Rice (Oryza sativa) response and management following exposure to sub-lethal rates of non-target herbicides

By

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A Dissertation
Submitted to the Faculty of
Mississippi State University
in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy
in Weed Science
in the Department of Plant and Soil Sciences

Mississippi State, Mississippi

August 2019
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2019
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Research was conducted at the Mississippi State University Delta Research and Extension Center from 2015 to 2018 to (1) determine the effects of sub-lethal concentrations of paraquat, metribuzin, fomesafen, and cloransulam-methyl applied at different rice growth stages, determine the effects on rice growth of simulated off-target paraquat applications at varying concentration based on a proportionally decreased carrier volume characterize rice response to a sub-lethal concentration of paraquat in combination with common POST and residual herbicides, assess whether starter N fertilizer or different N fertilizer management strategies can aide in rice recover after exposure to a sub-lethal concentration of paraquat, and define a maximum soil concentration of S-metolachlor that will allow rice to germinate and emerge.

Rice yield was negatively affected following exposure to paraquat applied any time after rice emergence. Paraquat applications to rice in early reproductive growth reduced rough rice yield and seed germination the greatest. Paraquat plus metribuzin injured rice 68 to 69% 14 and 28 d after treatment (DAT), which was 10 to 13% greater than 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%. In spite of starter N fertilizer applications, paraquat injured rice ≥41%, reduced height 57%, reduced dry weight prior to flooding 77%, delayed maturity 10 d, reduced dry weight at maturity 33%, and reduced rough rice yield 35%. Similar results were observed in the N Fertilizer Timing Study. Soil concentrations of s-metolachlor 28 DAT were 30, 31, 32, 36, 61, and 488 ppm following exposure to s-metolachlor applied at 0, 1/64, 1/32, 1/16, 1/4, and 1X concentration. A soil analysis would be the best option to determine levels of s-metolachlor prior to planting rice if an off-target herbicide movement containing s-metolachlor occurred. These data indicate that paraquat can have negative impact on rice growth and development. Therefore, it is crucial that if environmental conditions are conducive for off-target herbicide movement extreme caution should be exercised when applying paraquat adjacent to fields devoted to rice production.
DEDICATION

I would like to dedicate my work to my late grandfather, A.L. Whittington, for always encouraging me to pursue my dreams and instilling a love for agriculture early in my life. I would like to thank my wife Susan Lawrence for all the encouragement and support. Also I would like to dedicate my work to my family for encouraging me and being a great support system through this process.
ACKNOWLEDGEMENTS

I would like to thank Dr. Jason Bond for his patience, encouragement, and support through this process. I would also like to thank Dr. Bobby R. Golden, Dr. Thomas W. Allen Jr., Dr. Daniel B. Reynolds, and Dr. Taghi Bararpour for serving as members on my graduate committee. Your insight and mentoring has been next to none.

Also a special acknowledgment of appreciation to the Mississippi Rice Promotion Board for funding my research and allowing me to further my education because without them this would have never been possible. I would like to acknowledge and thank Matt Edwards and all the other staff at the Delta Research and Extension Center for the amount of work they put in to make sure I could do my research. I would also like to thank Tameka Sanders, Tyler Hydrick, Nelson Corban, Brian Perialisi, and Justin McCoy along with the other graduate students at Mississippi State University for their encouragement and friendship.

To my family this process would not have been possible without your continued love and support. Thank you all for the never ending encouragement because without it this would have never been possible.
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CHAPTER I
INTRODUCTION

Rice is an annual plant well adapted to aquatic environments (Buehring 2008; Moldenhauer et al. 2013) and is grown in over 100 countries between 40°S and 53°N latitudes (Chang 2003). Rice is a determinate plant reaching heights of 85 to 105 cm depending on cultivar (Buehring 2008; Moldenhauer and Gibbons 2003). Rice leaves are lanceolate with parallel veins on either side of the midrib and contain auricles at the basal portion which clasp around the stem (Chang and Bardenas 1965; Moldenhauer and Gibbons 2003). The culm or plant stem is contained within the leaf sheath and emerges with the panicle (Chang and Bardenas 1965; Moldenhauer and Gibbons 2003). Tillers are subsequent culms produced from the primary culm and contain properties to create a new plant (Chang and Bardenas 1965; Moldenhauer and Gibbons 2003). Nodal and crown roots are derived from nodes contained within the culm and are produced until rice panicle emergence (Chang and Bardenas 1965; Moldenhauer and Gibbons 2003). Panicles are the seed bearing portion of a rice plant comprised of a panicle neck, neck node, primary and secondary branch, pedicel, and spikelet (Chang and Bardenas 1965; Moldenhauer and Gibbons 2003).

Rice growth and development is described through vegetative, reproductive, grain filling, and ripening growth stages (Buehring 2008; Dunand and Saichuk 2014; Moldenhauer and Gibbons 2003; Moldenhauer et al. 2013). Rice seedling germination occurs when the seed has imbibed moisture and become malleable prior to emergence 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, while subsequent growth stages from PI to grain filling are regarded as reproductive (Buehring 2008; Dunanad 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 panicle$^{-1}$, 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).

Rice was domesticated in China approximately 8,200 to 13,500 years ago and is a staple food source worldwide (Molina et al. 2011; FAOSTAT 2013). Rice was first introduced to the United States through South Carolina in the late 1600s; however, commercial production in Mississippi did not begin until the mid-1940s in Washington County (Linscombe 2006; Miller and Street 2008). Seventy-five percent of U.S. rice ha are grown in Arkansas, Louisiana, Mississippi, and Texas (USDA-NASS 2018). Rice production in Mississippi occurs in the northwestern portion of Mississippi within the floodplain of the Mississippi and Yazoo rivers due to 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 ha (USDA-NASS 2018). In these primary rice-producing counties, land area devoted to rice production makes up 6.25% of row crop hectarage (USDA-NASS 2018).
Water-seeded and direct-seeded, delayed-flood are two rice production systems used in the southern U.S. (Harrell and Saichuk 2014; Sanders et al. 2000; Street and Bollich 2003). Water-seeded rice production is utilized primarily in southwestern Louisiana and California (Hardke and Scott 2013); whereas, the direct-seeded, delayed-flood production is most common in northern Louisiana, Arkansas, Mississippi, Missouri, and Texas (Buehring et al. 2008; Harrell and Saichuk 2014; McCauley 2014; Street and Bollich 2003). Rice produced in the direct-seeded, delayed-flood system is drill-seeded and managed as an upland crop until flood establishment 21 to 28 d after emergence (DAE) (Harrell and Saichuk 2014; Street and Bollich 2003). In Mississippi, rice is seeded ideally between April 1 and May 20 when the average air and/or soil temperatures ≥15 C (Buehring et al. 2008; Street and Bollich 2003).

Optimal rice seeding concentration depend on cultivar and production method (Hardke et al. 2013; Street and Bollich 2003; Wilson Jr., et al. 2013). Drill-seeded, inbred rice is seeded from 78 to 112 (kg ha⁻¹) while hybrid rice seeding concentration are approximately 28 kg ha⁻¹; however, seeding concentration can vary due to variation in cultivar seed weight (Anonymous 2016; Bond et al. 2005; Street and Bollich 2003; Wilson Jr., et al. 2013). Conventional inbred rice cultivar seeding concentration are approximately 322 seed m⁻² for an optimal stand density of 108 to 215 seeds m⁻²; whereas, hybrid rice cultivars are seeded at 108 to 161 seed m⁻² to obtain an optimal stand density of approximately 65 to 108 seeds m⁻² (Bond et al. 2005; Hardke et al. 2013; Wilson Jr., et al. 2013). Surface irrigation is utilized to stimulate seedling germination and emergence if adequate moisture is not present at the time of seeding (Street and Bollich 2003; Wilson Jr., et al. 2013). Rice is harvested when seed moisture reaches approximately 18 to 21% to minimize shattering and broken kernels (Bautista and Siebenmorgen 2008; Gardisser and Saichuk 2014; Street and Bollich 2003).
The top three most troublesome weeds in Mississippi rice production include barnyardgrass \([\textit{Echinochloa crus-galli} \text{ (L.) P. Beauv.}]\), Palmer amaranth \([\textit{Amaranthus palmeri} \text{ (S.) Watt}]\), and hemp sesbania \([\textit{Sesbania herbacea} \text{ (Mill.) McVaugh}]\) (Webster et al. 2012). Flooding is the principal weed control mechanism for rice (Chauhan and Johnson 2010; Kent and Johnson 2001; McClung 2003; Odero and Rainbolt 2014); however, weed control prior to flood establishment is crucial in the direct-seeded, delayed-flood production system to minimize weed interference with the crop (Chauhan BS 2012; Chauhan and Johnson 2010; Kendig et al. 2003; Odero and Rainbolt 2014). Herbicides such as clomazone are important PRE herbicides for midsouthern U.S. rice producers utilizing the direct-seeded, delayed-flood production method (Anonymous 2018; Scott et al. 2013; Shaner 2014a). Glyphosate and quinclorac are often mixed with clomazone PRE to control emerged weed species (Anonymous 2018). Herbicide options for delayed-PRE applications (DPRE), which are applications after rice seed have imbibed moisture for germination but prior to rice emergence, include selected auxin mimic herbicides and those which inhibit microtubule assembly, photosystem II (PSII), acetalactate synthase (ALS), and protoporphyringogen oxidase (PPO) alone or in combination (Anonymous 2018). Herbicides available for POST application to rice before and/or after flooding include selected auxin mimics and those that inhibit PSII, ALS, PPO, and chlorophyll formation (Anonymous 2018; Kendig et al 2003; Scott et al. 2013).

Nitrogen (N) fertilizer is applied to rice in greater quantity and frequency than all other nutrients to optimize yield (Norman et al. 2003). The most common source of N utilized in direct-seeded, delayed flood rice production is urea (Norman et al. 2009). Proper N application timing is crucial for maximized rice N use efficiency (Norman et al. 2013; Norman et al. 2009). Nitrogen is stored in stems and leaves of rice plants until ready for transport during grain filling,
making proper preflood N management crucial for maximizing yield (Bufogle et al. 1997; Guindo et al. 1994; Norman et al. 2013). A single N application applied just prior to flooding is optimum for maximum N use efficiency by rice (Norman et al. 2013; Norman et al. 2009; Rogers et al. 2013). Following N application, immediate flooding is recommended to incorporate urea into the soil to minimize ammonia volatilization losses (Griggs et al. 2007; Norman et al. 2009; Norman et al. 2013). Rice is capable of utilizing up to 75% of the total N applied if incorporated properly prior to flooding (Dillon et al. 2012; Norman et al. 2003; Wilson Jr., et al. 1998). Depending on cultivar, between 123 and 168 kg N ha\(^{-1}\) are applied during the growing season (Norman et al. 2013). Maintenance of flood for at least 3 wk following N fertilizer application is required for maximum N uptake from preflood N applications (Norman et al. 2013; Norman et al. 1992; Wilson Jr., et al. 1989). Therefore, in fields with limited irrigation availability and lengthy flood establishment period, a two-way split N application is recommended to minimize N losses (Norman et al. 2013). The two-way split N application involves applying 70% of total urea prior to flooding and applying the remaining 30% during early reproductive development (Bollich et al. 1994; Norman et al. 2013; Wilson Jr., et al. 1998).

Early-season rice stress can include factors such as animal and insect feeding, suboptimal temperatures, and herbicide drift (Walker et al. 2008a). A common N management practice is to apply starter N fertilizer as ammonium sulfate (AMS) at 24 kg N ha\(^{-1}\) to support stressed rice (Walker et al. 2008b). Starter N fertilizer applied during early vegetative growth stages has been reported as beneficial for increasing yield in numerous crops including corn (\textit{Zea mays} L.), cotton (\textit{Gossypium hirsutum} L.), grain sorghum [\textit{Sorghum bicolor} (L.) Moench], rice, and soybean [\textit{Glycine max} (L.) Merr.] (Bednarz et al. 2000; Gordon et al. 1998; Osborne and Riedell 2006; Walker et al. 2008b). Nitrogen fertilizer applied prior to rice tillering (i.e. preflood
application) influences grain yield more than applications at any other time; however, when starter N fertilizer was applied to two-leaf rice, grain yields increased ≥200 kg ha⁻¹ compared to where no starter N was applied (Walker et al. 2008a). Walker et al. (2008b) reported starter N fertilizer applied at two-leaf rice not only increased grain yield, but also early-season plant height compared to a no starter N control. Increased early-season rice plant height can improve crop management by allowing earlier flood establishment, thereby potentially reducing herbicide applications (Walker et al. 2008b).

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). Palmer amaranth is the most troublesome weed in corn, cotton, and soybean due to its evolution of resistance to multiple herbicide mode of action (MOA), prolific seed production, and genetic diversity (Ward et al. 2013; Webster 2013). Research has demonstrated 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 (Anonymous 2018). These PRE herbicide applications for GR weed control in corn, cotton, and soybean often include paraquat at 840 g ha⁻¹ as an additional MOA in a GR cropping system (Anonymous 2018).

Paraquat is a nonselective, broad spectrum, POST herbicide which inhibits the flow of electrons in photosystem I (PSI) in susceptible plants (Shaner 2014b). Paraquat is absorbed shortly following application and necrosis of foliage becomes visible within a few h (Shaner 2014b). Paraquat is absorbed into exposed plant foliage and remains at the point of contact, and
total vegetative necrosis typically occurs 1 to 3 d following application (Shaner 2014b).

Inhibition of PSI is caused by paraquat accepting an electron from PSI, creating a herbicide radical (Dodge 1982). The resulting herbicide radical reduces a molecular oxygen, creating a superoxide radical molecule (Dodge 1982). Superoxide dismutase can react with superoxide radicals to produce hydrogen peroxide (Dodge 1982). These superoxide radicals and hydrogen peroxide molecules cause lipid peroxidation and chlorophyll destruction resulting in plant death (Dodge 1982).

Paraquat is labeled preplant, PRE, or post-directed for nonselective weed control in corn, cotton, grain sorghum, peanut (*Arachis hypogaea* L.), soybean, and numerous vegetable and fruit crops (Anonymous 2019; Shaner 2014b). However, paraquat is only labeled preplant or PRE in rice (Anonymous 2018, 2019).

