute Inc., Cary, NC) with site-year and replication (nested within site-year) as random-effect parameters (Blouin et al. 2011). Type III Statistics were used to test the fixed effects of paraquat rate and companion herbicide treatment for rice injury, density, height, number of days to 50% heading, dry weight, and rice yield (rough, whole, and total milled rice). Least square means were calculated, and mean separation ($P \leq 0.05$) was produced using PDMIX800 in SAS, which is a macro for converting mean separation output letter groupings (Saxton 1998).

Residual Herbicide Mixture Study

A study was conducted from 2015 to 2017 in Stoneville, MS, to evaluate rice performance following exposure to a sublethal concentration of paraquat applied alone or in combination with 10 residual herbicides commonly utilized in Mississippi (Bond et al. 2018). The experimental design was a randomized block with four replications. Treatments included paraquat at 84 g ha⁻¹ applied alone or in mixtures with residual herbicides listed in Table 2. A nontreated control was included for comparison. Herbicide treatments were applied at the EPOST rice growth stage. Visual

Table 3. Rice injury 3, 14, and 28 d after treatment (DAT), density 14 DAT, and rough rice yield in the paraquat, metribuzin, and fomesafen mixture study at Stoneville, MS, from 2015 to 2017.^a

Paraquat rate	Companion herbicide treatment ^{bc}	Injury			Density	Rough rice yield
		3 DAT	14 DAT	28 DAT		
g ai ha ⁻¹		%			Plants m ⁻²	kg ha ⁻¹
0	No companion herbicide	0 d	0 d	0 d	282 a	7,800 a
	Metribuzin	11 c	10 c	8 c	279 a	7,900 a
	Fomesafen	13 c	8 c	6 c	276 a	7,850 a
84	No companion herbicide	42 b	54 b	56 b	233 b	5,990 b
	Metribuzin	50 a	68 a	69 a	193 c	5,140 c
	Fomesafen	46 a	55 b	58 b	242 b	5,830 b

^aData were pooled over 5 site-years. Means followed by the same letter for each parameter are not different at $P \leq 0.05$.

^bHerbicide treatments were applied to rice in the two- to three-leaf (EPOST) growth stage.

^cMetribuzin was applied at 42 g ai ha⁻¹, and fomesafen was applied at 39 g ai ha⁻¹.

Table 4. Influence of paraquat rate on rice plant height 14 d after treatment (DAT), days to 50% heading expressed as days after emergence (DAE), dry weight at maturity, and total and whole milled rice yield in the paraquat, metribuzin, and fomesafen mixture study at Stoneville, MS, from 2015 to 2017.^a

Paraquat rate	Height	Days to 50% heading	Dry weight	Total milled	Whole milled
g ai ha ⁻¹	cm	DAE	g m ⁻²	%	%
0	22 a	84 b	1,840 a	70 a	60 a
84	12 b	93 a	1,520 b	67 b	56 b

^aData were pooled over three companion herbicide treatments (no companion herbicide, metribuzin at 42 g ai ha⁻¹, and fomesafen at 39 g ai ha⁻¹), and 5 site-years for rice plant height and days to 50% heading, and 6 site-years for dry weight at maturity, total and whole milled rice yield. Means followed by the same letter for each parameter are not different at $P \leq 0.05$.

estimates of rice injury, rice density and height 14 DAT, and rice yield (rough, whole, and total milled rice) were collected and analyzed as previously described.

Results and Discussion

Paraquat, Fomesafen, and Metribuzin Mixture Study

An interaction between paraquat rate and companion herbicide was detected for rice injury 3, 14, and 28 DAT, density 14 DAT, and rough rice yield (Table 3). Except for the 3-DAT evaluation, rice injury was greater with paraquat plus metribuzin than all other treatments imposed in the study (Table 3). Metribuzin and fomesafen applied alone injured rice 11% to 13% 3 DAT (Table 3). Rice injury from paraquat alone was 42%; however, this level of injury was less than that observed with paraquat plus fomesafen or metribuzin, which injured rice 46% and 50%, respectively. Rice injury following metribuzin or fomesafen alone was $\leq 10\%$ 14 and 28 DAT, and the greatest rice injury 14 and 28 DAT occurred with paraquat plus metribuzin (Table 3). Bond et al. (2015) reported that rice injury from fomesafen applied at 25% of the recommended rate was $\leq 15\%$ regardless of evaluation interval. Paraquat plus metribuzin injured rice 68% and 69% 14 and 28 DAT, respectively, which was at least 10% greater than injury following paraquat alone or in mixture with fomesafen (Table 3).

