

Research Article

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Rice response to sublethal rates of paraquat, metribuzin, fomesafen, and cloransulam-methyl at different application timings

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Abstract

The application of paraquat mixtures with residual herbicides before planting rice is a common treatment in Mississippi, and rice in proximity is susceptible to off-target movement of these applications. Four concurrent studies were conducted in Stoneville, MS, to characterize rice performance following exposure to a sublethal rate of paraquat, metribuzin, fomesafen, and cloransulam-methyl at different application timings. Herbicides were applied to rice at the growth stages of spiking to one-leaf (VEPOST), two- to three-leaf (EPOST), three- to four-leaf (MPOST), 7 d postflood (PFLD), and panicle differentiation (PD). Regardless of application timing, rice injury following exposure to paraquat was $\geq 45\%$. Delays in maturity were increased by 0.3 d d⁻¹ following paraquat from emergence through PD. Dry weight, rough rice yield, panicle density, and germination were reduced by 18.7 g, 131.5 kg ha⁻¹, 5.6 m⁻², and 0.3%, respectively, per day from application of paraquat at emergence through PD. By 28 d after treatment (DAT), metribuzin injured rice 3% to 6%, and that injury did not translate into a yield reduction. Regardless of application timing, rice injury following fomesafen application ranged from 2% to 5% 28 DAT. Rice exposed to cloransulam-methyl EPOST exhibited the greatest root and foliar injury 21 DAT and 28 DAT, respectively. Additionally, when rice was exposed to cloransulam-methyl EPOST, yield was reduced to 6,540 kg ha⁻¹ compared with a yield of 7,850 kg ha⁻¹ from nontreated rice. Rice yield was negatively affected after paraquat was applied any time after rice emergence. However, applications of paraquat to rice at early reproductive growth stages reduced rough rice yield and seed germination the greatest. Application timing is crucial in determining severity of rice injury. Early-season injury to rice following paraquat application had less effect on yield compared with injury at later stages. Additionally, fields devoted to seed rice production are at risk for reduced seed germination if they are exposed to paraquat during early reproductive growth stages.

Introduction

Rice growth and development stages are described as vegetative, reproductive, grain filling, and ripening (Buehring 2008; Dunand and Saichuk 2014; Moldenhauer and Gibbons 2003; Moldenhauer et al. 2013). Rice seedling germination occurs when the seed has absorbed moisture and becomes malleable before emerging from the soil (Buehring 2008; Dunand and Saichuk 2014; Moldenhauer et al. 2013). Rice emergence is identified as coleoptile emergence above the soil line (Buehring 2008; Dunand and Saichuk 2014; Moldenhauer et al. 2013). Growth stages from rice seedling emergence to panicle initiation (PI) are considered vegetative, whereas subsequent growth stages from PI to grain filling are regarded as reproductive (Buehring 2008; Dunand and Saichuk 2014; Moldenhauer et al. 2013). Grain ripening begins following rice flower pollination (Moldenhauer and Gibbons 2003). Rice yield is primarily determined by panicle density (number of panicles per unit of area), grains per panicle, and individual grain weight (Buehring 2008; Moldenhauer et al. 2013). However, numerous environmental and non-environmental factors can affect grain development, including insects, cold water stress, diseases, nutrient deficiencies, temperature, and off-target herbicide injury (Buehring 2008; Hensley et al. 2012).

Herbicide drift is defined as the movement of herbicide particles in the air soon after application to any off-target location. Drift is influenced by environmental conditions, nozzle and

droplet size, spray pressure, nozzle angle, herbicide formulation, applicator speed, and boom height (Dexter 1995; Henry et al. 2004; USEPA 2015). Types of drift events include droplet, particle, and vapor (Fishel and Ferrell 2016). Droplet is the most common type of drift and occurs when herbicides move off target during application (Fishel and Ferrell 2016). Particle drift occurs when solid particles such as soil or dust formulations move off target (Fishel and Ferrell 2016; Jordan et al. 2009). Vapor drift events are functions of environmental conditions and herbicide formulation (Jordan et al. 2009).

Research suggests off-target herbicide concentrations can be as great as 1% to 10% of the suggested use rate for particle drift (Al-Khatib and Peterson 1999). Other research suggests that herbicide concentrations of vapor drift can be 0.1% of the recommended use rate (Egan et al. 2014). For example, cotton (*Gossypium hirsutum* L.) injury was 76% 48 h after exposure to ester formulations of 2,4-D compared with 5% injury from the choline formulation (Sosnoskie et al. 2015). Herbicide concentration 2 m from application ranged from 0.1% to 9% of the original use rate; however, herbicide concentrations decreased exponentially as the distance from application increased (Carlsen et al. 2006). Wind speeds ≥ 16 km h⁻¹ and temperature inversions can enhance the severity and distance of off-target herbicide movement (Henry et al. 2004; Jordan et al. 2009).

Spray droplet sizes with a volume median diameter ≤ 105 μ m are considered extremely fine and have the greatest tendency to move off target compared with larger droplet sizes (Dexter 1995; Hanks 1995; McCloskey et al. 2012). Extremely fine droplets can remain in the air for 10 min and travel distances of ≥ 13 m in wind speeds of 5 km h⁻¹ (Dexter 1995). Proper nozzle selection, pressure adjustment, and boom height for herbicide application will reduce off-target herbicide movement (Hanna et al. 2008; Jordan et al. 2009; McCloskey et al. 2012). A reduction in pressure results in a greater spray droplet size, making droplets heavier and less likely to move off target (Dexter 1995; Jordan et al. 2009).

Paraquat is labeled for use at preplant, PRE, or post-directed in corn (*Zea mays* L.), cotton, grain sorghum [*Sorghum bicolor* (L.) Moench], peanut (*Arachis hypogaea* L.), soybean [*Glycine max* (L.) Merr], and numerous vegetable and fruit crops for nonselective weed control (Anonymous 2019; Shaner 2014). However, paraquat is only labeled for preplant or PRE use with rice (Anonymous 2019; Bond 2020). Row crop producers in Mississippi have widely adopted the use of paraquat in mixture with herbicides representing multiple herbicide modes of action (MOAs) prior to planting to minimize glyphosate-resistant (GR) weed interference with crops (Anonymous 2018).