Herbicide drift is defined as the movement of herbicide particles in the air soon after application to any off-target location and is influenced by environment, nozzle and droplet size, spray pressure, nozzle angle, herbicide formulation, applicator speed, and boom height (Dexter 1995; EPA 2015; Henry et al. 2004). Types of drift events include droplet, particle, and vapor drift (Fishel and Ferrell 2016). Droplet drift occurs when herbicides move off-target during application and is considered the most common type (Fishel and Ferrell 2016). Particle drift occurs when solid particles such as soil or dust herbicide formulations move off-target (Fishel and Ferrell 2016; Jordan et al. 2009). Vapor drift events are functions of environmental condition 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 representing vapor drift can be 0.1% of the recommended use rate
For example, cotton injury was 76% 48 h after exposure to ester formulations of 2,4-D compared to 5% from the choline formulation (Sosnoskie et al. 2015). Herbicide concentration 2 m from application ranged from 0.1 to 9% of original use rate; however, herbicide concentrations decreased exponentially as 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 (VMD) ≤ 105 microns (µm) 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 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 reduce off-target herbicide movement (Hanna et al. 2008; Jordan et al. 2009; McCloskey et al. 2012). Reducing pressure increases spray droplet size, making droplets heavier and less likely to move off-target (Dexter 1995; Jordan et al. 2009). Jordan et al. (2009) concluded the best management practices for reducing drift include lower pressure and boom height, increased nozzle orifice size, avoiding applications if wind speeds ≥16 km h⁻¹, use drift control agents, and avoiding use of volatile herbicides when there is no wind.

The use of herbicides for weed control has increased production efficiency across all crops in the midsouthern U.S.; however, off-target herbicide movement has been documented to negatively impact numerous crops including corn, cotton, grain sorghum, peanut, soybean, and wheat (*Triticum aestivum* L.) (Al-Khatib et al. 2003; Anderson et al. 2004; Hensley et al. 2012; Johnson et al. 2012; Sperry et al. 2019). Glyphosate applied at 112 g ae ha⁻¹ injured grain sorghum up to 78% 2 w after treatment (WAT) (Al-Khatib et al. 2003). Anderson et al. (2004)
reported dicamba applied at 5.6 g ha\(^{-1}\) during the V3 soybean growth stage reduced yield 34%. 2,4-Dichlorophenoxyacetic acid (2,4-D) applied to V3 soybean 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\(^{-1}\) of the recommended use rate 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\(^{-1}\). Corn yield was reduced 0.5% d\(^{-1}\) when paraquat was applied at 105 g ha\(^{-1}\) anytime from corn emergence through V9 (Sperry et al. 2019). The greatest reductions in corn plant height were observed following exposure to paraquat applied at 105 g ha\(^{-1}\) during V1 and V3 growth stages (Sperry et al. 2019). Injury to corn with fomesafen applied at 86 g ha\(^{-1}\) was greatest 7 and 14 d after treatment (DAT) when applied to V5 and V7 corn; however, no reductions in yield were observed (Sperry et al. 2019). Wheat yield was reduced 54% following glyphosate at 140 g ha\(^{-1}\) during early flowering (Roider et al. 2007).

Rice is sensitive to off-target herbicide movement; 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). When applied to non-Clearfield\(^{\text{®}}\) rice, imazethapyr at 8.7 g ai ha\(^{-1}\) to one-tiller rice and 4.4 g ha\(^{-1}\) to rice at panicle differentiation reduced yields 59 to 75% of the nontreated (Hensley et al. 2012). When an imazethapyr plus imazapyr premix was applied at 7.9 g ha\(^{-1}\) to non-Clearfield\(^{\text{®}}\) rice at the two- to three-leaf growth stage, plant height was reduced 12% and injury was 19% 28 DAT (Bond et al. 2006). This research also reported delays in rice maturity, and reductions in yield were greatest with imazethapyr plus imazapyr premix applied at 7.9 g ha\(^{-1}\) (Bond et al. 2006). Non-Clearfield\(^{\text{®}}\) rice yield was reduced 39% following imazethapyr plus imazapyr premix applied at 7.9 g ha\(^{-1}\) during panicle differentiation.
(Bond et al. 2006). Imazamox applied at 2.7 and 5.5 g ha\textsuperscript{-1} injured non-Clearfield\textsuperscript{®} rice $\geq$ 20% regardless of rate 28 DAT (Webster et al. 2016). Total rice crop yield was reduced 72 and 60% of the nontreated following imazamox applied at 2.7 g ha\textsuperscript{-1} to one-tiller and booting rice, respectively (Webster et al. 2016).

Severe negative rice growth and development implications following glufosinate and/or glyphosate off-target movement have also been reported (Davis et al. 2011; Ellis et al. 2003; Kurtz and Street 2003; Webster et al. 2015). Webster et al. (2015) reported the greatest injury from glufosinate applied to rice at a sub-lethal rate during late reproductive development was 24% 7 DAT. When averaged across glufosinate concentration of 31 and 62 g ai ha\textsuperscript{-1}, applications during late reproductive development reduced primary rice yield to 90% of the nontreated control (Webster et al. 2015). Glufosinate applied to rice at 31 and 62 g ha\textsuperscript{-1} during late reproductive development reduced yield more than with any other application timing (Webster et al. 2015). Kurtz and Street (2003) reported glyphosate applied at 140 g ha\textsuperscript{-1} during rice booting injured rice $\leq$5%; however, yield was reduced $\geq$63% in 3 of 4 yr. Rice growth and development was most severely affected following glyphosate application at 70, 140, and 280 g ha\textsuperscript{-1} during reproductive development (Kurtz and Street 2003). Separate research reported rice injury following exposure to glyphosate at 140 g ha\textsuperscript{-1} applied during panicle differentiation was $\leq$ 15%; however, yield reductions were 54% (Ellis et al. 2003). Ellis et al. (2003) reported yield reductions $\leq$30% following glufosinate applied at 53 g ha\textsuperscript{-1} during panicle differentiation.

Glyphosate or glufosinate applied at 12.5 to 50% the recommended use concentration reduced rice canopy, flag leaf length, delayed maturity, and reduced yield regardless of application timing (Davis et al. 2011).
Two techniques for evaluating the effects of off-target herbicide movement are use of varying 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 varying carrier volume, the herbicide rate is reduced in proportion to a specified spray volume; whereas, testing with a constant carrier volume applies reduced herbicide concentration in a single carrier volume (Hensley et al. 2012; Davis et al. 2011). Both techniques are accepted to test the effects of off-target herbicide movement to sensitive plant species, but inconsistent results are possible (Banks and Schroeder 2002). Injury to wheat was 23% less when a systemic herbicide was applied in constant carrier volume compared with proportional carrier volume (Roider et al. 2008). Banks and Schroeder (2002) reported greater injury with systemic herbicides to cotton and sweet corn (Zea mays L. var. rugose Bonaf.) in varied carrier volume compared with constant carrier volume; however, additional research suggests no difference between techniques regardless of herbicide type when applied to soybean (Ellis et al. 2002).

In Mississippi, rice is ideally seeded between April 1 and May 20; however, these dates often coincide with preplant and/or PRE herbicide applications to corn, cotton, and soybean (Buehring 2008). Mississippi row crop producers have primarily chosen to continue to utilize GR cropping systems in the presence of GR weed biotypes (Jason A Bond 2016, Personal communication, Mississippi State University Delta Research and Extension Center Weed Scientist). In these systems, paraquat applied in mixture with residual herbicides prior to crop emergence offers an alternative MOA to aid in GR weed management (Anonymous 2018). Visual injury symptoms from off-target herbicide movement may vary based on herbicide MOA and may not always be indicative of total damage to rice growth and development (Davis et al. 2011; Ellis et al. 2003; Kurtz and Street 2003). Due to Mississippi’s diverse cropping systems,
incidents of off-target movement of paraquat from fields adjacent to rice have increased (Jason A Bond 2016, Personal communication, Mississippi State University Delta Research and Extension Center Weed Scientist). Extensive university research has documented the effects on rice growth and development of glyphosate, glufosinate, and ALS-inhibiting herbicides applied at reduced concentration (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 paraquat alone or in combination with residual herbicides with multiple MOA.

Therefore, research was conducted to (1) determine the effects of sub-lethal concentration of paraquat, metribuzin, fomesafen, and cloransulam-methyl applied at different rice growth stages, (2) determine the effects on rice growth of simulated off-target paraquat applications at varying concentration based on a proportionally decreased carrier volume, (3) characterize rice response to a sub-lethal rate of paraquat in combination with common POST and residual herbicides, (4) assess whether starter N fertilizer can aid rice recovery from exposure to a sub-lethal rate of paraquat, (5) evaluate rice response to different N fertilizer management strategies after exposure to a sub-lethal rate of paraquat, and (6) define a maximum soil concentration of S-metolachlor that will allow rice to germinate and emerge.
Literature Cited


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 (2018) 2019 Weed management suggestions for Mississippi row crops. Pages 19-23 in Bond JA. (ed.), Mississippi State Univ Ext Ser and Miss Agric and For Exp Stn Mississippi State, MS Pub 3171


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 soybean (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


Kurtz ME, Street JE (2003) Response of rice (Oryza sativa) to glyphosate applied to simulate drift. Weed Technol 17:234-238


Owen MDK (2000) Current use of transgenic herbicide-resistant soybean and corn in the USA Crop Prot 19:765-771


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CHAPTER II

RICE (ORYZA SATIVA) RESPONSE TO SUB-LETHAL CONCENTRATION OF PARAQUAT, METRIBUZIN, FOMESAFEN, AND CLORANSULAM-METHYL AT DIFFERENT APPLICATION TIMING

Abstract

Paraquat applied in mixture with residual herbicides prior to planting is a foundation treatment for glyphosate-resistant weed control in Mississippi row crops, and rice in proximity is susceptible to off-target movement of these applications. Four concurrent studies were conducted from 2015 to 2018 in Stoneville, MS, to characterize rice performance following exposure to a sub-lethal rate of paraquat, metribuzin, fomesafen, and cloransulam-methyl at different application timings. Applications were made to rice in the spiking to one-leaf (VEPOST), two- to three-leaf (EPOST), three- to four-leaf (MPOST), 7 d postflood (PFLD), and panicle differentiation (PD) growth stages. Regardless of application timing, rice injury following exposure to paraquat was \( \geq 45\% \). On average, delay in maturity were increased by 0.3 d d\(^{-1}\) following rice exposure to paraquat from emergence through PD. Inversely, dry weight, rough rice yield, panicle density, and germination were reduced 18.7 g, 131.5 kg ha\(^{-1}\), 5.6 m\(^2\), and 0.3%, respectively, d\(^{-1}\) from rice exposure to paraquat at emergence through PD. Although trends were detected for rice injury following exposure to metribuzin, rice injury was 5 to 12% regardless of application timing 3 DAT. At 28 DAT metribuzin injured rice 3 to 6%, and that injury did not translate into a yield reduction. Injury 3 DAT was greatest following rice
exposure to fomesafen applied PFLD; however, by 28 DAT injury was decreased to 5%.
Regardless of application timing, rice injury following fomesafen ranged from 2 to 5% 28 DAT. Rice exposed to cloransulam-methyl EPOST exhibited greatest foliar and below root injury 28 and 21 DAT, respectively. Rice height following cloransulam-methyl EPOST was 56% of the nontreated. Additionally, dry weight was reduced to 1,530 g m$^{-2}$ compared to 1,770 g m$^{-2}$ in the nontreated, and yields reduced to 6,540 kg ha$^{-1}$ compared with 7,850 kg ha$^{-1}$ in the nontreated when rice was exposed to cloransulam-methyl EPOST. Delays in rice maturity following exposure to paraquat increased as application timings were delayed. Rice yield was negatively affected following exposure to paraquat applied any time after rice emergence. However, applications of paraquat to rice in early reproductive growth reduced rough rice yield and seed germination the greatest. However, application timing is crucial in determining severity of rice injury. Early-season injury to rice following exposure to paraquat had less effect on yield compared with injury occurring at later developmental stages. Additionally, fields devoted to seed rice production are at risk for reduced seed germination if exposed to a sub-lethal paraquat rate during early reproductive growth stages.

**Nomenclature:** Rice (*Oryza sativa* L.); paraquat 1,1’-dimethyl-4,4’-bipyridinium ion; metribuzin 4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4H)-one; fomesafen 5-[2-chloro-4-(trifluoromethyl)phenoxy]-N-(methylsulfonyl)-2-nitrobenzamide; cloransulam-methyl methyl 3-chloro-2-[[5-ethoxy-7-fluoro[1,2,4]triazolo[1,5-c]pyrimidin-2-yl)sulfonyl]amino]benzoate

**Key words:** Application timing, off-target
Introduction

Rice growth and development is described through vegetative, reproductive, grain filling, and ripening growth stages (Buehring 2008; Dunand and Saichuk 2014; Moldenhauer and Gibbons 2003; Moldenhauer et al. 2013). Rice seedling germination occurs when the seed has imbibed moisture and become malleable prior to emergence 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, while subsequent growth stages from PI to grain filling are regarded as reproductive (Buehring 2008; Dunanad 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 panicle$^{-1}$, 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 and is influenced by environment, nozzle and droplet size, spray pressure, nozzle angle, herbicide formulation, applicator speed, and boom height (Dexter 1995; EPA 2015; Henry et al. 2004). Types of drift events include droplet, particle, and vapor drift (Fishel and Ferrell 2016). Droplet drift occurs when herbicides move off-target during application and is considered the most common type (Fishel and Ferrell 2016). Particle drift occurs when solid particles such as soil or dust formulations move off-target (Fishel and Ferrell
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 representing 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 to 5% from the choline formulation (Sosnoskie et al. 2015). Herbicide concentration 2 m from application ranged from 0.1 to 9% of original use rate; however, herbicide concentrations decreased exponentially as distance from application increased (Carlsen et al. 2006). Wind speeds ≥16 km per 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 (VMD) ≤105 microns (µm) 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 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 reduce off-target herbicide movement (Hanna et al. 2008; Jordan et al. 2009; McCloskey et al. 2012). Reducing pressure increases spray droplet size, making droplets heavier and less likely to move off-target (Dexter 1995; Jordan et al. 2009).