Related research suggests the level of injury observed with paraquat alone at 84 g ai ha⁻¹ during the EPOST rice growth stage in this study is not uncommon (Lawrence et al. 2017). Previously, increases in plant injury and weed control were

reported following applications of paraquat plus a photosystem II (PSII)-inhibiting herbicide (Eubank et al. 2008; Norsworthy et al. 2011). Eubank et al. (2008) reported control of GR horseweed [*Conyza canadensis* (L.) Cronq.] improved to 94% with the addition of metribuzin to paraquat compared to 55% control with paraquat alone. Additionally, Norsworthy et al. (2011) reported failed corn stand control was 97% when paraquat was applied in mixture with a PSII-inhibiting herbicide compared to 79% control with paraquat alone.

Rice density ranged from 276 to 282 m⁻² for all treatments with no paraquat (Table 3). Paraquat alone reduced density to 233 plants m⁻² compared with 276 plants m⁻² where no paraquat or companion herbicide was applied. The greatest reduction in rice density 14 DAT was observed following applications of paraquat plus metribuzin (Table 3). Similarly, in weed control studies paraquat alone reduced GR horseweed densities to 15 plants m⁻² compared to 24 plants m⁻²; however, paraquat plus metribuzin reduced GR horseweed to 1 plant m⁻² (Eubank et al. 2008). Rice density following paraquat plus metribuzin was reduced 30% and 31% compared with that following metribuzin or paraquat alone, respectively (Table 3).

A main effect of paraquat rate was detected for rice height 14 DAT, days to 50% heading, dry weight at maturity, and total and whole milled rice yield (Table 4). Averaged across three companion herbicide treatments, rice height 14 DAT was reduced 45%, maturity was delayed 9 d, and dry weight was reduced 17% following paraquat at 84 g ai ha⁻¹ (Table 4). Similar reductions in rice height and increased days to 50% heading following rice exposure to a sublethal concentration of paraquat EPOST were reported by Lawrence et al. (2017). Total and whole milled rice yield was 70% and 60%, respectively, where no paraquat was applied (Table 4). However, following exposure to paraquat at 84 g ai ha⁻¹, total and whole milled rice yield was reduced to 67% and 56%, respectively (Table 4).

Rough rice yield was similar following treatments that did not include paraquat (Table 3). However, rough rice yield was reduced 23% following paraquat at 84 g ai ha⁻¹ compared with yield of rice not exposed to paraquat or the companion herbicide treatments. Sperry et al. (2019) concluded that, although visual injury was observed following corn exposure to a sublethal rate of fomesafen, corn yield was unaffected. Complementing research reporting improved control of corn and GR horseweed with paraquat plus a PSII-inhibiting herbicide (Eubank et al. 2008; Norsworthy et al. 2011), the greatest reduction in rough rice yield was observed following paraquat plus metribuzin. Rough rice yield was

Table 5. Rice injury 3, 14, and 28 d after treatment (DAT), plant height and density 14 DAT, and rough rice yield in the residual herbicide study at Stoneville, MS, from 2015 to 2017.^a