The use of herbicides for weed control has increased production efficiency across all crops in the midsouthern United States; however, off-target herbicide movement has been documented to negatively affect numerous crops including corn, cotton, grain sorghum, peanut, soybean, and wheat (*Triticum aestivum* L.; Al-Katib et al. 2003; Anderson et al. 2004; Hensley et al. 2012; Johnson et al. 2012). Glyphosate applied at 112 g ae ha⁻¹ injured up to 78% of grain sorghum 2 wk after treatment (WAT; Al-Khatib et al. 2003). Wheat yield was reduced 54% following glyphosate application at 140 g ha⁻¹ during early flowering (Roider et al. 2007). Anderson et al. (2004) reported dicamba applied to soybean at 5.6 g ae ha⁻¹ during the V3 growth stage reduced yield by 34%. When applied to V3 soybean, 2,4-dichlorophenoxyacetic acid (2,4-D) at 11.2, 56, and 112 g ae ha⁻¹ resulted in 5%, 23%, and 33% injury, respectively (Anderson et al. 2004). Marple et al. (2008) reported 88% injury 28 d following 2,4-D at 2.8 g ha⁻¹ applied to three- to four-leaf cotton. McCoy et al. (2017) reported

18% to 28% rice grain yield reductions for inbred rice cultivars following late-season exposure to paraquat applied at 0.028 kg ha⁻¹. Additionally, extensive research has documented the effects of glyphosate, glufosinate, and acetolactate synthase (ALS)-inhibiting herbicides to rice; however, limited data have been published on how rice responds to paraquat (Bond et al. 2006; Davis et al. 2011; Webster et al. 2015).

In recent years, cases of off-target movement of paraquat to rice have increased. Problematically, additional herbicide MOAs are often mixed with paraquat in preplant applications. Photosystem II, protoporphyrinogen oxidase, and ALS-inhibiting herbicides represent common MOAs present in paraquat mixtures applied preplant and/or PRE. Diagnosing the severity of rice injury following off-target paraquat drift is challenging due to the potential complexity of symptoms associated with the MOAs mixed with paraquat. Therefore, four concurrent studies were conducted to evaluate rice response to sublethal concentration of paraquat, metribuzin, fomesafen, and cloransulam-methyl applied at five rice growth stages.

Materials and Methods

Four concurrent studies were conducted from 2015 to 2018 at the Mississippi State University Delta Research and Extension Center in Stoneville, MS, to determine the effects of paraquat (Paraquat Timing Study), metribuzin (Metribuzin Timing Study), fomesafen (Fomesafen Timing Study), and cloransulam-methyl (Cloransulam-methyl Timing Study) applied at different rice growth stages. Global positioning system coordinates, soil series, soil description, previous crop, soil pH, and soil organic matter for each study are described in Table 1.

Glyphosate (Roundup PowerMax 4.5 L, 1,120 g ha⁻¹; Bayer CropScience, 800 N. Lindburgh Blvd., St. Louis, MO 63167), paraquat (Gramoxone 2.0 SL, 560 g ai ha⁻¹; Syngenta Crop Protection, P.O. Box 18300 Greensboro, NC 27409), and/or 2,4-D (2,4-D Amine 3.8 SL, 560 g ha⁻¹; Agri Star, 1525 NE 36th St., Ankeny, IA 50021) were applied in late March to early April at each site-year to control emerged vegetation. Clomazone (Command 3 ME, 498 g ai ha⁻¹; FMC Corporation, 1735 Market St., Philadelphia, PA 19103) plus saflufenacil (Sharpen 2.85 SC, 4.5 g ai ha⁻¹; BASF Crop Protection, 26 Davis Dr., Research Triangle Park, NC 27709) were 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, 2 T.W. Alexander Dr., Research Triangle Park, NC 27709) and quinclorac (Facet 1.50 SL, 375 g ai ha⁻¹; BASF Crop Protection) plus halosulfuron (Permit 75 DF, 12 g ai ha⁻¹; Gowan Company, P.O. Box 5569, Yuma, AZ 85364) plus petroleum oil surfactant (Herbimax, 83% petroleum oil; Loveland Products, P.O. Box 1286, Greeley, CO 80632) at 1% (vol/vol) were applied at three- to four-leaf (MPOST) rice to maintain experimental sites weed free.

Rice was drill-seeded on June 9, 2015; May 11 and 17, 2016; May 9 and 18, 2017; and May 7, 2018, to a depth of 2 cm using a small-plot grain drill (Great Plains 1520; Great Plains Mfg, Inc., 1525 East North St., Salina, KS 67401). Rice cultivar, 'CL151' (HorizonAg, 8275 Tournament Dr. Suite 255, Memphis, TN 38125) 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 that contained no rice and on each side by identically sized plots as a buffer were included to minimize treatment contamination. Plots were flooded to an approximate depth of 6 to 10 cm when rice reached the one- to two-tiller stage. Herbicide treatments were

Table 1. soil series, soil description, previous crop, soil pH, and soil organic matter in four concurrent studies evaluating rice performance following exposure to sublethal rates of paraquat, metribuzin, fomesafen, and cloransulam-methyl at five growth stages.

Site-year	Coordinates	Soil series	Description	Previous crop	pH	OM ^a
2015	33.44°N, 90.90°W	Sharkey very-fine clay	Very-fine, smectitic, thermic Chromic Epiaquerts	1:1 Rice:fallow	1:2(v:v) 7.8	% 2.4
2016A	33.41°N, 90.92°W	Sharkey very-fine clay	Very-fine, smectitic, thermic Chromic Epiaquerts	Rice:fallow	8.2	2.2
2016B	33.43°N, 90.93°W	Sharkey very-fine clay	Very-fine, smectitic, thermic Chromic Epiaquerts	Soybean: rice	8.1	2.1
2017A	33.44°N, 90.90°W	Sharkey very-fine clay	Very-fine, smectitic, thermic Chromic Epiaquerts	Rice:fallow	7.8	2.4
2017B	33.43°N, 90.90°W	Commerce silty clay loam	Fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquerts	Soybean: rice	7.1	1.7
2018	33.42°N, 90.90°W	Bosket very fine sandy loam	Fine-loamy, mixed, active, thermic Mollic Hapludalfs	Rice:rice	7.9	1.2

^aAbbreviation: OM, organic matter.

applied using a CO₂-pressurized backpack sprayer equipped with flat-fan nozzles (AIRMIX11002 nozzle; Greenleaf Technologies, 230 E Gibson St., Covington, LA 70433) set to deliver 140 L ha⁻¹ at 206 kPa using water as a carrier. All herbicide treatments included a nonionic surfactant (Activator 90, 90% nonionic surfactant; Loveland Products) at 0.5% (vol/vol) and ammonium sulfate as a water-conditioning agent (Class Act NG, 50% nitrogen fertilizer; WinField Solutions, P.O. Box 64589, St. Paul, MN 55164) at 2.5% (vol/vol). Rice in all studies was managed throughout the growing season to optimize yield (Buehring 2008).