Paraquat is labeled 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 2016; Jordan et al. 2009).
2018; Shaner 2014). However, paraquat is only labeled preplant or PRE in rice (Anonymous 2018, 2019). Row crop producers in Mississippi have widely adopted the use of paraquat in mixture with herbicides representing multiple herbicide modes of action (MOA) 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 U.S.; however, off-target herbicide movement has been documented to negatively impact 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 grain sorghum up to 78% 2 wk after treatment (WAT) (Al-Khatib et al. 2003). Wheat yield was reduced 54% following glyphosate at 140 g ha\(^{-1}\) during early flowering (Roider et al. 2007). Anderson et al. (2004) reported dicamba at 5.6 g ae ha\(^{-1}\) during the V3 soybean growth stage reduced yield 34%. 2,4-Dichlorophenoxyacetic acid (2,4-D) applied to V3 soybean 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 ALS-inhibiting herbicides to rice; however, limited data has 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 MOA are often mixed with paraquat in preplant applications. Photosystem II (PSII), protoporphyrinogen oxidase (PPO), and acetolactate
synthase (ALS)-inhibiting herbicides represent common MOA present in paraquat mixtures applied preplant and/or PRE. Diagnosing severity of rice injury following off-target paraquat incidents is challenging due to the potential complexity of symptoms associated with the MOA mixed with paraquat. Therefore, four concurrent studies were conducted to evaluate rice response to sub-lethal 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 (OM) for each study are described in Table 2.1.

Glyphosate (Roundup PowerMax 4.5 L, 1120 g ha\(^{-1}\), Monsanto Company, 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 each siteyear 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 siteyear 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, 26 Davis Dr., Research Triangle Park, NC, 27709) 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% (v/v) 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 siteyears. 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 buffer plots 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 applied using a CO\(_2\)-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 NIS (Activator 90, 90% non-ionic surfactant, Loveland Products, P.O. Box 1286, Greeley, CO 80632) at 0.5% (v/v) and ammonium sulfate (AMS) water-conditioning agent (Class Act NG, 50% nitrogen fertilizer, WinField Solutions, P.O. Box 64589, St. Paul, MN 55164) at 2.5% (v/v). 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 sub-lethal rate of 10% of their suggested use
rate in Mississippi (Al-Khatib and Peterson 1999; Anonymous 2018). 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, P.O. Box 18300 Greensboro, NC 27409) 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 postflood (PFLD), and panicle differentiation (PD) 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 to those of plants from nontreated plots in the same replication. Plant height were 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 were 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 d 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 d to 50% heading data were converted to delay in maturity calculated by subtracting d to 50% heading in an individual plot from that in the nontreated. 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 grain panicle\(^{-1}\), and 1,000-grain weight), and seed germination percentage.

All studies 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 yield are expressed as a mass fraction of the original 120-g sample of rough rice.

Hand-harvested samples were greenhouse dried at 32 to 49 (± 5) C for 2 wk, weighed to determine rice dry weight, and weight were converted to g m\(^{-2}\). The total number of seed bearing panicles in each hand-harvested sample were counted to determine panicle density (panicle number m\(^{-2}\)). Panicles from each hand-harvested sample were threshed with a plot thresher, and the number of filled grains was counted to determine the average number of filled grain panicle\(^{-1}\) for each treatment. Grain was dried to approximately 12% moisture content, and weight recorded. Five 1,000-grain subsamples were then weighed to determine 1,000-grain weight. Seed germination percentage was determined based on number of germinated seed out of 100 after 48 h exposure to 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 non-significant model terms were removed sequentially until a satisfactory model was obtained (Golden et al. 2006). All other
data were regressed against d after emergence (DAE) allowing for both linear and quadratic terms with coefficients depending on DAE, and non-significant model terms were removed sequentially until a satisfactory model was obtained. Data which did not exhibit a significant trend were subjected to ANOVA using the PROC MIXED procedure in SAS v. 9.3 (SAS Institute Inc. 100 SAS Campus Drive Cary, NC 27513-2414, USA) with siteyear and replication (nested within experimental run) as random effects parameters (Blouin et al. 2011). Least square means were calculated and mean separation (p ≤ 0.05) was produced using PDMIX800 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 seed panicle$^{-1}$ following rice exposure to paraquat (Table 2.2 and 2.3). However, nonlinear portions of the fitted line were no different from zero for MPOST and PFLD timings (Table 2.2 and Figure 2.1). Linear trends were detected for rough rice yield, dry weight, panicle density, and seed germination (Table 2.3).

Regardless of application timing, rice injury following paraquat exposure ranged from 37 to 47% 3 DAT (Figure 2.1). 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 2.1). For both VEPOST and EPOST timings, rice appeared to exhibit some recovery; however, injury 28 DAT was still 45 and 52% with VEPOST and EPOST timings, respectively (Figure 2.1). Rice exposed to paraquat MPOST and PFLD showed a similar trend in which injury progressively increased from 3 to 28 DAT (Figure 2.1). Similar to other timings, injury 3 DAT
for rice exposed to paraquat MPOST and PFLD was 40 and 39%, respectively (Figure 2.1). Rice injury 28 DAT for both MPOST and PFLD was ≥53% (Figure 2.1). Rice injury from paraquat exposure at PD was 47% 3 DAT, decreased to 41% by 14 DAT, but increased again to 51% by 28 DAT (Figure 2.1). 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 sub-lethal 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 later in the growing season (Figure 2.2). On average, delays in rice maturity increased 0.26 d d\(^{-1}\) following paraquat exposure from VEPOST through PD (Figure 2.2). Inversely, dry weight, rough rice yield, panicle density, and seed germination were reduced 18.7 g, 131.5 kg ha\(^{-1}\), 5.6 m\(^2\), and 0.3%, respectively, d\(^{-1}\) from paraquat exposure at VEPOST through PD timings (Table 2.3 and Figure 2.2). 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 panicle\(^{-1}\); however, the linear term of the fitted line was no different than zero (Table 2.3 and Figure 2.2). Seed panicle\(^{-1}\) were reduced exponentially following rice exposure to paraquat approximately 10 DAE. Rice exposed to paraquat at 50 DAE produced 28 seed panicle\(^{-1}\) compared with 97 seed panicle\(^{-1}\) in the nontreated (Figure 2.2).

Rice height, 1,000-grain weight, total, and whole milled rice yield were affected by paraquat timing (Table 2.4). Rice height 14 DAT was more negatively impacted when rice was exposed to paraquat prior to flooding compared with postflood timings (Table 2.4). However, rice height 14 DAT following paraquat at PD was reduced 15% compared to the nontreated
Conversely, 1,000-grain weight was more negatively impacted following exposure to paraquat postflood (Table 2.4). Averaged over five siteyears, 1,000-grain weight was reduced to 17 and 12 g following rice exposure to paraquat PFLD and PD, respectively (Table 2.4).

Total and whole milled rice yield were affected by paraquat at different timings. Plots not treated with paraquat produced 58 and 70% whole and total milled rice, respectively (Table 2.4). However, milling yield was similar to those for the nontreated 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 EPOST, MPOST, and PD (Table 2.4).

**Metribuzin Timing Study**

In the study evaluating rice response to a sub-lethal rate of metribuzin at different growth stages, only rice injury exhibited a quadratic trend (Table 2.2). 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 2.3). Lawrence et al. (2018) reported similar injury for rice exposed to metribuzin at 42 g ha⁻¹ EPOST. Rice injury was ≤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. However, application timing influenced rice height 14 DAT (Table 2.5). Rice exposed to metribuzin VEPOST exhibited height 14 DAT which was 93% of the nontreated (Table 2.5). This was comparable to rice height following exposure to metribuzin EPOST and PD (Table 2.5).
**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 2.2). Additionally, quadratic terms were not different from zero for EPOST and PFLD timings (Table 2.2). The linear term was not different from zero for the MPOST application timing (Table 2.2).

Although trends in rice injury were detected following all application timings, injury only exceeded 11% with the PFLD timing (Figure 2.4). Injury 3 DAT following fomesafen PFLD was 18%; however, by 28 DAT, that injury had decreased to 5% (Figure 2.4). Regardless of fomesafen timing, rice injury ranged from 2 to 5% 28 DAT (Figure 2.4). 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 sub-lethal 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 2.6). Rice height 14 DAT were 95% of the nontreated following fomesafen exposure VEPOST; however, height ranged from 98 to 103% of the nontreated control following other timings (Table 2.6). Rough rice yield was reduced to 7,950 kg ha$^{-1}$ following fomesafen PD compared to 8,550 kg ha$^{-1}$ with no exposure to fomesafen (Table 2.6). However, rough rice yield following PD application was comparable to that following EPOST, MPOST, and PFLD timings (Table 2.6). Rice in plots exposed to fomesafen VEPOST produced comparable yields to those treated EPOST or with no exposure to fomesafen (Table 2.6). Similarly, Sperry et al. (2019) reported a 10% decrease in corn yield from fomesafen applied at 35 g ha$^{-1}$ to corn in the V7 and V9 growth stages compared with fomesafen PRE.
Cloransulam-methyl Timing Study

For all cloransulam-methyl timings, a quadratic trend was detected for rice foliar injury across all evaluation intervals and for panicle density (Table 2.2 and 2.7). Additionally, a linear trend was detected for root injury 21 DAT (Table 2.7). Greater rice foliar injury occurred with VEPOST and EPOST timings compared with MPOST and postflood timings. At 3 DAT, foliar injury for both VEPOST and EPOST timings was 8 and 9%, respectively (Figure 2.5). By 28 DAT, foliar injury for VEPOST and EPOST timings was $\geq$41%. Rice foliar injury was lower following exposure to cloransulam-methyl from MPOST through PD compared with that following VEPOST and EPOST timings (Figure 2.5). Application timings from MPOST through PD also produced the least impact on height 14 DAT, dry weight, and rough rice yields compared to the nontreated (Table 2.8). Foliar injury from cloransulam-methyl MPOST timings was maximized at 25% 21 DAT and decreased to 22% by 28 DAT. A similar trend in foliar injury was observed for PFLD and PD application timings. Webster et al. (2016) observed 25 to 36% rice injury following exposure to a sub-lethal rate of imazamox, which is also an ALS-inhibiting herbicide. Applications of cloransulam-methyl had the least impact on rice foliar injury when applied at PD (Figure 2.5). Additionally, rice foliar injury 21 DAT was 5 to 14% when imazamox was applied at a reduced rate to rice at PD and prior to panicle exertion (boot) growth stages (Webster et al. 2016). Rice height was 93% of the nontreated control following cloransulam-methyl at PD, and dry weight, rough rice yield, and seed panicle$^1$ were comparable to the nontreated (Table 2.8).

Rice exposed to cloransulam-methyl EPOST exhibited the greatest root injury 21 DAT, and height were reduced to 64% of the nontreated (Table 2.8 and Figure 2.6). Additionally, cloransulam-methyl applied EPOST reduced dry weight to 1,530 g m$^{-2}$ compared to 1,770 g m$^{-2}$
in the nontreated, and rough rice yield was reduced to 6,540 kg ha\(^{-1}\) compared with 7,850 kg ha\(^{-1}\) in the nontreated (Table 2.8). Webster et al. (2016) suggested that rice is more sensitive to a sub-lethal rate 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 seed panicle\(^{-1}\) was reduced to 55 seed panicle\(^{-1}\) with PFLD timing compared with 77 seed panicle\(^{-1}\) in the nontreated, no reductions in yield (rough, whole, and total milled) or dry weight were detected (Table 2.8). However, based on the quadratic trend for panicle density, applications in the PFLD range of DAE indicated an increased number of panicles compared to the nontreated (Figure 2.6).

The current research demonstrates that rice is highly sensitive to a sub-lethal rate 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 for reduced seed germination if 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 at PFLD and PD timings reduced yields compared to the nontreated, VEPOST, and EPOST timings. Cloransulam-methyl injured rice more with exposure prior to 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 of Webster et al. (2016) where 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 sub-lethal concentration of non-target herbicides. In Mississippi, application timings for preplant weed control in corn, cotton, and soybean can occur across a broad range of dates in which 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 MOA had a negative impact on 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.
Table 2.1  Coordinates, soil series, soil description, previous crop, soil pH, and soil organic matter (OM) in four concurrent studies evaluating rice performance following exposure to sub-lethal concentrations of paraquat, metribuzin, fomesafen, and cloransulam-methyl at five growth stages at the Mississippi State University Delta Research and Extension Center in Stoneville, MS.

<table>
<thead>
<tr>
<th>Year</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Soil Series</th>
<th>Soil Description</th>
<th>Previous Crop</th>
<th>Soil pH</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>33.44°N,</td>
<td>90.90°W</td>
<td>Sharkey very-fine clay</td>
<td>Very-fine, smectitic, thermic Chromic Epiaquerts</td>
<td>Rice:fallow</td>
<td>7.8</td>
<td>2.4</td>
</tr>
<tr>
<td>2016A</td>
<td>33.41°N,</td>
<td>90.92°W</td>
<td>Sharkey very-fine clay</td>
<td>Very-fine, smectitic, thermic Chromic Epiaquerts</td>
<td>Rice:fallow</td>
<td>8.2</td>
<td>2.2</td>
</tr>
<tr>
<td>2016B</td>
<td>33.43°N,</td>
<td>90.93°W</td>
<td>Sharkey very-fine clay</td>
<td>Very-fine, smectitic, thermic Chromic Epiaquerts</td>
<td>Soybean:rice</td>
<td>8.1</td>
<td>2.1</td>
</tr>
<tr>
<td>2017A</td>
<td>33.44°N,</td>
<td>90.90°W</td>
<td>Sharkey very-fine clay</td>
<td>Very-fine, smectitic, thermic Chromic Epiaquerts</td>
<td>Rice:fallow</td>
<td>7.8</td>
<td>2.4</td>
</tr>
<tr>
<td>2017B</td>
<td>33.43°N,</td>
<td>90.90°W</td>
<td>Commerce silty clay loam</td>
<td>Fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts</td>
<td>Soybean:rice</td>
<td>7.1</td>
<td>1.7</td>
</tr>
<tr>
<td>2018</td>
<td>33.42°N,</td>
<td>90.90°W</td>
<td>Bosket very fine sandy loam</td>
<td>Fine-loamy, mixed, active, thermic Molllic Hapludalfs</td>
<td>Rice:rice</td>
<td>7.9</td>
<td>1.2</td>
</tr>
</tbody>
</table>
Table 2.2  Regression coefficients for rice injury across evaluation intervals following exposure to paraquat at 84 g ai ha\(^{-1}\) (Paraquat Timing Study), metribuzin at 42 g ai ha\(^{-1}\) (Metribuzin Timing Study), fomesafen at 39 g ai ha\(^{-1}\) (Fomesafen Timing Study), and cloransulam-methyl at 3.5 g ai ha\(^{-1}\) (Cloransulam-methyl Timing Study) at Stoneville, MS, from 2015 to 2018\(^a\).