Treatment ^{bc}	3 DAT	14 DAT	28 DAT	Height	Density	Yield
	%			cm	Plants m ⁻²	kg ha ⁻¹
Nontreated	–	–	–	22 a	365 a	8,070 a
No mixture (paraquat alone)	40 de	49 de	56 de	13 b	312 bcd	6,080 bc
Sulfentrazone plus metribuzin	50 ab	61 ab	65 b	12 bc	288 cde	5,220 cd
S-metolachlor plus metribuzin	52 a	62 ab	65 b	11 c	287 cde	5,100 d
S-metolachlor plus fomesafen	39 de	47 e	51 e	13 b	334 ab	6,090 bc
Sulfentrazone plus cloransulam-methyl	42 cd	51 cd	58 de	11 c	294 cde	6,290 b
Flumioxazin plus pyroxasulfone	40 de	48 de	51 e	12 bc	323 bc	6,190 b
Chlorimuron-ethyl plus flumioxazin plus thifensulfuron-methyl	42 cd	53 cd	60 bcd	12 bc	299 bcd	6,290 b
Metribuzin plus chlorimuron	42 cd	55 bc	64 bc	13 b	322 bc	5,150 d
S-metolachlor plus mesotrione plus atrazine	46 bc	64 a	73 a	12 bc	262 e	5,000 d
Thiencarbazone-methyl plus isoxaflutole	37 e	52 cd	63 bc	12 bc	309 bcd	5,550 bcd
Fluometuron	46 bc	59 abc	63 bc	12 bc	282 de	5,050 d

^aData were pooled over 5 site-years. Means followed by the same letter for each parameter are not different at $P \leq 0.05$.

^bAll treatments except the nontreated contained paraquat at 84 g ai ha⁻¹.

^cAll herbicides were applied at 10% of the recommended use rate in Mississippi.

comparable following paraquat alone and paraquat plus fomesafen (Table 3). However, paraquat plus metribuzin reduced rough rice yield to 5,140 kg ha⁻¹ from 7,800 kg ha⁻¹ where no herbicide was applied, and from 5,990 kg ha⁻¹ following paraquat applied alone (Table 3). Previous research evaluating whether altering N fertilizer aids rice recovery from exposure to a sublethal rate of paraquat found rough rice yield losses of 56% to 58% with paraquat alone (Lawrence et al. 2017).

Residual Herbicide Mixture Study

Rice injury was maximized at 64% 14 DAT with a mixture of paraquat with S-metolachlor plus mesotrione plus atrazine, and this level of injury was comparable with that following paraquat in mixtures with fluometuron (59%), sulfentrazone plus metribuzin (61%), or S-metolachlor plus metribuzin (62%) (Table 5). Woodyard et al. (2009) reported a synergistic effect on weed control when mesotrione and atrazine were applied in mixture. Common lambsquarters (*Chenopodium album* L.) control 30 DAT ranged from 52% to 60% following mesotrione alone at 105 g ha⁻¹, and control increased to $\geq 98\%$ for mesotrione plus atrazine at 280 g ha⁻¹. Chlorimuron-ethyl plus flumioxazin plus thifensulfuron-methyl injured rice 53% 14 DAT, and that injury level was similar to that following fluometuron (59%), metribuzin plus chlorimuron (55%), thiencarbazone-methyl plus isoxaflutole (52%), and sulfentrazone plus cloransulam-methyl (51%). S-metolachlor plus fomesafen injured rice 47% 14 DAT, which was similar to flumioxazin plus pyroxasulfone (48%) and paraquat alone (no mixture; 49%). Rice injury with paraquat alone (no mixture) was comparable to that from flumioxazin plus pyroxasulfone, sulfentrazone plus cloransulam-methyl, and thiencarbazone-methyl plus isoxaflutole (Table 5).

Rice injury 28 DAT was 73% following exposure to a mixture of paraquat with S-metolachlor plus mesotrione plus atrazine (Table 5). S-metolachlor plus metribuzin (65%), sulfentrazone plus metribuzin (65%), metribuzin plus chlorimuron (64%), fluometuron (63%), thiencarbazone-methyl plus isoxaflutole (63%), and chlorimuron-ethyl plus flumioxazin plus thifensulfuron-methyl (60%) produced similar levels of rice injury 28 DAT. Palhano et al. (2018) reported an increase in wheat control with paraquat plus metribuzin compared with paraquat alone. Flumioxazin plus pyroxasulfone and S-metolachlor plus fomesafen