The experimental design for all studies was a randomized complete block with four replications. Paraquat treatments were applied at a sublethal rate of 10% of their suggested use rate in Mississippi (Al-Khatib and Peterson 1999; Anonymous 2019). Paraquat at 84 g ha⁻¹, metribuzin (Tricor 75 DF, herbicide; United Phosphorus, Inc., 630 Freedom Business Center, Suite 402, King of Prussia, PA 19406) at 42 g ai ha⁻¹, fomesafen (Flexstar 1.88 SL, herbicide; Syngenta Crop Protection) at 39 g ai ha⁻¹, or cloransulam-methyl (FirstRate 0.84 DF, herbicide Dow AgroSciences, LLC, 9330 Zionsville Rd., Indianapolis, IN 46268) at 3.5 g ai ha⁻¹ were applied to rice in the spiking to one-leaf (VEPOST), two- to three-leaf (EPOST), MPOST, 7 d post-flood (PFLD), and panicle differentiation (PD) growth stages. These growth stages were used to best represent rice in varying ranges of vegetative and early reproductive growth stages.

In all four studies, visible estimates of aboveground rice injury were recorded 3, 7, 14, 21, and 28 d after treatment (DAT) on a scale of 0% to 100% where 0% indicated no visible effect of herbicides and 100% indicated complete plant death. Rice root injury was recorded 21 DAT on the previously described scale by comparing roots of five randomly selected plants in each plot with those of plants from nontreated plots in the same replication. Plant height was determined 14 DAT by measuring from the soil surface to the upper most extended leaf and calculating the mean height of five randomly selected plants in each plot. Plant height was converted to a percentage of the nontreated control in each replication to account for differences in rice growth stage at time of treatment application and data collection. Percentage of nontreated control data were calculated by dividing the data from the treated plot by that in the nontreated control plot in the same replication and multiplying by 100. 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. Number of days to 50% heading data were converted to delay in maturity calculated by subtracting

days to 50% heading in an individual plot from that in the non-treated. At maturity, a randomly selected area measuring 1 m was hand-harvested from rows 2 or 7 in each plot to determine rice dry weight, yield components (panicle density, filled grains per panicle, and 1,000-grain weight), and seed germination percentage.

All study plants were harvested with a small-plot combine (Wintersteiger Delta; Wintersteiger, Inc., 4705 W. Amelia Earhart Dr., Salt Lake City, UT 84116) at a moisture content of approximately 20%. Grain weight and moisture contents were recorded, and rough rice grain yield was adjusted to a uniform moisture content of 12% for statistical analysis. Whole and total milled rice yield was 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 (Grain Machinery Manufacturing Corp., 1130 NW 163 Dr., Miami, FL 33169) No. 2 miller for 30 s and size-separated with a No. 12 (4.76-mm) screen. Whole and total milled rice yields were expressed as a mass fraction of the original 120-g sample of rough rice.

Hand-harvested samples were dried in a greenhouse at 32 to 49 (±5) C for 2 wk, and weighed to determine rice dry weight. Individual weights were converted to grams per square meter. The total number of seed-bearing panicles in each hand-harvested sample was counted to determine panicle density (panicle number per square meter). Panicles from each hand-harvested sample were processed with a plot thresher, and the number of filled grains was counted to determine the average number of filled grains per panicle for each treatment. Grain was dried to approximately 12% moisture content, and weight was recorded. Five 1,000-grain subsamples were then weighed to determine 1,000-grain weight. Seed germination percentage was determined based on the number of germinated seeds out of 100 after 48 h of exposure to a 14-h photoperiod at 35 C.

Injury data in all studies were regressed against DAT allowing for both linear and quadratic terms with coefficients depending on DAT and nonsignificant model terms were removed sequentially until a satisfactory model was obtained (Golden et al. 2006). All other data were regressed against days after emergence (DAE) allowing for both linear and quadratic terms with coefficients depending on DAE, and nonsignificant model terms were removed sequentially until a satisfactory model was obtained. Data that did not exhibit a significant trend were subjected to ANOVA using the MIXED procedure in SAS version 9.3 (SAS Institute Inc., 100 SAS Campus Drive, Cary, NC 27513-2414) with site-year and replication (nested within experimental run) as random effects

Table 2. Regression coefficients in four concurrent studies for rice injury across evaluation intervals following exposure to paraquat at 84 g ai ha⁻¹ (Paraquat Timing Study), metribuzin at 42 g ha⁻¹ (Metribuzin Timing Study), fomesafen at 39 g ha⁻¹ (Fomesafen Timing Study), and cloransulam-methyl at 3.5 g ha⁻¹ (Cloransulam-methyl Timing Study).^a

Application timing ^b	Intercept	Linear	Quadratic
Paraquat Timing Study			
VEPOST	40.4919	1.1831	-0.03624
EPOST	31.2244	2.1207	-0.04964
MPOST	36.0826	1.4159	-0.01983 ^c
PFLD	36.0638	0.9669	-0.01286 ^c
PD	50.4405	-1.4095	0.05119
Metribuzin Timing Study			
VEPOST	12.1595	-0.0744 ^c	-0.00616
EPOST	6.6089	0.5507 ^c	-0.02090
MPOST	8.6781	0.7055	-0.02973
PFLD	10.3486	-0.5030	0.008004 ^c
PD	3.4917	0.3908	-0.01520
Fomesafen Timing Study			
VEPOST	9.3102	0.02088 ^c	-0.00581 ^c
EPOST	12.0202	-0.4081	0.004230 ^c
MPOST	9.1663	0.2436 ^c	-0.01736
PFLD	20.6232	-0.8323	0.009617 ^c
PD	6.6335	0.6377	-0.02588 ^c
Cloransulam-methyl Timing Study			
VEPOST	-7.3447 ^c	5.6102	-0.1269
EPOST	-7.7616 ^c	5.9274	-0.1495
MPOST	-3.3935 ^c	2.7704	-0.06701
PFLD	9.4456	1.1895	-0.03886
PD	0.8186 ^c	1.0494	-0.02983

^aData for the paraquat, metribuzin, and fomesafen timing studies are pooled across six site-years and three site-years for the cloransulam-methyl timing study.

^bApplication timings included spiking to one-leaf (VEPOST), two- to three-leaf (EPOST), three- to four-leaf (MPOST), 7 d postflood (PFLD), and panicle differentiation (PD).

^cCoefficient is not significantly different than zero.

parameters (Blouin et al. 2011). Least square means were calculated and mean separation ($P \leq 0.05$) was produced using the PDMIX800 procedure in SAS, which is a macro for converting mean separation output to letter groupings (Saxton 1998).