<table>
<thead>
<tr>
<th>Application timing(^b)</th>
<th>Intercept</th>
<th>Linear</th>
<th>Quadratic</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Paraquat Timing Study</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VEPOST</td>
<td>40.4919</td>
<td>1.1831</td>
<td>-0.03624</td>
</tr>
<tr>
<td>EPOST</td>
<td>31.2244</td>
<td>2.1207</td>
<td>-0.04964</td>
</tr>
<tr>
<td>MPOST</td>
<td>36.0826</td>
<td>1.4159</td>
<td>-0.01983(^c)</td>
</tr>
<tr>
<td>PFLD</td>
<td>36.0638</td>
<td>0.9669</td>
<td>-0.01286(^c)</td>
</tr>
<tr>
<td>PD</td>
<td>50.4405</td>
<td>-1.4095</td>
<td>0.05119</td>
</tr>
<tr>
<td><strong>Metribuzin Timing Study</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VEPOST</td>
<td>12.1595</td>
<td>-0.0744(^c)</td>
<td>-0.00616</td>
</tr>
<tr>
<td>EPOST</td>
<td>6.6089</td>
<td>0.5507(^c)</td>
<td>-0.02090</td>
</tr>
<tr>
<td>MPOST</td>
<td>8.6781</td>
<td>0.7055</td>
<td>-0.02973</td>
</tr>
<tr>
<td>PFLD</td>
<td>10.3486</td>
<td>-0.5030</td>
<td>0.008004(^c)</td>
</tr>
<tr>
<td>PD</td>
<td>3.4917</td>
<td>0.3908</td>
<td>-0.01520</td>
</tr>
</tbody>
</table>
### Table 2.2 (continued)

#### Fomesafen Timing Study

<table>
<thead>
<tr>
<th></th>
<th>Regression Coefficient</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>VEPOST</td>
<td>9.3102</td>
<td>0.02088§</td>
</tr>
<tr>
<td>EPOST</td>
<td>12.0202</td>
<td>-0.4081</td>
</tr>
<tr>
<td>MPOST</td>
<td>9.1663</td>
<td>0.2436§</td>
</tr>
<tr>
<td>PFLD</td>
<td>20.6232</td>
<td>-0.8323</td>
</tr>
<tr>
<td>PD</td>
<td>6.6335</td>
<td>0.6377</td>
</tr>
</tbody>
</table>

#### Cloransulam-methyl Timing Study

<table>
<thead>
<tr>
<th></th>
<th>Regression Coefficient</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>VEPOST</td>
<td>-7.3447§</td>
<td>5.6102</td>
</tr>
<tr>
<td>EPOST</td>
<td>-7.7616§</td>
<td>5.9274</td>
</tr>
<tr>
<td>MPOST</td>
<td>-3.3935§</td>
<td>2.7704</td>
</tr>
<tr>
<td>PFLD</td>
<td>9.4456</td>
<td>1.1895</td>
</tr>
<tr>
<td>PD</td>
<td>0.8186§</td>
<td>1.0494</td>
</tr>
</tbody>
</table>

---

*a* Data for Paraquat, Metribuzin, and Fomesafen Timing Studies are pooled across six siteyears, and data for the Cloransulam-methyl Timing Study are pooled across three siteyears.  
*b* Application timings included spiking to one-leaf (VEPOST), two- to three-leaf (EPOST), three- to four-leaf (MPOST), seven d postflood (PFLD), and panicle differentiation (PD).  
*c* Coefficient not significantly different than zero are indicated by §.
paraquat at 84 g ai ha\(^{-1}\) in the Paraquat Timing Study at Stoneville, MS, from 2015 to 2018\(^a\).

<table>
<thead>
<tr>
<th>Parameter(^b)</th>
<th>Intercept</th>
<th>Linear</th>
<th>Quadratic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delay in maturity (d)</td>
<td>4.7041</td>
<td>0.2655</td>
<td>n/s</td>
</tr>
<tr>
<td>Yield (kg ha(^{-1}))</td>
<td>8289.48</td>
<td>-131.51</td>
<td>n/s</td>
</tr>
<tr>
<td>Dry weight (g m(^{-2}))</td>
<td>1744.22</td>
<td>-18.72</td>
<td>n/s</td>
</tr>
<tr>
<td>Panicle density (no. m(^{-2}))</td>
<td>412.05</td>
<td>-5.6633</td>
<td>n/s</td>
</tr>
<tr>
<td>Seed panicle(^{-1}) (no.)</td>
<td>97.77</td>
<td>0.5810§</td>
<td>-0.03930</td>
</tr>
<tr>
<td>Germination (%)</td>
<td>93.45</td>
<td>-0.3002</td>
<td>n/s</td>
</tr>
</tbody>
</table>

\(^a\)Data for delay in maturity are pooled across six siteyears, and data for all other parameters are pooled across five siteyears.

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

\(^c\)Coefficient is not significantly different than zero are indicated by §.
<table>
<thead>
<tr>
<th>Application timing&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Height</th>
<th>1,000-grain weight</th>
<th>Total milled</th>
<th>Whole milled</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% of nontreated</td>
<td>g</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>Nontreated</td>
<td>-</td>
<td>21 a</td>
<td>70 ab</td>
<td>58 a</td>
</tr>
<tr>
<td>VEPOST</td>
<td>69 c</td>
<td>22 a</td>
<td>71 a</td>
<td>58 a</td>
</tr>
<tr>
<td>EPOST</td>
<td>62 c</td>
<td>21 a</td>
<td>69 abc</td>
<td>56 ab</td>
</tr>
<tr>
<td>MPOST</td>
<td>54 e</td>
<td>21 a</td>
<td>67 bc</td>
<td>53 bc</td>
</tr>
<tr>
<td>PFLD</td>
<td>77 b</td>
<td>17 b</td>
<td>64 c</td>
<td>51 c</td>
</tr>
<tr>
<td>PD</td>
<td>85 a</td>
<td>12 c</td>
<td>68 abc</td>
<td>54 abc</td>
</tr>
</tbody>
</table>

<sup>a</sup>Data for height are pooled over six siteyears, and data for total and whole milled rice, 1,000-grain seed weight, and dry weight are pooled over five siteyears. Means followed by the same letter for each parameter are not different at p ≤ 0.05.  
<sup>b</sup>Application timings included spiking to one-leaf (VEPOST), two- to three-leaf (EPOST), three- to four-leaf (MPOST), seven d postflood (PFLD), and panicle differentiation (PD).
Table 2.5  Rice height 14 d after treatment (DAT) following exposure to metribuzin at 42 g ai ha\(^{-1}\) in the Metribuzin Timing Study at Stoneville, MS, from 2015 to 2018\(^a\).

<table>
<thead>
<tr>
<th>Application timing(^b)</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% of nontreated</td>
</tr>
<tr>
<td>VEPOST</td>
<td>93 b</td>
</tr>
<tr>
<td>EPOST</td>
<td>95 ab</td>
</tr>
<tr>
<td>MPOST</td>
<td>101 a</td>
</tr>
<tr>
<td>PFLD</td>
<td>101 a</td>
</tr>
<tr>
<td>PD</td>
<td>97 ab</td>
</tr>
</tbody>
</table>

\(^a\)Data were pooled over six siteyears. Means followed by the same are not different at p ≤ 0.05.

\(^b\)Application timings included spiking to one-leaf (VEPOST), two- to three- leaf (EPOST), three- to four-leaf (MPOST), seven d postflood (PFLD), and panicle differentiation (PD).
Table 2.6  Rice height 14 d after treatment (DAT) and rough rice yield following exposure to fomesafen at 39 g ai ha\(^{-1}\) in the Fomesafen Timing Study at Stoneville, MS, from 2015 to 2018\(^a\).

<table>
<thead>
<tr>
<th>Application timing(^b)</th>
<th>Height</th>
<th>Rough rice yield</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% of nontreated</td>
<td>kg ha(^{-1})</td>
</tr>
<tr>
<td>Nontreated</td>
<td></td>
<td>8,550 a</td>
</tr>
<tr>
<td>VEPOST</td>
<td>95 b</td>
<td>8,510 a</td>
</tr>
<tr>
<td>EPOST</td>
<td>103 a</td>
<td>8,250 ab</td>
</tr>
<tr>
<td>MPOST</td>
<td>98 ab</td>
<td>7,950 b</td>
</tr>
<tr>
<td>PFLD</td>
<td>100 ab</td>
<td>8,010 b</td>
</tr>
<tr>
<td>PD</td>
<td>100 ab</td>
<td>7,950 b</td>
</tr>
</tbody>
</table>

\(^a\)Data for height are pooled over six siteyears, and data for rough rice yield are pooled over five siteyears. Means followed by the same letter for each parameter are not different at p \(\leq 0.05\).

\(^b\)Application timings include spiking to one-leaf (VEPOST), two- to three- leaf (EPOST), three- to four-leaf (MPOST), seven d postflood (PFLD), and panicle differentiation (PD).
Table 2.7  Regression coefficients for rice root injury 21 d after treatment (DAT) and panicle density at maturity following exposure to cloransulam-methyl at 3.5 g ai ha-1 in the Cloransulam-methyl Timing Study at Stoneville, MS, from 2015 to 2017a.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Intercept</th>
<th>Linear</th>
<th>Quadratic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Root injury (%)</td>
<td>91.25</td>
<td>-1.3495</td>
<td>n/s</td>
</tr>
<tr>
<td>Panicle density (no. m⁻²)</td>
<td>373.22</td>
<td>7.1132</td>
<td>-0.1063</td>
</tr>
</tbody>
</table>

a. Data were pooled across three siteyears.
b. Application timings include spiking to one-leaf (VEPOST), two- to three- leaf (EPOST), three- to four-leaf (MPOST), seven d postflood (PFLD), and panicle differentiation (PD).

Table 2.8  Rice height 14 d after treatment (DAT), dry weight at maturity, rough rice yield, and seed panicle-1 following exposure to cloransulam-methyl at 3.5 g ai ha-1 in the Cloransulam-methyl Timing Study at Stoneville, MS, from 2015 to 2017a.
<table>
<thead>
<tr>
<th>Application timing&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Height</th>
<th>Dry weight</th>
<th>Rough rice yield</th>
<th>Seed panicle&lt;sup&gt;-1&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% nontreated</td>
<td>g</td>
<td>kg ha&lt;sup&gt;-1&lt;/sup&gt;</td>
<td>no.</td>
</tr>
<tr>
<td>Nontreated</td>
<td>-</td>
<td>1,770 a</td>
<td>7,850 a</td>
<td>77 a</td>
</tr>
<tr>
<td>VEPOST</td>
<td>56 c</td>
<td>1,530 b</td>
<td>6,540 c</td>
<td>75 a</td>
</tr>
<tr>
<td>EPOST</td>
<td>64 b</td>
<td>1,770 a</td>
<td>6,940 bc</td>
<td>79 a</td>
</tr>
<tr>
<td>MPOST</td>
<td>88 a</td>
<td>1,930 a</td>
<td>7,600 a</td>
<td>63 ab</td>
</tr>
<tr>
<td>PFLD</td>
<td>87 a</td>
<td>1,840 a</td>
<td>7,590 a</td>
<td>55 b</td>
</tr>
<tr>
<td>PD</td>
<td>93 a</td>
<td>1,740 ab</td>
<td>7,560 ab</td>
<td>78 a</td>
</tr>
</tbody>
</table>

<sup>a</sup>Data were pooled over three siteyears for height, and data were pooled over two siteyears for dry weight, rough rice yield, and seeds panicle<sup>-1</sup>. Means followed by the same letter for each parameter are not different at p ≤ 0.05.