injured rice 51% 28 DAT, which was less than all other treatments. However, this treatment caused injury comparable to that following sulfentrazone plus cloransulam-methyl (58%), paraquat alone (no mixture; 56%), and S-metolachlor plus fomesafen (56%). Rice injury with paraquat alone (no mixture), thiencarbazone-methyl plus isoxaflutole, chlorimuron-ethyl plus flumioxazin plus thifensulfuron-methyl, sulfentrazone plus cloransulam-methyl, S-metolachlor plus fomesafen were similar 28 DAT (Table 5). Armel et al. (2009) reported that annual bluegrass (*Poa annua* L.) control 3 wk after treatment (WAT) was 57% to 84% following applications of mesotrione at 0.16 kg ha⁻¹; however, control was increased to 99% when mesotrione was applied in mixture with paraquat plus acetochlor. A similar response was detected in the current work, in which greater rice injury was observed with the addition of a 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibiting herbicide to paraquat mixtures at the 10% recommended use rate (Table 5).

Rice height and density 14 DAT and rough rice yield were reduced with all treatments compared to the nontreated control (Table 5). Rice density 14 DAT following S-metolachlor plus fomesafen was 334 plants m⁻², which was comparable to densities in the nontreated and following paraquat alone (no mixture), flumioxazin plus pyroxasulfone, metribuzin plus chlorimuron, thiencarbazone-methyl plus isoxaflutole, and chlorimuron-ethyl plus flumioxazin plus thifensulfuron-methyl. S-metolachlor plus mesotrione plus atrazine reduced rice density to 262 plants m⁻², and this was similar to all herbicide treatments except S-metolachlor plus fomesafen, flumioxazin plus pyroxasulfone, metribuzin plus chlorimuron, and paraquat alone (no mixture; Table 5).

Rough rice yield was 5,000 to 6,290 kg ha⁻¹ in all treated plots, and this was 38% and 22% lower than in the nontreated, respectively (Table 5). Sperry et al. (2019) reported that paraquat at 105 g ha⁻¹ reduced corn yield 25 kg d⁻¹ if exposure occurred during vegetative growth. Based on these data, it is plausible to expect greater reductions in rice yield as multiple MOAs are added to herbicide mixtures containing paraquat. Previous research confirmed increased levels of weed control when a PSII-inhibiting herbicides are applied together or in mixture with paraquat (Norsworthy et al. 2011; Palhano et al. 2018). The greatest rough rice yield reductions in the current research were following metribuzin plus chlorimuron (5,150 kg ha⁻¹), S-metolachlor plus

metribuzin (5,100 kg ha⁻¹), S-metolachlor plus mesotrione plus atrazine (5,000 kg ha⁻¹), and flumeturon (5,050 kg ha⁻¹). However, rough rice yields following these treatments were comparable to those following sulfentrazone plus metribuzin (5,220 kg ha⁻¹) and thiencazone-methyl plus isoxaflutole (5,550 kg ha⁻¹). Rough rice yield reductions following sulfentrazone plus cloransulam-methyl were similar to that from chlorimuron-ethyl plus flumioxazin plus thifensulfuron-methyl (6,290 kg ha⁻¹), paraquat alone (no mixture; 6,080 kg ha⁻¹), flumioxazin plus pyroxasulfone (6,190 kg ha⁻¹), S-metolachlor plus fomesafen (6,090 kg ha⁻¹), and thiencazone-methyl plus isoxaflutole (5,550 kg ha⁻¹).