Results and Discussion

Paraquat Timing Study

Quadratic trends were detected for rice injury, delay in maturity, and seeds per panicle following rice exposure to paraquat (Tables 2 and 3). However, nonlinear portions of the fitted line were no different from zero for MPOST and PFLD timings (Table 2). Linear trends were detected for rough rice yield, dry weight, panicle density, and seed germination (Table 3).

Regardless of application timing, rice injury following paraquat exposure ranged from 37% to 47% 3 DAT (Figure 1). Rice exposed to paraquat VEPOST and EPOST exhibited similar trends in rice injury. Rice injury was maximized at 50% 14 DAT for rice exposed VEPOST; however, maximum injury with paraquat (54%) EPOST did not occur until 21 DAT (Figure 1). For both VEPOST and EPOST timings, rice appeared to exhibit some recovery; however, injury at 28 DAT was still 45% and 52% with VEPOST and EPOST timings, respectively (Figure 1). Rice exposed to paraquat MPOST and PFLD showed a similar trend in which injury progressively increased from 3 DAT to 28 DAT (Figure 1). Similar to other timings, injury 3 DAT for rice exposed to paraquat MPOST and PFLD was 40% and 39%, respectively (Figure 1). Rice injury 28 DAT for both MPOST and PFLD was $\geq 53\%$ (Figure 1). Rice injury from

Table 3. Regression coefficients for delay in maturity, rough rice yield, mature dry weight, seed panicle⁻¹, panicle density, and seed germination following exposure to paraquat at 84 g ai ha⁻¹ in the Paraquat Timing Study.

Parameter ^b	Intercept	Linear	Quadratic
Delay in maturity, d	4.7041	0.2655	-
Yield, kg ha ⁻¹	8289.48	131.51	-
Dry weight, g m ⁻²	1744.22	-18.72	-
Panicle m ⁻² , no.	412.05	-5.6633	-
Seed panicle ⁻¹ , no.	97.77	0.5810 ^c	-0.03930
Germination, %	93.45	-0.3002	-

^aData for delay in maturity are pooled across six site-years, and data for all other parameters are pooled across five site-years.

^bApplication timings included spiking to one-leaf (VEPOST), two- to three-leaf (EPOST), three- to four-leaf (MPOST), 7 d postflood (PFLD), and panicle differentiation (PD).

^cCoefficient is not significantly different than zero, identifying there is no relationship in that portion of the line or curve.

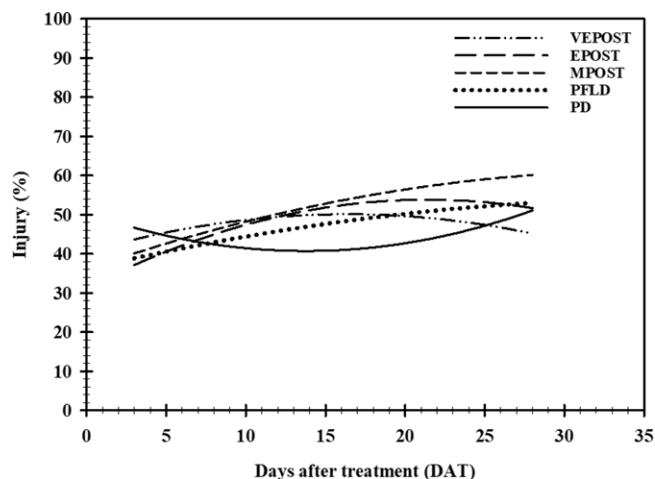


Figure 1. Rice injury following exposure to paraquat at 84 g ai ha⁻¹ in the Paraquat Timing Study.

paraquat exposure at PD was 47% 3 DAT, decreased to 41% by 14 DAT, but increased again to 51% by 28 DAT (Figure 1). Lawrence et al. (2018) reported similar rice injury following paraquat at 84 g ha⁻¹ applied to rice at an EPOST timing in a study evaluating rice response to a sublethal rate of paraquat alone or in mixtures with metribuzin or fomesafen. Although application timing was not a component of that research, rice injury ranged from 54% to 58% 14 and 28 DAT, respectively (Lawrence et al. 2018).

Delay in maturity increased linearly as paraquat exposure timing was delayed to later in the growing season (Figure 2). On average, delays in rice maturity increased 0.26 d d⁻¹ following paraquat exposure from VEPOST through PD (Figure 2). Inversely, dry weight, rough rice yield, panicle density, and seed germination were reduced by 18.7 g, 131.5 kg ha⁻¹, 5.6 m⁻², and 0.3%, respectively, per day from paraquat exposure at VEPOST through PD timings (Table 3; Figure 2). Lawrence et al. (2018) reported a 28% reduction in rough rice yield and a 9-d delay in maturity following exposure to paraquat EPOST. A quadratic trend was detected for seed per panicle; however, the linear term of the fitted line was no different than zero (Table 3; Figure 2). Seeds per panicle were reduced exponentially following rice exposure to paraquat approximately 10 DAE. Rice exposed to paraquat at 50 DAE produced 28 seeds per panicle compared with 97 seeds per panicle from the nontreated plants (Figure 2).