<sup>b</sup>Application timings include spiking to one-leaf (VEPOST), two- to three-leaf (EPOST), three- to four-leaf (MPOST), seven d postflood (PFLD), and panicle differentiation (PD).
Figure 2.1 Rice injury following exposure to paraquat at 84 g ai ha\(^{-1}\) in the Paraquat Timing Study at Stoneville, MS, from 2015 to 2018.
Figure 2.2  Rice delay in maturity (a), dry weight (b), rough rice yield (c), panicle density (d), seed panicle$^{-1}$ (e), and seed germination (f) following exposure to paraquat at 84 g ai ha$^{-1}$ in the Paraquat Timing Study at Stoneville, MS, from 2015 to 2018.
Figure 2.3  Rice injury following exposure to metribuzin at 42 g ai ha\(^{-1}\) in the Metribuzin Timing Study at Stoneville, MS, from 2015 to 2018.
Figure 2.4  Rice injury following exposure to fomesafen at 39 g ai ha\(^{-1}\) in the Fomesafen Timing Study at Stoneville, MS, from 2015 to 2018.
Figure 2.5  Rice foliar injury following exposure to cloransulam-methyl at 3.5 g ai ha\(^{-1}\) in the Cloransulam-methyl Timing Study at Stoneville, MS, from 2015 to 2017.
Figure 2.6  Rice root injury (a) 21 days after treatment (DAT) and panicle density m$^{-2}$ (b) following exposure to cloransulam-methyl at 3.5 g ai ha$^{-1}$ in the Cloransulam-methyl Timing Study at Stoneville, MS, from 2015 to 2017
Literature Cited


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


CHAPTER III

RICE (*ORYZA SATIVA*) PERFORMANCE FOLLOWING EXPOSURE TO A SUB-LETHAL CONCENTRATION OF PARAOQUAT ALONE OR IN MIXTURE WITH RESIDUAL HERBICIDES

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, formulation, and carrier volume. Therefore, research was conducted from 2015 to 2018 in Stoneville, MS, to determine the effects on rice growth from simulated off-target paraquat applications at varying concentration based on a proportionally decreased carrier volume and characterize rice response to a sub-lethal rate of paraquat in combination with common PRE and POST residual herbicides. Rice injury was less severe as carrier volume decreased with a proportional paraquat rate; however, paraquat at any carrier volume severely injured rice, reduced plant height, delayed maturity, and reduced dry weights. Paraquat plus metribuzin injured rice 68 to 69% 14 and 28 d after treatment (DAT), which was 10 to 13% greater than 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 sub-lethal rate of paraquat alone or in mixture with common PRE and POST 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.  
**Nomenclature:** Rice (*Oryza sativa* L.); paraquat 1,1’-dimethyl-4,4’-bipyridinium ion  
**Key words:** Herbicide mixture, residual herbicide, off-target  

**Introduction**  
Seventy-five percent of U.S. rice ha are grown in Arkansas, Louisiana, Mississippi, and Texas (USDA-NASS 2018). Rice was first introduced to the United States through South Carolina in the late 1600s; however, commercial production in Mississippi did not begin until the mid-1940s in Washington County (Linscombe 2006; Miller and Street 2008). Rice production in Mississippi occurs in the northwestern portion of Mississippi within the floodplain of the Mississippi and Yazoo rivers due to the region’s clay-textured soils, environment, and water availability (Miller and Street 2008; Buehring 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 ha (USDA-NASS 2018). In these primary rice-producing counties, land area devoted to rice production makes up 6.25% of row crop hectarage (USDA-NASS 2018).  

Water-seeded and direct-seeded, delayed-flood are two rice production systems used in the southern U.S. (Harrell and Saichuk 2014; Sanders et al. 2000; Street and Bollich 2003). Water-seeded rice production is utilized primarily in southwestern Louisiana and California (Hardke and Scott 2013); whereas, the direct-seeded, delayed-flood production is most common in northern Louisiana, Arkansas, Mississippi, Missouri, and Texas (Buehring et al. 2008; Harrell
and Saichuk 2014; McCauley 2014; Street and Bollich 2003). Rice produced in the direct-seeded, delayed-flood system is drill-seeded and managed as an upland crop until flood establishment 21 to 28 d after emergence (DAE) (Harrell and Saichuk 2014; Street and Bollich 2003).

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 MOA to aid in GR weed management (Anonymous 2018). Palmer amaranth [Amaranthus palmeri (S.) Watts] is the most troublesome weed in corn, cotton, and soybean due to its evolution of resistance to multiple herbicide MOA, prolific seed production, and genetic diversity (Ward et al. 2013; Webster 2012, 2013). Research has demonstrated 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 (Anonymous 2018). In GR cropping systems, PRE herbicide applications for GR weed control often include paraquat at 840 g ai ha\(^{-1}\) as an additional MOA (Anonymous 2018).

Paraquat is a nonselective, broad-spectrum, POST herbicide, which 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 [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 2018, 2019).

Early-season rice stress can include factors such as animal and insect feeding, sub-optimal temperatures, and herbicide drift (Walker et al. 2008). In Mississippi, rice is ideally seeded between April 1 and May 20, 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). Rice is sensitive to off-target herbicide movement; 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). 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). Webster et al. (2015) reported the greatest rice injury from a sub-lethal 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 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. Rice growth and development was most severely affected following glyphosate application at 70, 140, and 280 g ha\(^{-1}\) during reproductive development (Kurtz and Street 2003). Separate research reported rice injury following exposure to glyphosate at 140 g ha\(^{-1}\) during
panicle differentiation was ≤15%; however, yield reductions were 54% (Ellis et al. 2003). Ellis et al. (2003) reported yield reductions ≤30% following glufosinate applied at 53 g ha\(^{-1}\) during panicle differentiation. Glyphosate or glufosinate applied at 12.5 to 50% the recommended use rates reduced rice canopy, flag leaf length, delayed maturity, and reduced yield regardless of application timing (Davis et al. 2011).

Two techniques for evaluating the effects of off-target herbicide movement are use of varying 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 varying carrier volume, the herbicide rate is reduced in proportion to a specified spray volume; whereas, testing with a constant carrier volume applies reduced herbicide rates in a single carrier volume (Hensley et al. 2012; Davis et al. 2011). 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 of glyphosate, glufosinate, and acetylacetate synthase (ALS)-inhibiting herbicides applied at sub-lethal 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 sub-lethal concentration of paraquat alone or in combination with residual herbicides representing different MOA. Therefore, research was conducted to (1) determine the
effects on rice growth following simulated off-target paraquat applications at varying concentration based on a proportionally decreased carrier volume, and (2) characterize rice response to sub-lethal concentration of paraquat in combination with common residual herbicides.

**Materials and Methods**

A study evaluating rice response following paraquat applied with proportionally decreasing carrier volume and herbicide rate (Carrier Volume Study) was conducted from 2016 to 2017 at the Mississippi State University Delta Research and Extension Center in Stoneville, MS. Additionally, two separate herbicide mixture studies (Paraquat, Fomesafen, and Metribuzin Mixture Study and Residual Herbicide Mixture Study) to characterize rice response to a sub-lethal rate of paraquat applied alone or in combination with common PRE and POST 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 rotation, soil pH, and soil organic matter (OM) for all three studies are described in Tables 3.1 and 3.2.

Glyphosate (Roundup PowerMax 4.5 L, 1,120 g ha\(^{-1}\), Monsanto Company, 800 N. Lindburgh Blvd., St. Louis, MO 63167), paraquat (Gramoxone 2.0 SL, 560 g 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 ae ha\(^{-1}\), Agri Star, 1525 NE 36th St., Ankeny, IA 50021) were applied in late-March to early-April each siteyear 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)
was applied PRE each siteyear 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) plus quinclorac (Facet 1.50 SL, 375 g ai ha\(^{-1}\), BASF Crop Protection, 26 Davis Dr., Research Triangle Park, NC, 27709) 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% (v/v) was applied at two- to three-leaf rice (EPOST) to maintain experimental sites weed free.

Rice was drill-seeded on June 9, 2015, May 11 and 17, 2016, and May 9 and 18, 2017 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 siteyears. 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 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 39194) 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.

All herbicide treatments in the Paraquat, Fomesafen, and Metribuzin Mixture Study, and the Residual Herbicide Mixture Study were applied at a sub-lethal rate of 10% of their suggested use rate in Mississippi (Al-Khatib and Peterson 1999; Anonymous 2018) using a CO\(_2\)-pressurized backpack sprayer equipped with flat-fan nozzles (AIRMIX 11002, 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 NIS (Activator 90, 90% non-ionic surfactant, Loveland Products, P.O. Box 1286, Greeley, CO 80632) at 0.5% (v/v) and ammonium sulfate (AMS) water-conditioning agent (Class Act NG, 50% nitrogen fertilizer, WinField Solutions, P.O. Box 64589, St. Paul, MN 55164) at 2.5% (v/v). Rice in all studies was managed throughout the growing season to optimize yield (Buehring 2008).

**Carrier Volume Study**

The experimental design was a randomized block with four replications. Carrier volumes were decreased to 25 and 10% proportionally from a recommended carrier volume of 187 L ha\(^{-1}\) (Anonymous 2019). Paraquat concentrations were proportionally decreased to 25 and 10% of the 840 g ha\(^{-1}\) and applied in respective carrier volumes. Therefore, herbicide treatments were paraquat at 210 g ha\(^{-1}\) applied in 47 L ha\(^{-1}\) and paraquat at 84 g ha\(^{-1}\) applied in 19 L ha\(^{-1}\). Treatments were applied to rice during the three- to four-leaf (MPOST) growth stage using a CO\(_2\)-pressurized sprayer mounted on an all-terrain vehicle with speed adjusted to obtain targeted carrier volumes. A nontreated control was included for comparison.

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 upper most extended leaf and calculating the mean height of five randomly selected plants in each plot. Delay in rice maturity was calculated by subtracting time from seedling emergence until 50% of rice plants in an individual plot had visible panicles in treated plots from the nontreated. A randomly selected area measuring 1 m was hand-harvested 21 DAT 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, weighed to determine rice dry weight, and weights were converted to g m⁻². Plant height and dry weight 21 DAT were converted to a percentage of the nontreated control in each replication. 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.

All data were subjected to ANOVA using the PROC MIXED procedure in SAS (Statistical software Release 9.3, SAS Institute, SAS Institute Inc., 100 SAS Campus Drive, Cary, NC 27513-2414) with siteyear and replication (nested within siteyear) as random effect parameters (Blouin et al. 2011). The nontreated control was removed for analyses of visible estimates of injury. Type III Statistics were used to test the fixed effects of paraquat treatment for rice injury, height, delay in rice maturity, and dry weight. Least square means were calculated and mean separation (p ≤ 0.05) was produced using PDMIX800 in SAS, which is a macro for converting mean separation output letter groupings (Saxton 1998).

**Paraquat, Fomesafen, and Metribuzin Mixture Study**

A study conducted from 2015 to 2017 in Stoneville, MS, to evaluate rice performance following exposure to a sub-lethal rate of paraquat applied alone or in mixture with sub-lethal concentration of metribuzin and fomesafen. Treatments were arranged as a two-factor factorial within a randomized complete block design and 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., 630 Freedom Business Center, Suite 402, King of Prussia, PA 19406) at 42 g ai ha⁻¹, and fomesafen (Reflex 2L, herbicide, Syngenta Crop Protection, P.O. Box 18300 Greensboro, NC 27409) at 39
Herbicide treatments were applied at the EPOST rice growth stage. Rice injury was evaluated 3, 14, and 28 DAT. Plant height and rice dry weight at maturity were collected as previously described. 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 and drying as previously described. The remaining area in each plot was 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% 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 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. Data were analyzed as previously described in the Carrier Volume Study.

**Residual Herbicide Mixture Study**

A study was conducted from 2015 to 2017 in Stoneville, MS, to evaluate rice performance following exposure to a sub-lethal rate of paraquat applied alone or in mixture with 10 PRE and POST residual herbicides commonly utilized in Mississippi (Anonymous 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 PRE and POST residual herbicides listed in Table 3.3. A nontreated control was included for comparison. Herbicide treatments were applied at the EPOST rice growth stage. Visible estimates of rice injury, rice density and height 14 DAT, and rice yield (rough, whole and total milled rice) were collected and analyzed based on the previously described scales and analyses.

**Results and Discussion**

**Carrier Volume Study**

At all evaluations, rice injury with the greater paraquat rate and carrier volume was at least 10% greater than the lower rate and volume (Table 3.4). At 3, 21, and 28 DAT, rice injury decreased 19% when paraquat rate and carrier volume were reduced from 25 to 10%. Rice height 14 DAT, dry weight 21 DAT, and delay in maturity were affected by proportional changes in carrier volume and paraquat rate. Rice height was 58% of the nontreated control following paraquat at 25% of the recommended use rate and carrier volume; however, at 10% carrier volume and paraquat rate, rice height was 66% of the nontreated control. Delay in rice maturity was 12 d following paraquat applied at 10% of the recommended use rate in a proportionally reduced carrier volume compared with 16 d with paraquat applied at 25% the recommended use rate in a proportional 25% carrier volume. A similar trend was observed for dry weight 21 DAT (Table 3.4).

In the current research, rice injury, plant height, dry weight, and delays in maturity following simulated off-target paraquat applications were decreased when carrier volume and/or paraquat rate decreased. Banks and Schroeder (2002) reported similar findings with simulated off-target applications of 2,4-D on cotton and concluded that injury decreased as carrier volume

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and 2,4-D rate decreased proportionally. Rice dry weight was different between carrier volumes. Banks and Schroeder (2002) observed less reduction in sweet corn fresh weights and marketable ears as carrier volume and glyphosate rates decreased.

Although paraquat is a contact herbicide, its effect on rice was similar to that reported for systemic herbicides applied to sweet corn and cotton in proportional carrier volumes (Banks and Schroeder 2002). Rice injury from paraquat was less severe as carrier volume decreased with a proportional paraquat rate; however, simulated off-target applications of paraquat at any carrier volume injured rice, reduced plant height, delayed maturity, and reduced dry weight.

**Paraquat, Fomesafen, and Metribuzin Mixture Study.**

With the exception of the 3 DAT evaluation, rice injury was greater with paraquat plus metribuzin than all other treatments imposed in the study (Table 3.5). Metribuzin and fomesafen applied alone injured rice 11 to 13% 3 DAT (Table 3.5). 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 ≤10% 14 and 28 DAT, and the greatest rice injury 14 and 28 DAT occurred with paraquat plus metribuzin (Table 3.5). Bond et al. (2015) reported rice injury from fomesafen applied at 25% of the recommended rate was ≤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 3.5).

Related research suggests this level of injury from paraquat alone at 84 g ha⁻¹ during the two-to three-leaf rice growth stage is not uncommon (Lawrence et al. 2017). Similar increases in crop 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.

An interaction between paraquat and companion herbicide was detected for rice density 14 DAT (Table 3.5). Rice density ranged from 276 to 282 m$^{-2}$ for all treatments with no paraquat (Table 3.5). 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 3.5). Similarly, 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 3.5).

A main effect of paraquat rate was detected for rice height 14 DAT, d to 50% heading, dry weight at maturity, and total and whole milled rice yield (Table 3.6). Averaged across three companion herbicide treatments, rice height 14 DAT was reduced 54%, maturity delayed 10 d, and dry weight reduced 17% following paraquat (Table 3.6). Similar reductions in rice plant height and increased d to 50% heading following rice exposure to a sub-lethal rate 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 3.6). However, following exposure to paraquat, total and whole milled rice yield was reduced to 67 and 56%, respectively (Table 3.6).