Based on these data, negative effects on rice growth and development can occur following exposure to a sublethal concentration of paraquat applied alone or in mixture with residual herbicides. The current research indicates that, although degrees of severity in rice injury vary across herbicide mixtures, paraquat alone or in combination with nontarget herbicides can have a detrimental effect on rough rice yield. The greatest levels of injury occurred with paraquat plus a PSII-inhibiting herbicide, and rough rice yield was reduced the greatest following applications of paraquat plus a PSII- plus HPPD-inhibiting herbicide. In the current research, rice never recovered from paraquat exposure at EPOST at 10% of the recommended use rate. Additionally, previous research by Lawrence et al. (2017) indicated that adding starter N or altering N fertilizer strategies did not aid rice recovery from injury from exposure to a sublethal concentration of paraquat. These data indicate that additional herbicide MOAs can affect rice injury and induce rough rice yield losses. Because of the extent of rice injury from paraquat alone, diagnosing symptoms of an individual herbicide MOA that may have been in mixture with paraquat would be challenging. In cases of off-target herbicide movement, herbicide concentrations and MOAs are rarely known. Therefore, in conditions conducive for off-target herbicide movement, caution should be exercised when making applications adjacent to fields devoted to rice production.

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References

- Adair CR, Bollich CN, Bowman DH, Jordon NE, Johnson TH, Webb BD, Atkins JG (1972) Rice breeding and testing methods in the United States. Pages 25–75 in *Rice in the United States: Varieties and Production Handbook* 289. Washington, DC: U.S. Department of Agriculture–Agricultural Research Service
- Al-Khatib K, Peterson DE (1999) Soybean (*Glycine max*) response to simulated drift from selected sulfonylurea herbicides, dicamba, glyphosate, and glufosinate. *Weed Technol* 7:97–102
- Anonymous (2019) Gramoxone SL herbicide label. <http://www.cdms.net/ldat/ldAGR000.pdf>. Accessed: May 4, 2019
- Armell GR, Richardson RJ, Wilson PH, Hines TE (2009) Strategies for control of horseweed (*Conyza canadensis*) and other winter annual weeds in no-till corn. *Weed Technol* 23:379–383
- Banks PA, Schroeder J (2002) Carrier volume affects herbicide activity in simulated drift studies. *Weed Technol* 16:833–837
- Blouin DC, Webster EP, Bond JA (2011) On the analysis of combined experiments. *Weed Technol* 25:165–169
- Bond J, Golden B, Allen T, Gore J (2015) Off-target herbicide movement to rice. Mississippi Crop Situation. Starkville, MS: Mississippi State University Extension Service Publication
- Bond JA, Griffin JL, Ellis JM, Linscombe SD, Williams BJ (2006) Corn and rice response to simulated drift of imazethapyr plus imazapyr. *Weed Technol* 20:113–117
- Bond JA, Lawrence BH, Bararpour TM, Dodds DM, Golden BR, Irby JT, Larson EJ, Reynolds DB, eds (2018) 2019 Weed Management Suggestions for Mississippi Row Crops. MS Publication 3171. Mississippi State, MS: Mississippi State University Extension Service and Mississippi Agriculture and Forestry Experiment Station. Pp 19–23
- Buehring N (2008) Rice growth and development. Mississippi Rice Growers Guide. Starkville, MS: Mississippi State University Extension Service Publication 2255
- Culpepper SA, Webster TM, Sosnoskie LM, York AL (2010) Glyphosate-resistant Palmer amaranth in the United States. Page 207 in Nandula VK, ed, *Glyphosate Resistance in Crops and Other Weeds History Development and Management*. Hoboken, NJ: Wiley Inc
- Davis B, Scott RC, Norsworthy JK, Gbur E (2011) Response of rice (*Oryza sativa*) to low rates of glyphosate and glufosinate. *Weed Technol* 25:198–203
- Edwards, CB (2013) Postemergence and residual control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) with dicamba. Master's Thesis. Starkville, MS: Mississippi State University. 30 p
- Ellis JM, Griffin JL, Jones CA (2002) Effects of carrier volume on corn (*Zea mays*) and soybeans (*Glycine max*) response to simulated drift of glyphosate and glufosinate. *Weed Technol* 16:587–592
- Ellis JM, Griffin JL, Linscombe SD, Webster EP (2003) Rice (*Oryza sativa*) and corn (*Zea mays*) response to simulated drift of glyphosate and glufosinate. *Weed Technol* 17:452–460
- Eubank TW, Poston DH, Nandula VK, Koger CH, Shaw DR, Reynolds DB (2008) Glyphosate-resistant horseweed (*Conyza canadensis*) control using glyphosate-, paraquat-, and glufosinate-based herbicide programs. *Weed Technol* 22:16–21
- Heap IM (2019) International herbicide-resistant weed database. <http://www.weedsdatabase.org/Home.aspx>. Accessed: April 29, 2019
- Hensley JB, Webster EP, Blouin DC, Harrell DL, Bond JA (2012) Impact of drift rates of imazethapyr and low carrier volume on non-Clearfield rice. *Weed Technol* 26:236–242
- Kurtz ME, Street JE (2003) Response of rice (*Oryza sativa*) to glyphosate applied to simulate drift. *Weed Technol* 17:234–238
- Lawrence BH, Bond JA, Golden BR, Hydrick HT, Edwards HM (2017) Nitrogen fertilizer programs following rice exposure to paraquat. *Proc South Weed Sci Soc* 70:178
- Miller T, Street J (2008) Introduction. Page 2 in *Mississippi Rice Growers Guide*. Publication 2255. Starkville, MS: Mississippi State University Extension Service
- Norman RJ, Slaton NA, Roberts TL (2013) Soil fertility. Pages 69–102 in Hardke TJ, ed, *Rice Production Handbook*. MP192. Fayetteville, AR: University of Arkansas Division of Agriculture Cooperative Extension Service
- Norsworthy JK, Smith KL, Griffith G (2011) Evaluation of combinations of paraquat plus photosystem II-inhibiting herbicides for controlling failed stands of maize (*Zea mays*). *Crop Prot* 30:307–310
- Owen MDK (2000) Current use of transgenic herbicide-resistant soybean and corn in the USA *Crop Prot* 19:765–771
- Palhano MG, Norsworthy JK, Barber T (2018) Evaluation of chemical termination options for cover crops. *Weed Technol* 32:227–235
- Roider CA, Griffin JL, Harrison SA, Jones CA (2008) Carrier volume affects wheat response to simulated glyphosate drift. *Weed Technol* 22:453–458
- Saxton AM (1998) A macro for converting mean separation output into letter grouping in ProcMixed. Pages 1243–1246 in *Proceedings of the 23rd SAS users Group International*. Cary, NC: SAS Institute
- Shaner DL, ed (2014) *Herbicide Handbook*. 10th edn. Lawrence, KS: Weed Science Society of America. Pp 337–338
- Sperry BP, Lawrence BH, Bond JA, Reynolds DB (2019) Corn response to sub-lethal rates of paraquat and fomesafen at vegetative growth stages. *Weed Technol* 33:595–600