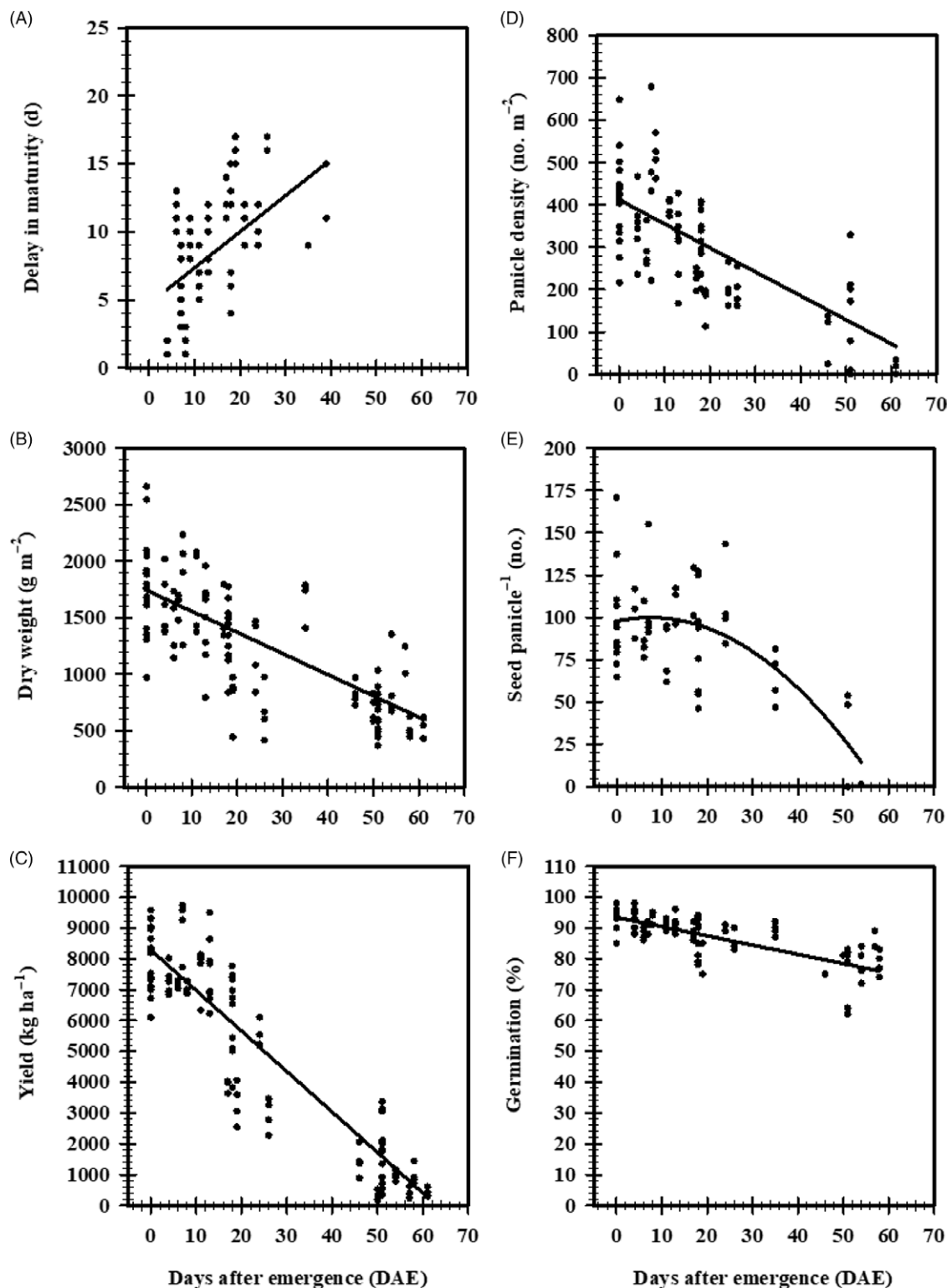


Figure 2. Rice delay in maturity (A), dry weight (B), rough rice yield (C), panicle density (D), seeds per panicle (E), and seed germination (F) following exposure to paraquat at 84 g ai ha^{-1} in the Paraquat Timing Study.

Rice height, 1,000-grain weight, total, and whole milled rice yield were affected by paraquat timing (Table 4). Rice height 14 DAT was more negatively impacted when rice was exposed to paraquat before flooding compared with postflood timings (Table 4). However, rice height 14 DAT following paraquat at PD was reduced by 15% compared with nontreated rice (Table 4). Conversely, 1,000-grain weight

was more negatively impacted following exposure to paraquat post-flood (Table 4). Averaged over five site-years, 1,000-grain weight was reduced to 17 g and 12 g following rice exposure to paraquat at PFLD and PD timings, respectively (Table 4).

Total and whole milled rice yield were affected by paraquat at different timings. Plots not treated with paraquat produced 70%

Table 4. Rice height 14 d after treatment, 1,000-grain seed weight, total, and whole milled rice yield following exposure to paraquat at 84 g ai ha⁻¹ in the Paraquat Timing Study.^a

Application timing ^b	Height % of nontreated	1,000-grain weight g	Yield	
			Total milled %	Whole milled %
Nontreated	–	21 a	70 ab	58 a
VEPOST	69 c	22 a	71 a	58 a
EPOST	62 c	21 a	69 abc	56 ab
MPOST	54 e	21 a	67 bc	53 bc
PFLD	77 b	17 b	64 c	51 c
PD	85 a	12 c	68 abc	54 abc

^aData for height are pooled over six site-years, and data for total and whole milled rice, 1,000-grain seed weight, and dry weight are pooled over five site-years. Means followed by the same letter for each parameter are not different at $P \leq 0.05$.

^bApplication timings included spiking to one-leaf (VEPOST), two- to three-leaf (EPOST), three- to four-leaf (MPOST), 7 d postflood (PFLD), and panicle differentiation (PD).

and 58% total and whole milled rice, respectively (Table 4). However, milling yield was similar to that of the nontreated plants following paraquat exposure VEPOST, EPOST, and PD. Rice exposed to paraquat PFLD exhibited the most reduction in milling yield at 51% and 64% whole and total milled rice, respectively. However, these milling yield were comparable to milling yield following paraquat applied EPOST, MPOST, and PD (Table 4).

Metribuzin Timing Study

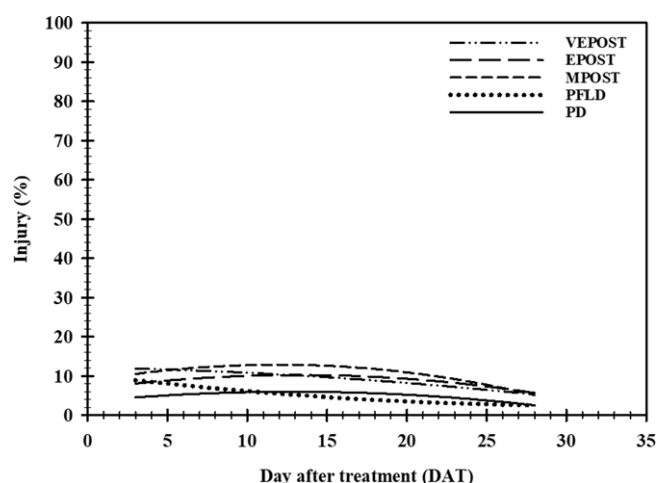
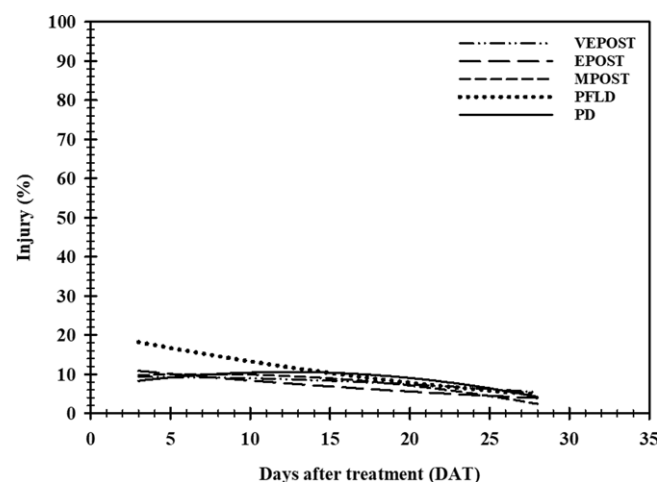
In the study evaluating rice response to a sublethal rate of metribuzin at different growth stages, only rice injury exhibited a quadratic trend (Table 2). Although significant trends were detected, rice injury was 5% to 12% regardless of application timing 3 DAT, and by 28 DAT, injury was 3% to 6% (Figure 3). Lawrence et al. (2018) reported similar injury for rice exposed to metribuzin at 42 g ha⁻¹ EPOST. Rice injury was $\leq 10\%$ 14 and 28 DAT following exposure to metribuzin (Lawrence et al. 2018). No trends detected for rice injury translated into delays in maturity or reductions in dry weight, yield parameters, yield, or seed germination.