An interaction of paraquat rate and companion herbicide treatment was detected for rough rice yield. No differences in rough rice yield were observed among treatments that did not include paraquat (Table 3.5). Sperry et al. (2019) concluded that although visual injury was observed following corn exposure to a sub-lethal rate of fomesafen, corn yield was unaffected. However, rough rice yield was reduced 23% following paraquat at 84 g ha\(^{-1}\) compared with yield of rice not exposed to paraquat or the companion herbicide treatments (Table 3.5).

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 comparable following paraquat alone and paraquat plus fomesafen (Table 3.5). 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 3.5).

Previous research evaluating whether altering N fertilizer aids in rice recovery from exposure to a sub-lethal rate of paraquat indicated 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 applications of paraquat with \(s\)-metolachlor plus mesotrione plus atrazine, and this level of injury was comparable to fluometuron (59%), sulfentrazone plus metribuzin (61%), and \(s\)-metolachlor plus metribuzin (62%). 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 ≥98% for mesotrione plus with atrazine at 280 g ha\(^{-1}\). At 14 DAT, injury from *s*-metolachlor plus mesotrione plus atrazine was comparable to that with sulfentrazone plus metribuzin (62%), sulfentrazone plus metribuzin (62%), and fluometuron (59%). 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 3.7).

Rice injury 28 DAT was 73% following exposure to *s*-metolachlor plus mesotrione plus atrazine (Table 3.7). *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 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 3.7). Armel et al. (2009) reported 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.

Rice height and density 14 DAT and rough rice yield were reduced with all treatments compared with the nontreated control (Table 3.7). 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 3.7).

Rough rice yield was 5,000 to 6,290 kg ha⁻¹ for all treated plots, and these were all lower than in the nontreated where rough rice yield was 8,070 kg ha⁻¹ (Table 3.7). Sperry et al. (2019) reported paraquat at 105 g ha⁻¹ reduced corn yield 0.5% daily if exposure occurred during vegetative growth. Therefore, it is plausible to expect greater reductions in rice yield as multiple MOA are added to herbicide mixtures containing paraquat. Previous research confirmed increased levels of weed control when a 4-hydroxyphenylpyruvate dioxygenase (HPPD) and/or PSII-inhibiting herbicide 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 fluometuron (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 thiencarbazone-methyl plus isoxaflutole (5,550 kg ha\(^{-1}\)). Rough rice yield reductions following sulfentrazone plus cloransulam-methyl was 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 thiencarbazone-methyl plus isoxaflutole (5,550 kg ha\(^{-1}\)).

Based on these data, negative effects on rice growth and devolvement can occur following exposure to a sub-lethal rate of paraquat applied alone or in mixture with common residual herbicides. The current research indicates that, although degrees of severity in rice injury vary across herbicide mixtures, rice exposed to paraquat alone or in combination with non-target 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 the addition of starter N or altering N fertilizer strategies did not aid rice recovery when observed injury levels were ≥56\%. These data indicate that additional herbicide MOA can affect rice injury and rough rice yield losses. Due to the level of rice injury from paraquat alone, diagnosing symptoms of individual herbicide MOA that may have been in mixture with paraquat
would be challenging. In instances of off-target herbicide movement, herbicide concentrations and MOA are rarely known. Therefore, in instances conducive for off-target herbicide movement, caution should be exercised when making applications adjacent to fields devoted to rice production.
Table 3.1  Coordinates, soil series, soil description, previous crops, soil pH, and soil organic matter (OM) for the Carrier Volume Study in Stoneville, MS, from 2016 to 2017.

<table>
<thead>
<tr>
<th>Siteyear</th>
<th>Coordinates</th>
<th>Soil series</th>
<th>Soil description</th>
<th>Previous crop rotation</th>
<th>pH</th>
<th>OM</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>33°24'23.09&quot;N, 90°56'8.88&quot;W</td>
<td>Commerce silty clay loam</td>
<td>Fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts</td>
<td>Soybean:rice</td>
<td>7.1</td>
<td>2.1</td>
</tr>
<tr>
<td>2017A</td>
<td>33°26'26.32&quot;N, 90°54'11.82&quot;W</td>
<td>Sharkey very-fine clay</td>
<td>Very-fine, smectitic, thermic Chromic Epiaquerts</td>
<td>Rice:fallow</td>
<td>7.8</td>
<td>2.4</td>
</tr>
<tr>
<td>2017B</td>
<td>33°26'19.03&quot;N, 90°54'25.06&quot;W</td>
<td>Commerce silty clay loam</td>
<td>Fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts</td>
<td>Soybean:rice</td>
<td>7.1</td>
<td>1.7</td>
</tr>
</tbody>
</table>
Table 3.2  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.

<table>
<thead>
<tr>
<th>Siteyear</th>
<th>Coordinates</th>
<th>Soil series</th>
<th>Soil description</th>
<th>Previous crop</th>
<th>pH</th>
<th>OM</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>33°26'26.57&quot;N, 90°54'11.92&quot;W</td>
<td>Sharkey very-fine clay</td>
<td>Very-fine, smectitic, thermic Chromic Epiaquerts</td>
<td>Rice:fallow</td>
<td>7.8</td>
<td>2.4</td>
</tr>
<tr>
<td>2016A</td>
<td>33°26'34.25&quot;N, 90°54'12.07&quot;W</td>
<td>Sharkey very-fine clay</td>
<td>Very-fine, smectitic, thermic Chromic Epiaquerts</td>
<td>Rice:fallow</td>
<td>8.2</td>
<td>2.2</td>
</tr>
<tr>
<td>2016B</td>
<td>33°24'23.09&quot;N, 90°56'8.88&quot;W</td>
<td>Sharkey very-fine clay</td>
<td>Very-fine, smectitic, thermic Chromic Epiaquerts</td>
<td>Soybean:rice</td>
<td>8.1</td>
<td>2.1</td>
</tr>
<tr>
<td>2017A</td>
<td>33°26'26.32&quot;N, 90°54'11.82&quot;W</td>
<td>Sharkey very-fine clay</td>
<td>Very-fine, smectitic, thermic Chromic Epiaquerts</td>
<td>Rice:fallow</td>
<td>7.8</td>
<td>2.4</td>
</tr>
<tr>
<td>2017B</td>
<td>33°26'19.03&quot;N, 90°54'25.06&quot;W</td>
<td>Commerce silty clay loam</td>
<td>Fine-silty, mixed, superactive, nonacid,thermic Fluvaquentic Endoaquepts</td>
<td>Soybean:rice</td>
<td>7.1</td>
<td>1.7</td>
</tr>
</tbody>
</table>
Table 3.3  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.

<table>
<thead>
<tr>
<th>Common name</th>
<th>Rate</th>
<th>Trade name</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paraquat</td>
<td>84</td>
<td>Gramoxone SL 2.0</td>
<td>Syngenta Crop Protection, P.O. Box 18300</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Greensboro, NC 27409</td>
</tr>
<tr>
<td>Sulfentrazone plus metribuzin</td>
<td>23 plus 34</td>
<td>Authority MTZ 45 DF</td>
<td>FMC Corporation, 1735 Market St.,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Philadelphia, PA 19103</td>
</tr>
<tr>
<td>S-metolachlor plus metribuzin</td>
<td>183 plus 43</td>
<td>Boundary 6.5 EC</td>
<td>Syngenta Crop Protection, P.O. Box 18300</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Greensboro, NC 27409</td>
</tr>
<tr>
<td>S-metolachlor plus fomesafen</td>
<td>120 plus 26</td>
<td>Prefix 5.29 EC</td>
<td>Syngenta Crop Protection, P.O. Box 18300</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Greensboro, NC 27409</td>
</tr>
<tr>
<td>Sulfentrazone plus cloransulam-methyl</td>
<td>28 plus 3.5</td>
<td>Sonic 70 DF</td>
<td>Dow AgroSciences, 9330 Zion Rd.,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Indianapolis, IN 46268</td>
</tr>
<tr>
<td>Flumioxazin plus pyroxasulfone</td>
<td>8.6 plus 11</td>
<td>Fierce 76 DG</td>
<td>Valent U.S.A, P.O. Box 8025, Walnut Creek,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>CA 94596</td>
</tr>
</tbody>
</table>
Table 3.3 (continued)

<table>
<thead>
<tr>
<th>Herbicide Combination</th>
<th>Rate (g/L)</th>
<th>Product Name</th>
<th>Company Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorimuron-ethyl plus flumioxazin plus thifensulfuron-methyl</td>
<td>2.55 plus 8 plus 0.77</td>
<td>Envive 41.3 DG</td>
<td>DuPont, 1007 North Market St., Wilmington, DE 19898</td>
</tr>
<tr>
<td>Metribuzin plus chlorimuron</td>
<td>27 plus 45</td>
<td>Canopy 75 DF</td>
<td>DuPont, 1007 North Market St., Wilmington, DE 19898</td>
</tr>
<tr>
<td>S-metolachlor plus mesotrione plus atrazine</td>
<td>145 plus 19 plus 145</td>
<td>Lexar EZ 3.7 EC</td>
<td>Syngenta Crop Protection, P.O. Box 18300 Greensboro, NC 27409</td>
</tr>
<tr>
<td>Thiencarbazone-methyl plus isoxaflutole</td>
<td>3.5 plus 9.1</td>
<td>Corvus 2.63 EC</td>
<td>Bayer CropScience, 2 T.W. Alexander Dr., Research Triangle Park, NC 27709</td>
</tr>
<tr>
<td>Fluometuron</td>
<td>111</td>
<td>Cotoran 4 L</td>
<td>DuPont, 1007 North Market St., Wilmington, DE 19898</td>
</tr>
</tbody>
</table>
Table 3.4  Rice injury 3, 21, and 28 d after treatment (DAT), height 14 DAT and dry weight 21 DAT expressed as a percentage of the nontreated control and delay in maturity in the Carrier Volume Study at Stoneville, MS, from 2016 to 2017\textsuperscript{a}.

<table>
<thead>
<tr>
<th>Carrier volume</th>
<th>Paraquat rate</th>
<th>3 DAT</th>
<th>21 DAT</th>
<th>28 DAT</th>
<th>Height</th>
<th>Dry weight</th>
<th>Maturity delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>L ha\textsuperscript{-1} g ai ha\textsuperscript{-1}</td>
<td></td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>d</td>
</tr>
<tr>
<td>47</td>
<td>210</td>
<td>59 a</td>
<td>61 a</td>
<td>69 a</td>
<td>58 a</td>
<td>31 b</td>
<td>16 a</td>
</tr>
<tr>
<td>19</td>
<td>84</td>
<td>40 b</td>
<td>48 b</td>
<td>59 b</td>
<td>66 b</td>
<td>44 a</td>
<td>12 b</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Data were pooled over three siteyears. Means followed by the same letter for each parameter are not different at \( p \leq 0.05 \).
Table 3.5  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\textsuperscript{a,b}.

<table>
<thead>
<tr>
<th>Paraquat rate</th>
<th>Companion herbicide treatment\textsuperscript{c}</th>
<th>Injury</th>
<th>Density</th>
<th>Rough rice yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>g ai ha\textsuperscript{-1}</td>
<td></td>
<td>3 DAT</td>
<td>14 DAT</td>
<td>28 DAT</td>
</tr>
<tr>
<td>0</td>
<td>No companion herbicide</td>
<td>0 d</td>
<td>0 d</td>
<td>0 d</td>
</tr>
<tr>
<td></td>
<td>Metribuzin</td>
<td>11 c</td>
<td>10 c</td>
<td>8 c</td>
</tr>
<tr>
<td></td>
<td>Fomesafen</td>
<td>13 c</td>
<td>8 c</td>
<td>6 c</td>
</tr>
<tr>
<td>84</td>
<td>No companion herbicide</td>
<td>42 b</td>
<td>54 b</td>
<td>56 b</td>
</tr>
<tr>
<td></td>
<td>Metribuzin</td>
<td>50 a</td>
<td>68 a</td>
<td>69 a</td>
</tr>
<tr>
<td></td>
<td>Fomesafen</td>
<td>46 a</td>
<td>55 b</td>
<td>58 b</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Data were pooled over five siteyears. Means followed by the same letter for each parameter are not different at p ≤ 0.05.

\textsuperscript{b}Herbicide treatments were applied to rice in the two- to three-leaf (EPOST) growth stage

\textsuperscript{c}Metribuzin was applied at 0 and 42 g ai ha\textsuperscript{-1}, and fomesafen was applied at 0 and 39 g ai ha\textsuperscript{-1}. 

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Table 3.6  Influence of paraquat rate on rice plant height 14 d after treatment (DAT), d to 50% heading expressed as d 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 2017a.

<table>
<thead>
<tr>
<th>Treatmentb</th>
<th>Height</th>
<th>D to 50% heading</th>
<th>Dry weight</th>
<th>Total milled</th>
<th>Whole milled</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>cm</td>
<td>DAE</td>
<td>g m⁻²</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>No paraquat</td>
<td>22 a</td>
<td>84 b</td>
<td>1,840 a</td>
<td>70 a</td>
<td>60 a</td>
</tr>
<tr>
<td>Paraquat</td>
<td>12 b</td>
<td>93 a</td>
<td>1,520 b</td>
<td>67 b</td>
<td>56 b</td>
</tr>
</tbody>
</table>

aData were pooled over two concentrations of metribuzin (0 and 42 g ai ha⁻¹), two concentrations of fomesafen (0 and 39 g ai ha⁻¹), and five siteyears for rice plant height and d to 50% heading, and six siteyears 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 ≤ 0.05.
bParaquat was applied at 0 and 84 g ai ha⁻¹.
Table 3.7  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 2017a.