- [USDA-NASS] United States Department of Agriculture National Agriculture Statistics Service (2018) Statistics by Subject. http://www.nass.usda.gov/Statistics_by_Subject. Accessed: April 22, 2019
- Walker TW, Bond JA, Ottis BV, Harrell DL (2008) The effects of starter nitrogen to rice seeded at various densities. *Crop Manag* 7, 10.1094/CM-2008-0911-01-RS
- Ward SM, Webster TM, Steckel LE (2013) Palmer amaranth (*Amaranthus palmeri*): a review. *Weed Technol* 27:12–27
- Webster EP, Hensley JB, Blouin DC, Harrell DL, Bond JA (2015) Impact of off-site deposition of glufosinate to non-Clearfield rice. *Weed Technol* 29:207–216
- Webster EP, Hensley JB, Blouin DC, Harrell DL, Bond JA (2016) Rice crop response to simulated drift of imazamox. *Weed Technol* 30:99–105
- Webster TM (2012) Weed Survey–southern states: grass crops subsection. *Proc South Weed Sci Soc* 65:267–288
- Webster TM (2013) Weed Survey–southern states: broadleaf crops subsection. *Proc South Weed Sci Soc* 66:275–287
- Woodyard AJ, Bollero GA, Riechers DE (2009) Broadleaf weed management in corn utilizing synergistic postemergence herbicide combinations. *Weed Technol* 23:513–518