Fomesafen Timing Study

Quadratic trends were detected for rice injury following exposure to fomesafen; however, linear and quadratic terms were not different from zero for VEPOST timing (Table 2). Additionally, quadratic terms were not different from zero for EPOST and PFLD timings (Table 2). The linear term was not different from zero for the MPOST application timing (Table 2).

Although trends in rice injury were detected following all application timings, injury exceeded 11% only with the PFLD timing (Figure 4). Injury 3 DAT following fomesafen applied at the PFLD timing was 18%; however, by 28 DAT, that injury had decreased to 5% (Figure 4). Regardless of fomesafen application timing, rice injury ranged from 2% to 5% at 28 DAT (Figure 4). Sperry et al. (2019) reported greater injury following corn exposure to fomesafen at 35 g ha⁻¹ at different vegetative growth stages. Regardless of application timing, injury to corn following exposure to a sublethal rate of fomesafen was 5% to 16% 28 DAT (Sperry et al. 2019).

No trends were detected for all other parameters evaluated. However, differences in rice height 14 DAT and rough rice yield were detected using ANOVA (Table 5). Rice height 14 DAT was 95% of that of nontreated control following fomesafen exposure VEPOST; however, height ranged from 98% to 103% of the nontreated control following other timings (Table 5). Rough rice yield

**Figure 3.** Rice injury following exposure to metribuzin at 42 g ai ha⁻¹ in the Metribuzin Timing Study.**Figure 4.** Rice injury following exposure to fomesafen at 39 g ai ha⁻¹ in the Fomesafen Timing Study.

was reduced to 7,950 kg ha⁻¹ following fomesafen applied at the PD stage compared to 8,550 kg ha⁻¹ with no exposure to fomesafen (Table 5). However, rough rice yield following application at the PD stage was comparable to that following EPOST, MPOST, and PFLD timings (Table 5). Rice in plots exposed to fomesafen

Table 5. Rice height 14 d after treatment and rough rice yield following exposure to fomesafen at 39 g ai ha⁻¹ in the Fomesafen Timing Study.^a

Application timing ^b	Height	Rough rice yield
	% of nontreated	kg ha ⁻¹
Nontreated	-	8,550 a
VEPOST	95 b	8,510 a
EPOST	103 a	8,250 ab
MPOST	98 ab	7,950 b
PFLD	100 ab	8,010 b
PD	100 ab	7,950 b

^aData for height are pooled over six site-years, and data for rough rice yield are pooled over five site-years. Means followed by the same letter for each parameter are not different at $P \leq 0.05$.

^bApplication timings include spiking to one-leaf (VEPOST), two- to three- leaf (EPOST), three- to four-leaf (MPOST), 7 d postflood (7DPFLD), and panicle differentiation (PD).

Table 6. Regression coefficients for rice root injury 21 d after treatment and panicle density at maturity following exposure to cloransulam-methyl at 3.5 g ai ha⁻¹ in the Cloransulam-methyl Timing Study.^a

Parameter ^b	Intercept	Linear	Quadratic
Root injury	91.25	-1.3495	-
Panicles m ⁻²	373.22	7.1132	-0.1063

^aData are pooled across three site-years.

^bApplication timings include spiking to one-leaf (VEPOST), two- to three- leaf (EPOST), three- to four-leaf (MPOST), 7 d postflood (PFLD), and panicle differentiation (PD).

VEPOST produced comparable yields to those treated EPOST or with no exposure to fomesafen (Table 5). Similarly, Sperry et al. (2019) reported a 10% decrease in corn yield from fomesafen applied at 35 g ha⁻¹ to corn at the V7 and V9 growth stages compared with fomesafen applied PRE.

Cloransulam-Methyl Timing Study

For all cloransulam-methyl applications, a quadratic trend was detected for rice foliar injury across all evaluation intervals and for panicle density (Tables 2 and 6). Additionally, a linear trend was detected in root injury at 21 DAT (Table 6). Greater rice foliar injury occurred with VEPOST and EPOST timings compared with injury at MPOST and postflood timings. At 3 DAT, foliar injury for both VEPOST and EPOST timings was 8% and 9%, respectively (Figure 5). By 28 DAT, foliar injury for VEPOST and EPOST timings was $\geq 41\%$. Rice foliar injury was lower following exposure to cloransulam-methyl from MPOST through PD compared with that following VEPOST and EPOST timings (Figure 5). Foliar injury from cloransulam-methyl MPOST timings was maximized at 25% 21 DAT and decreased to 22% by 28 DAT. A similar trend in foliar injury was observed when cloransulam-methyl was applied at PFLD and PD timings. Webster et al. (2016) observed 25% to 36% rice injury following exposure to a sublethal rate of imazamox, which is also an ALS-inhibiting herbicide. Applications of cloransulam-methyl had the least impact on rice foliar injury when applied at PD (Figure 5). Additionally, rice foliar injury at 21 DAT was 5% to 14% when imazamox was applied at a reduced rate to rice at PD and before panicle exertion (boot) growth stages (Webster et al. 2016). Rice height was 93% of the nontreated control following cloransulam-methyl use at PD, and dry weight, rough rice yield, and seeds per panicle were comparable to those of the nontreated (Table 7).