<table>
<thead>
<tr>
<th>Treatment b,c</th>
<th>3 DAT</th>
<th>14 DAT</th>
<th>28 DAT</th>
<th>Height</th>
<th>Density</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td>cm</td>
<td>no. m²</td>
<td>kg ha⁻¹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nontreated</td>
<td>-</td>
<td>22 a</td>
<td>365 a</td>
<td>8,070 a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No mixture</td>
<td>40 de</td>
<td>49 de</td>
<td>56 de</td>
<td>13 b</td>
<td>312 bcd</td>
<td>6,080 bc</td>
</tr>
<tr>
<td>Sulfentrazone plus metribuzin</td>
<td>50 ab</td>
<td>61 ab</td>
<td>65 b</td>
<td>12 bc</td>
<td>288 cde</td>
<td>5,220 cd</td>
</tr>
<tr>
<td>S-metolachlor plus metribuzin</td>
<td>52 a</td>
<td>62 ab</td>
<td>65 b</td>
<td>11 c</td>
<td>287 cde</td>
<td>5,100 d</td>
</tr>
<tr>
<td>S-metolachlor plus fomesafen</td>
<td>39 de</td>
<td>47 e</td>
<td>51 e</td>
<td>13 b</td>
<td>334 ab</td>
<td>6,090 bc</td>
</tr>
<tr>
<td>Sulfentrazone plus cloransulam-methyl</td>
<td>42 cd</td>
<td>51 cd</td>
<td>58 de</td>
<td>11 c</td>
<td>294 cde</td>
<td>6,290 b</td>
</tr>
<tr>
<td>Flumioxazin plus pyroxasulfone</td>
<td>40 de</td>
<td>48 de</td>
<td>51 e</td>
<td>12 bc</td>
<td>323 bc</td>
<td>6,190 b</td>
</tr>
<tr>
<td>Chlorimuron-ethyl plus flumioxazin plus thifensulfuron-methyl</td>
<td>42 cd</td>
<td>53 cd</td>
<td>60 bcd</td>
<td>12 bc</td>
<td>299 bcd</td>
<td>6,290 b</td>
</tr>
<tr>
<td>Metribuzin plus chlorimuron plus atrazine</td>
<td>42 cd</td>
<td>55 bc</td>
<td>64 bc</td>
<td>13 b</td>
<td>322 bc</td>
<td>5,150 d</td>
</tr>
<tr>
<td>S-metolachlor plus mesotrione plus atrazine</td>
<td>46 bc</td>
<td>64 a</td>
<td>73 a</td>
<td>12 bc</td>
<td>262 e</td>
<td>5,000 d</td>
</tr>
<tr>
<td>Thiencarbazone-methyl plus isoxaflutole</td>
<td>37 e</td>
<td>52 cd</td>
<td>63 bc</td>
<td>12 bc</td>
<td>309 bcd</td>
<td>5,550 bcd</td>
</tr>
<tr>
<td>Fluometuron</td>
<td>46 bc</td>
<td>59 abc</td>
<td>63 bc</td>
<td>12 bc</td>
<td>282 de</td>
<td>5050 d</td>
</tr>
</tbody>
</table>

aData were pooled over five siteyears. Means followed by the same letter for each parameter are not different at p ≤ 0.05.
bAll treatments contained paraquat at 84 g ai ha⁻¹.
cAll herbicides were applied at 10% of the recommended use rate in Mississippi.
Literature Cited


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 (2018) 2019 Weed management suggestions for Mississippi row crops. Pages 19-23 in Bond JA. (ed.), Mississippi State Univ Ext Ser and Miss Agric and For Exp Stn Mississippi State, MS Pub 3171


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


Kurtz ME, Street JE (2003) Response of rice (Oryza sativa) to glyphosate applied to simulate drift. Weed Technol 17:234-238


Owen MDK (2000) Current use of transgenic herbicide-resistant soybean and corn in the USA Crop Prot 19:765-771


CHAPTER IV
NITORGEN FERTILIZER PROGRAMS FOLLOWING RICE (ORYZA SATIVA) EXPOSURE TO A SUB-LETHAL CONCENTRATION OF PARAQUAT

Abstract

Off-target paraquat movement to rice has become a major issue in recent years for rice producers in the midsouthern U.S. Nitrogen (N) fertilizer is applied to rice in greater quantity and frequency than all other nutrients to optimize rice yield. Two separate field studies were conducted from 2015 to 2018 in Stoneville, MS, to assess whether starter N fertilizer can aid rice recovery from exposure to a sub-lethal rate of paraquat and to evaluate rice response to different N fertilizer management strategies following exposure to a sub-lethal rate of paraquat. In both studies, paraquat treatments consisted of paraquat at 0 and 84 g ai ha\(^{-1}\) applied to rice in the two- to three-leaf (EPOST) growth stage. In the Starter Fertilizer Study, N fertilizer at 24 kg ha\(^{-1}\) as ammonium sulfate (AMS) was applied to rice at different growth stages before and after paraquat treatment. In the N Fertilizer Timing Study, N fertilizer at 168 kg N ha\(^{-1}\) was applied in a single LPOST application or two-, three-, and two four-way split applications. In spite of starter N fertilizer applications, paraquat injured rice ≥41%, reduced height 57%, reduced dry weight prior to flooding 77%, delayed maturity 10 d, reduced dry weight at maturity 33%, and reduced rough rice yield 35% in the Starter Fertilizer Study. Similarly, in the N Fertilizer Timing Study, paraquat injured rice ≥45%, reduced height 14%, delayed maturity 10 d, reduced dry weight at maturity 44%, and reduced rough rice yield 50% for all N fertilizer management
strategies. Both studies indicate severe rice growth and development issues can occur from rice exposure to a sub-lethal rate of paraquat. In both studies, manipulation of N fertilizer management did not facilitate rice recovery from early-season exposure to paraquat.

**Nomenclature:** Rice (*Oryza sativa* L.); paraquat 1,1’-dimethyl-4,4’-bipyridinium ion

**Key words:** Ammonium sulfate; nitrogen management; off-target; starter fertilizer; urea

**Introduction**

Rice production in Mississippi is concentrated in the alluvial floodplain of the Mississippi and Yazoo rivers, which is referred to as the Mississippi Delta, due to the clay-textured soils, environment, and water availability in the area (Buehring 2008; Miller and Street 2008). Bolivar, Sunflower, Tunica, Quitman, and Washington counties are primary rice-producing counties in Mississippi (USDA-NASS 2018). Mississippi rice producers harvested 56,275 ha\(^{-1}\) in 2018, which is small compared with other commodities such as soybean [*Glycine max* (L.) Merr.] (USDA-NASS 2018). However, the primary rice-producing counties planted 68% of Mississippi rice hectarage (USDA-NASS 2018). In Mississippi, rice is ideally seeded in a direct-seeded, delayed-flood production system between April 1 and May 20 when the average air and/or soil temperatures are ≥15 C (Buehring et al. 2008; Street and Bollich 2003). Rice produced in the direct-seeded, delayed-flood system is drill-seeded and managed as an upland crop until flood establishment 21 to 28 d after emergence (DAE) (Harrell and Saichuk 2014a; Street and Bollich 2003).

Nitrogen (N) fertilizer is applied to rice in greater quantity and frequency than all other nutrients to optimize yield (Norman et al. 2003). Following N fertilizer application, immediate flooding is recommended to incorporate fertilizer into the soil to minimize ammonia volatilization losses (Griggs et al. 2007; Norman et al. 2009, 2013). The most common source of
N fertilizer utilized in direct-seeded, delayed-flood rice production is urea (Norman et al. 2009). Proper N fertilizer application timing is crucial to maximize rice N use efficiency (Norman et al. 2009, 2013). Nitrogen is stored in stems and leaves of rice plants until prepared for transport during grain filling, making proper N fertilizer management prior to flooding crucial for maximizing yield (Bufogle et al. 1997a; Guindo et al. 1994; Norman et al. 2013). A single N fertilizer application just prior to flooding is optimum for maximum N use efficiency by rice (Norman et al. 2009, 2013). Rice is capable of utilizing up to 75% of the total N fertilizer applied if incorporated properly prior to flooding (Dillon et al. 2012; Norman et al. 2003; Wilson Jr., et al. 1998). Depending on rice cultivar, between 123 and 168 kg N ha\(^{-1}\) are applied during the growing season (Norman et al. 2013). Maintenance of flood for at least 3 wk following N fertilizer application is required for maximum N uptake from preflood N fertilizer applications (Norman et al. 1992, 2013; Wilson Jr. et al. 1989). Therefore, in fields with limited irrigation availability and lengthy flood establishment period, a two-way split N fertilizer application is recommended to minimize N losses (Norman et al. 2013). The two-way split N fertilizer application involves applying 70% of total N fertilizer prior to flooding with the remaining 30% applied during early reproductive development (Bollich et al. 1994; Norman et al. 2013; Wilson Jr., et al. 1998).

Rice can undergo numerous early-season environmental stresses, including animal and insect feeding, sub-optimal temperatures, and herbicide drift (Walker et al. 2008a). A common N fertilizer management practice is to apply starter N fertilizer as ammonium sulfate (AMS) at 24 kg N ha\(^{-1}\) to support stressed rice (Walker et al. 2008a). Starter N fertilizer applied during early vegetative growth stages has been reported to increase yield in corn (\textit{Zea mays} L.), cotton (\textit{Gossypium hirsutum} L.), grain sorghum [\textit{Sorghum bicolor} (L.) Moench], rice, and soybean
Walker et al. (2008a) reported starter N fertilizer applied to two-leaf rice not only increased grain yield but also early-season plant height compared to a control receiving no starter N fertilizer. Increased early-season rice plant height can assist crop management by allowing earlier flood establishment, thereby potentially reducing herbicide applications (Walker et al. 2008a).

Glyphosate-resistant (GR) corn, cotton, and soybean cropping systems revolutionized weed control after their introduction two decades ago (Edwards 2013; Owen 2000). However, since the commercialization of GR cropping technologies, GR weed biotypes have evolved rapidly (Heap 2019). Palmer amaranth [Amaranthus palmeri (S.) Wats] is the most troublesome weed in corn, cotton, and soybean due to its evolution of resistance to multiple herbicide modes of action (MOA), prolific seed production, and genetic diversity (Ward et al. 2013; Webster 2013). Research has demonstrated 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 (Anonymous 2018). These PRE herbicide applications for GR weed control in corn, cotton, and soybean often include paraquat at 840 g ha\(^{-1}\) to control emerged weeds in a GR cropping system (Anonymous 2018).

Paraquat applications are labeled preplant, PRE, or post-directed in corn, cotton, grain sorghum, peanut (Arachis hypogaea L.), soybean, and numerous vegetable and fruit crops for nonselective weed control (Anonymous 2019; Shaner 2014). However, paraquat is only labeled preplant or PRE in rice (Anonymous 2018, 2019). Row crop producers in Mississippi have widely adopted the use of paraquat prior to planting to minimize GR weed interference with
crops (Anonymous 2018). Due to Mississippi’s diverse cropping systems, incidents of off-target movement of paraquat from fields adjacent to rice are common.

Rice is sensitive to off-target herbicide movement; 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). When applied to non-Clearfield® rice, imazethapyr at 8.7 g ai ha\(^{-1}\) to one-tiller rice and 4.4 g ha\(^{-1}\) to rice at panicle differentiation reduced yield 59 to 75% of the nontreated (Hensley et al. 2012). When an imazethapyr plus imazapyr premix was applied at 7.9 g ai ha\(^{-1}\) to non-Clearfield® rice at the two- to three-leaf growth stage, plant heights were reduced 12% and injury was 19% 28 DAT (Bond et al. 2006). Non-Clearfield® rice yield was reduced 39% following imazethapyr plus imazapyr premix applied at 7.9 g ha\(^{-1}\) during panicle differentiation (Bond et al. 2006). Imazamox applied at 2.7 and 5.5 g ha\(^{-1}\) injured non-Clearfield® rice ≥20% regardless of rate 28 DA-PT (Webster et al. 2016). Total rice crop yield following imazamox applied at 2.7 g ha\(^{-1}\) to one-tiller and prior to panicle exertion (booting) rice was reduced to 72 and 60% of the nontreated, respectively (Webster et al. 2016).

In Mississippi, rice seeding dates often coincide with preplant and/or PRE herbicide applications to corn, cotton, and soybean (Buehring 2008). In these systems, paraquat applied in mixture with residual herbicides prior to crop emergence offers an alternative MOA to aid in GR weed management (Anonymous 2018). Visual injury symptoms from off-target herbicide movement may vary based on herbicide MOA and may not always be indicative of total damage to rice growth and development (Davis et al. 2011; Ellis et al. 2003; Kurtz and Street 2003). Extensive university research has documented the effects on rice growth and development of glyphosate, glufosinate, and ALS-inhibiting herbicides applied at reduced 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 sub-lethal rate of paraquat and if altering N fertilizer strategies might reduce problems associated with paraquat injury. Therefore, research was conducted to evaluate (1) whether starter N fertilizer can aid in rice recovery from exposure to a sub-lethal rate of paraquat and (2) rice response to different N fertilizer management strategies following exposure to a sub-lethal rate of paraquat.

Materials and Methods

Two studies were conducted from 2015 to 2018 at the Mississippi State University Delta Research and Extension Center in Stoneville, MS, to evaluate starter N fertilizer applications or altering N fertilizer strategies following exposure to a sub-lethal rate of paraquat. Global positioning system coordinates, soil series, soil description, previous crop rotation, soil pH, and soil organic matter (OM) for all studies are listed in Table 4.1.

Glyphosate (Roundup PowerMax 4.5 L, 1,120 g ae ha\(^{-1}\), Monsanto Company, 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 ae ha\(^{-1}\), Agri Star, 1525 NE 36th St., Ankeny, IA 50021) were applied in late-March to early-April each site-year to control emerged vegetation. Clomazone (Command 3 ME, 498 g ha\(^{-1}\), FMC Corporation, 1735 Market St., Philadelphia, PA 19103) plus saflufenacil (Sharpen 2.85 SC, 4.5 g 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 ha\(^{-1}\), Bayer CropScience, 2 T.W. Alexander Dr., Research Triangle Park, NC 27709) and quinclorac (Facet 1.50 SL, 375 g ha\(^{-1}\), BASF Crop Protection, 26 Davis Dr., Research Triangle Park, NC, 27709) plus halosulfuron ( Permit 75 DF, 12 g 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% (v/v) 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 May 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 siteyears. 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 buffer plots 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. Paraquat was applied using a CO₂-pressurized backpack sprayer equipped with flat-fan nozzles (AM11002 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 NIS (Activator 90, 90% non-ionic surfactant, Loveland Products, P.O. Box 1286, Greeley, CO 80632) at 0.5% v/v and ammonium sulfate (AMS) water-conditioning agent (Class Act NG, 50% nitrogen fertilizer, WinField Solutions, P.O. Box 64589, St. Paul, MN 55164) at 2.5% v/v. Rice in all studies was managed throughout the growing season to optimize yield (Buehring 2008).