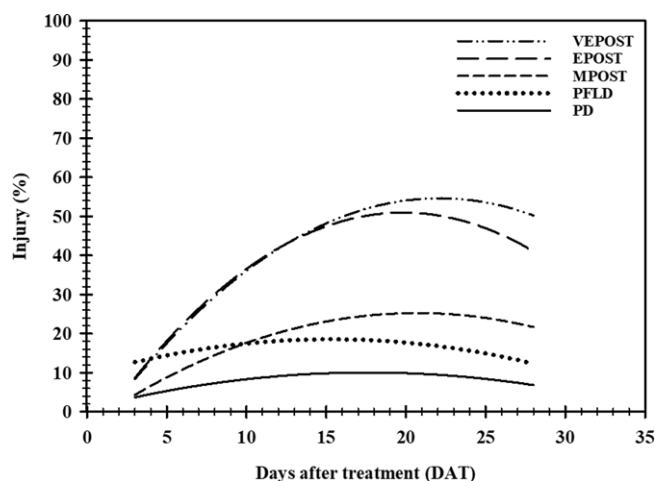
Rice exposed to cloransulam-methyl EPOST exhibited the greatest root injury at 21 DAT, and height was reduced to 64% of the nontreated (Table 7; Figure 6). Additionally, cloransulam-methyl

Table 7. Rice height 14 d after treatment, dry weight at maturity, rough rice yield, and seeds per panicle following exposure to cloransulam-methyl at 3.5 g ai ha⁻¹ in the Cloransulam-methyl Timing Study.^a

Application timing ^b	Height	Dry weight	Rough rice yield	Seeds per panicle
	% non-treated	g	kg ha ⁻¹	no.
Nontreated	-	1,770 a	7,850 a	77 a
VEPOST	56 c	1,530 b	6,540 c	75 a
EPOST	64 b	1,770 a	6,940 bc	79 a
MPOST	88 a	1,930 a	7,600 a	63 ab
7DPFLD	87 a	1,840 a	7,590 a	55 b
PD	93 a	1,740 ab	7,560 ab	78 a

^aData are pooled over three site-years for height, and data are pooled over two site-years for dry weight, rough rice yield, and seeds per panicle. Means followed by the same letter for each parameter are not different at $P \leq 0.05$.

^bApplication timings include spiking to one-leaf (VEPOST), two- to three- leaf (EPOST), three- to four-leaf (MPOST), 7 d postflood (7DPFLD), and panicle differentiation (PD).

**Figure 5.** Rice foliar injury following exposure to cloransulam-methyl at 3.5 g ai ha⁻¹ in the Cloransulam-methyl Timing Study.

applied EPOST reduced dry weight to 1,530 g m⁻² compared with 1,770 g m⁻² by the nontreated, and rough rice yield was reduced to 6,540 kg ha⁻¹ compared with 7,850 kg ha⁻¹ by the nontreated (Table 7). Webster et al. (2016) suggested that rice is more sensitive to a sublethal dose of an ALS-inhibiting herbicide during early vegetative growth stages. Data from the current research indicate a similar finding. Greater rice root and foliar injury, and greatest reduction in rough rice yield occurred with cloransulam-methyl applied VEPOST and EPOST compared with later timings. Although seeds per panicle were reduced to 55 seeds per panicle with PFLD timing compared with 77 seeds per panicle for the nontreated, no reductions were detected in yield (rough, whole, and total milled) or dry weight (Table 7). However, based on the quadratic trend for panicle density, applications in the PFLD range of DAE indicated an increased number of panicles compared with that from the nontreated control plants (Figure 6).

The current research demonstrates that rice is sensitive to a sublethal concentration of paraquat. Early-season injury to rice following exposure to paraquat had less effect on rough rice yield compared with injury occurring at later developmental stages. However, harvest efficiency could be affected regardless of growth stage at which exposure occurred due to delays in maturity. Additionally, fields devoted to seed rice production are at risk

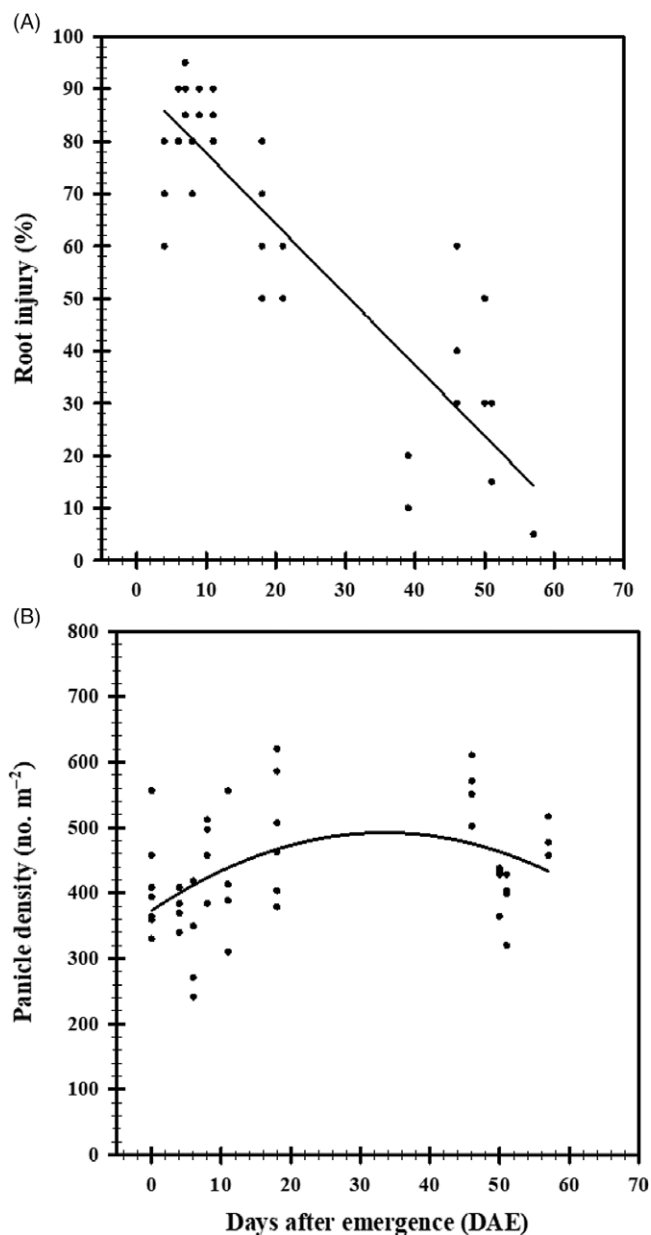


Figure 6. Rice root injury (A) 21 d after treatment and panicle density per square meter (B) following exposure to cloransulam-methyl at 3.5 g ai ha⁻¹ in the Cloransulam-methyl Timing Study.

for reduced seed germination if they are exposed to paraquat during early reproductive growth stages.

Although injury occurred following rice exposure to metribuzin, no impact on yield was detected. Rice injury 28 DAT following exposure to fomesafen ranged from 2% to 5%, but fomesafen applied at PFLD and PD timings reduced yields compared to the nontreated VEPOST and EPOST timings. Cloransulam-methyl caused greater rice injury when it was used at exposure before flooding compared with postflood timings. Additionally, rough rice yield was reduced more following exposure to cloransulam-methyl at VEPOST than all other application timings. The current research complements findings by Webster et al. (2016) who reported early-season exposure to an ALS-inhibiting herbicide at a reduced rate impacted rice yield more than any other timing.

These data indicate that application timing can have an impact on rice growth and development following exposure to a sublethal concentration of nontarget herbicides. In Mississippi, application of herbicides for preplant weed control in corn, cotton, and soybean can occur across a broad range of dates when rice can be in different developmental growth stages. Additionally, rice in Mississippi is often grown in proximity to corn, cotton, and soybean. In the current research, three of the four herbicide MOAs negatively impacted rough rice yield depending on application timing. Therefore, it is crucial that if environmental conditions are conducive for off-target herbicide movement, extreme caution should be exercised when applying herbicides in close proximity to rice.

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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, Claassen MM, Stahlman W, Geier PW, Regehr DL, Duncan SR, Heer WF (2003) Grain sorghum response to simulated drift from glufosinate, glyphosate, imazethapyr, and sethoxydim. *Weed Technol* 17:261–265
- 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
- Anderson SM, Clay SA, Wrage LJ, Matthees D (2004) Soybean foliage residues of dicamba and 2,4-D and correlation to application rates and yield. *Agron J* 96:750–760
- Anonymous (2019) Gramoxone SL herbicide label. <http://www.syngenta-us.com/current-label/gramoxone-sl-2.0>. Accessed: May 4, 2019
- Bond JA, ed (2020) Weed Management Suggestions for Mississippi Row Crops. MS Publication 3171. Mississippi State: Mississippi State University Extension Service. Pp 24–28
- Blouin DC, Webster EP, Bond JA (2011) On the analysis of combined experiments. *Weed Technol* 25:165–169
- 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
- Buehring N (2008) Rice growth and development. Pages 9–15 in Mississippi Rice Growers Guide. Publication 2255. Starkville: Mississippi State University Extension Service
- Carlsen SC, Spliid NH, Svensmark B (2006) Drift of 10 herbicides after tractor spray application 2. Primary drift (droplet drift). *Chemosphere* 64:778–786
- 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
- Dexter AG (1995) Herbicide spray drift. Publication A-687. Fargo: North Dakota State University Extension Service
- Dunand R, Saichuk J (2014) Rice growth and development. Pages 41–53 in Saichuk J ed. Louisiana Rice Production Handbook. Publication 2321. Baton Rouge: Louisiana State University Division of Agriculture Cooperative Extension Service
- Egan JF, Barlow KM, Mortensen DA (2014) A meta-analysis on the effects of 2,4-D and dicamba drift to soybean and cotton. *Weed Sci* 62:193–206
- Fishel FM, Ferrell JA (2016) Managing pesticide drift. <http://edis.ifas.ufl.edu/pi232>. Accessed: November 29, 2017
- Golden BR, Slaton NA, Norman RJ, Gbur EE Jr, Brye KR, Delong RE (2006) Recovery of nitrogen in fresh and pelletized poultry litter by rice. *Soil Sci Soc Am J* 70:1359–1369

- Hanks JE (1995) Effect of drift retardant adjuvants on spray droplet size of water and paraffinic oil applied at ultralow volume. *Weed Technol* 9:380–384
- Hanna HM, Schaefer KJ (2008) Factors affecting pesticide drift. Publication 175. Ames: Iowa State University Agriculture and Environmental Extension
- Henry WB, Shaw DR, Reddy KR, Bruce KM, Tamhankar HD (2004) Remote sensing to detect herbicide drift of crops. *Weed Technol* 18:358–368
- 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
- Johnson VA, Fisher LR, Jordan DL, Edmisten KE, Stewart AM, York AC (2012) Cotton, peanut, and soybean response to sub-lethal rates of dicamba, glufosinate and 2,4-D. *Weed Technol* 26:195–206
- Jordan T, Nice G, Johnson B, Bauman T (2009) Reducing spray drift from glyphosate and growth regulator herbicide drift caution. <https://ag.purdue.edu/btny/weedscience/documents/reducingdrift09.pdf>. Accessed: March 29, 2018
- Lawrence BH, Bond JA, Golden BR, Edwards HM, Peeples JD, McCoy JM (2018) Effect of a sub-lethal rate of paraquat applied to rice at different growth stages. *Proc South Weed Sci Soc* 71:242
- Marple ME, Al-Khatib K, Peterson DE (2008) Cotton injury and yield as affected by simulated drift of 2,4-D and dicamba. *Weed Technol* 21:954–960
- McCloskey W, Sanchez PA, Brown L (2012) Nozzles and droplets: what do they mean? University of Arizona Extension. http://cals.arizona.edu/crop/cotton/filesColorsofNozzles_Droplets.pdf. Accessed: November 29, 2016
- McCoy JM, Bond JA, Golden BR, Lawrence BH (2017) Rice cultivar response to late-season exposure to glyphosate or paraquat. *Proc South Weed Sci Soc* 71:257
- Moldenhauer KA, Gibbons JH (2003) Rice morphology and development. Pages 103–125 in Smith CW, Dilday RH, eds. *Rice Origin, History, Technology, and Production*. Hoboken, NJ: John Wiley & Sons Inc
- Moldenhauer K, Wilson CE Jr, Counce P, Hardke J (2013) Rice growth and development. Pages 9–20 in Hardke TJ, ed. *Rice Production Handbook MP192*. Fayetteville: University of Arkansas Division of Agriculture Cooperative Extension Service
- Roider CA, Griffin JL, Harrison SA, Jones CA (2007) Wheat response to simulated glyphosate drift. *Weed Technol* 21:1010–1015
- 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 ed. Lawrence, KS: Weed Science Society of America. 109 p
- Sosnoskie LM, Culpepper SA, Braxton LB, Richburg JS (2015) Evaluating the volatility of three formulations of 2,4-D when applied in the field. *Weed Technol* 29:177–184
- 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
- [USEPA] U.S. Environmental Protection Agency (2015) Introduction to pesticide drift. <http://www.epa.gov/reducing-pesticide-drift/introduction-pesticide-drift>. Accessed: October 3, 2015
- 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