All studies 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 weights 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.

**Starter N Fertilizer Study:**

A study was conducted at Mississippi State University Delta Research and Extension Center in Stoneville, MS, to assess whether starter N fertilizer as AMS promoted rice recovery from exposure to a sub-lethal rate of paraquat. Treatments were arranged as a two-factor factorial within a randomized complete block design and four replications. Factor A was paraquat treatment and consisted of paraquat at 0 and 84 g ha\(^{-1}\) applied EPOST. Paraquat treatments were applied at a sub-lethal rate of 10% of their suggested use rate in Mississippi (Al-Khatib and Peterson 1999; Anonymous 2018). Factor B was starter N fertilizer timing and consisted of no starter N fertilizer and starter N fertilizer at 24 kg ha\(^{-1}\) as AMS [AGRI-AFC LLC, ammonium sulfate (AMS 21-00-00-24S), 310 E. Railroad Ave. N., Magnolia, MS 39652] applied to rice in the spiking to one-leaf rice (VEPOST), EPOST, and MPOST stages. Nitrogen fertilizer was applied at 168 kg N ha\(^{-1}\) as urea (46-0-0) to all plots in the study immediately prior to flooding (Norman et al. 2013).

Visible estimates of aboveground rice injury were recorded 3, 14, and 21 d after paraquat treatment (DA-PT) on a scale of 0 to 100% where 0 indicated no visual effect from herbicide and 100 indicated complete plant death. Plant heights were determined 14 DA-PT 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. Rice dry weight was determined prior to flooding by hand-harvesting a randomly selected area measuring 1 m from rows 2 or 7 in each plot to
determine starter N fertilizer effect prior to preflood N fertilizer application. The number of d 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. Additionally, 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. The remaining area in each plot was harvested with a small-plot combine to determine yield (rough, whole, and total milled rice) after all subsamples had been collected. Hand-harvested samples were greenhouse dried at 32 to 49 (± 5) C for 2 wk, weighed to determine rice dry weight, and weights were converted to g m$^{-2}$.

Arcsine transformations of the square roots of visible injury estimates were performed to improve homogeneity of variances. Transformed data were subjected to analysis of variance (ANOVA) using the PROC MIXED procedure in SAS v. 9.4 (Statistical software Release 9.4, SAS Institute, SAS Institute Inc., 100 SAS Campus Drive, Cary, NC 27513-2414) with siteyear and replication (nested within siteyear) as random effect parameters (Blouin et al. 2011). Type III Statistics were used to test the fixed effects of paraquat and starter N fertilizer timing on rice injury, plant height 14 DA-PT, d to 50% heading, rice dry weight prior to flooding and at maturity, and yield (rough, whole, and total milled rice). Least-square means were calculated and mean separation (p ≤ 0.05) was produced using PDMIX800 in SAS, which is a macro for converting mean separation output letter groupings (Saxton 1998). Non-transformed data are presented for clarity.

**Nitrogen Fertilizer Timing Study:**

A study was conducted at Mississippi State University Delta Research and Extension Center in Stoneville, MS, to evaluate rice response to different N fertilizer application timings
following exposure to a sub-lethal rate of paraquat. Treatments were arranged as a two-factor factorial within a randomized complete block design and four replications. Factor A was paraquat treatment and consisted of paraquat at 0 and 84 g ha⁻¹ applied EPOST. Paraquat treatments were applied at a sub-lethal rate of 10% of their suggested use rate in Mississippi (Al-Khatib and Peterson 1999; Anonymous 2018). Factor B was N fertilizer application timings and consisted of N fertilizer at 168 kg N ha⁻¹ as urea (46-00-00, SouthernGRO Fertilizer, J&J Bagging, Yazoo City, MS 39194) applied in a single application at four-leaf to one-tiller rice (LPOST); in two sequential applications of 112 and 56 kg N ha⁻¹ applied LPOST followed by (fb) panicle differentiation (PD); in three sequential application of 84, 42, and 42 kg N ha⁻¹ applied LPOST fb 14 d postflood (14 DPF) fb PD; in four sequential applications of 42, 42, 42, and 42 kg N ha⁻¹ applied LPOST fb 14 DPF fb PD fb 5% heading (5% HD). All N fertilizer was treated with a urease inhibitor (AGROTAIN Ultra, 1 Angelica Street, St. Louis, MO 63147) at 3.1 ml kg⁻¹ N fertilizer. Rice injury 3, 7, 14, 21 and 28 DA-PT, number of d to 50% heading, plant height at 50% heading, rice dry weight at maturity, and yield (rough, whole, and total milled rice) were collected and analyzed as previously described for the Starter N Fertilizer Study.

**Results and Discussion**

**Starter N Fertilizer Study:**

A main effect of paraquat treatment was significant for all parameters (Tables 4.2 and 4.3). Rice injury following exposure to a sub-lethal rate of paraquat ranged from 41 to 55% at all evaluations (Table 4.2). Rice dry weight prior to flooding was reduced from 106 to 24 g m⁻²
following exposure to paraquat (Table 4.3). Rice height was 16 cm following exposure to paraquat compared with 28 cm with no exposure to paraquat (Table 4.3). Averaged across six siteyears and four starter N fertilizer application timings, rice dry weight at maturity was reduced from 1,731 to 1,157 g m$^{-2}$, and rough rice yield was reduced from 8,400 to 5,490 kg ha$^{-1}$ following exposure to paraquat EPOST (Table 4.3). Walker et al. (2008a) reported N fertilizer applied prior to rice tillering, i.e. preflood application, influenced grain yield more than applications at any other time; however, when starter N fertilizer was applied to two-leaf rice, grain yield increased $\geq 200$ kg ha$^{-1}$ compared to where no starter N fertilizer was applied. In the current research, starter N fertilizer had no influence on rice growth, development, or yield following exposure to paraquat.

Regardless of starter N fertilizer applications, paraquat injured rice $\geq 41\%$, reduced rice height 57%, reduced dry weight prior to flooding 77%, delayed rice maturity 10 d, reduced dry weight at maturity 33%, and reduced rough rice yield 35% regardless of starter N fertilizer application timing (Tables 4.2 and 4.3). In the absence of a starter N fertilizer application, Lawrence et al. (2018) reported $\geq 6$ d delay in rice maturity and $\geq 28\%$ reduction in rough rice yield from exposure to a sub-lethal rate of paraquat at different growth stages. Results from the Starter N Fertilizer Study indicated that AMS applied before, at, or after exposure to a sub-lethal rate of paraquat did not aid in rice recovery from injury.

**Nitrogen Fertilizer Timing Study:**

A main effect of paraquat treatment was detected for rice injury 3, 14, and 21 DA-PT, rice height at 50% maturity, d to 50% heading, dry weight at maturity, rough and total milled rice yield (Tables 4.4 and 4.6). An interaction of paraquat treatment and N fertilizer timing was
detected for rice injury 7 and 28 DA-PT (Table 4.5). Additionally, a main effect of N fertilizer timing was detected for d to 50% heading and rough rice yield (Table 4.7).

Rice was injured 45 to 62% 3, 14, and 21 DA-PT following exposure to paraquat regardless of N fertilizer timing (Table 4.4). An interaction of paraquat treatment and N fertilizer timing was detected for rice injury 28 DA-PT (Table 4.5). Regardless of N fertilizer timing following rice exposure to paraquat, rice injury 28 DA-PT was ≥60%; however, the greatest rice injury (67%) was recorded in plots exposed to paraquat when 100% of N fertilizer was applied in a single LPOST application (Table 4.5). Similar levels of rice injury were previously reported following rice exposure to a sub-lethal rate of paraquat applied to rice EPOST (Lawrence et al. 2016). Lawrence et al. (2018) reported injury to rice with paraquat was ≥41% 14 and 28 DA-PT regardless of growth stage at time of paraquat exposure.

Paraquat reduced rice height from 108 to 93 cm, increased d to 50% heading 10 d, reduced dry weight at maturity from 1,800 to 1,000 g m⁻², total milled rice yield from 70 to 69 g, and rough rice yield from 7,930 to 4,430 kg ha⁻¹ (Table 4.6). A main effect of N fertilizer timing was detected for d to 50% heading and rough rice yield (Table 4.7). Rice maturity was 86 to 88 d regardless of N fertilizer timing; however, a timing with 100% of N fertilizer applied LPOST increased d to 50% heading more than when a split application was utilized (Table 4.7). Nitrogen fertilizer management strategies in which N fertilizer was applied at 42 kg N ha⁻¹ in four equal dosages at MPOST fb LPOST fb 14 DPF fb PD and LPOST fb14 DPF fb PD fb 5% HD timings increased d to 50% heading to 86 d compared with 88 d following 100% of N fertilizer being applied LPOST (Table 4.7). Rough rice yield was 6,300 kg ha⁻¹ when data were averaged across paraquat treatments and N fertilizer was applied at 42 kg N ha⁻¹ in four equal doses at MPOST fb LPOST fb 14 DPF fb PD; however, this N fertilizer management strategy
produced rough rice yield comparable to all single LPOST application, two-, and three-way split applications of N fertilizer (Table 4.7). Similarly, Bufogle Jr. (1997b) concluded that total N uptake was no different with split-midseason N applications compared with single preflood N fertilizer applications. Rogers et al. (2013) reported the greatest rice yield following 134 kg N ha\(^{-1}\) applied the day prior to flooding. Additionally, N uptake by rice was decreased as N fertilizer application timing was delayed greater than 1 d prior to flooding (Rogers et al. 2013). When pooled across rice cultivars, Bond and Bollich (2007) concluded the greatest rice yields occurred following 168 kg N ha\(^{-1}\) fertilizer applied immediately prior to flooding.

Rough rice yield were least (5,520 kg ha\(^{-1}\)) following N fertilizer applied at 42 kg N ha\(^{-1}\) in four equal doses at LPOST \(\pm\) 14 DPF \(\pm\) PD \(\pm\) 5% HD timings (Table 4.7). Bond and Bollich (2007) reported no interaction or main effect on rough rice yield of N fertilizer applied during rice panicle exertion (booting). Similarly, Walker et al. (2008b) reported no yield advantage from applying additional N fertilizer at panicle emergence compared with a single preflood N application containing season-long N requirement. In Mississippi, a four-way split N fertilizer strategy is commonly utilized for rice fertilization. However, current and previous research demonstrate all N fertilizer should be applied prior to rice panicle exertion (booting) regardless of N fertilizer timing (Bond and Bollich 2007; Walker et al. 2008b). Unfortunately, up to 10 d is often required for flood establishment in commercial rice fields due to N fertilizer application difficulty, water management complications, producer familiarity with N fertilizer management, field history of rice physiological disorders, and field moisture content (Harrell and Saichuk 2014b). In these instances, an N fertilizer management strategy that utilizes split N fertilizer applications is recommended to minimize N loss due to volatilization (Harrell and Saichuk 2014b).
Regardless of N fertilizer timing, paraquat injured rice ≥45%, reduced rice plant height 14%, increased d to 50% heading 10 d, reduced dry weight at maturity 44%, and reduced rough rice yield 50% regardless of N fertilizer management strategies (Tables 4.5, 4.6, and 4.7). Lawrence et al. (2018) reported rice yield as 20% of the nontreated control following exposure to paraquat during PD. Rice injury 7 and 28 DA-PT was influenced by N fertilizer timing following exposure to a sub-lethal rate of paraquat; however, rice injury was still ≥60% 28 DA-PT. Although an interaction between paraquat treatment and N fertilizer timing was detected for rice injury 7 and 28 DA-PT, N fertilizer timing following rice exposure to a sub-lethal rate of paraquat had no effect on rice height, d to 50% heading, dry weight, rough and total milled rice yield. Differences in rice yield were not observed due to N fertilizer timing following exposure to a sub-lethal rate of paraquat. Yield losses reduced due to paraquat was 50% regardless of N fertilizer timing. However, when data were averaged over paraquat treatments, N fertilizer management strategies utilizing all N prior to heading produced rough rice yield comparable to the other strategies, and rough rice yield was ≥6,120 kg ha⁻¹ (Table 4.7). Nitrogen fertilizer timing utilizing 25% of N fertilizer applied at 5% HD produced lower rough rice yield than all strategies except an N fertilizer timing utilizing 50% of N applied LPOST and 25% applied at both 14 DPF and PD. Both studies indicate severe rice growth and development issues can occur from rice exposure to a sub-lethal rate of paraquat. Additionally, rice was unable to overcome early-season exposure to paraquat. Adding starter N fertilizer or manipulating N fertilizer management timings did not aid rice recovery from early-season exposure to paraquat.
Table 4.1  Coordinates, soil series, soil description, previous crop rotation, soil pH, and soil organic matter (OM) in the Starter N Fertilizer Study and the Nitrogen Fertilizer Timing Study conducted from 2015 to 2018 at the Mississippi State University Delta Research and Extension Center in Stoneville, MS.

<table>
<thead>
<tr>
<th>Siteyear</th>
<th>Coordinates</th>
<th>Soil series</th>
<th>Description</th>
<th>Previous crop rotation</th>
<th>pH</th>
<th>OM</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>33.44°N, 90.90°W</td>
<td>Sharkey very-fine clay</td>
<td>Very-fine, smectitic, thermic Chromic Epiaquerts</td>
<td>Rice:fallow</td>
<td>7.8</td>
<td>2.4</td>
</tr>
<tr>
<td>2016A</td>
<td>33.41°N, 90.92°W</td>
<td>Sharkey very-fine clay</td>
<td>Very-fine, smectitic, thermic Chromic Epiaquerts</td>
<td>Rice:fallow</td>
<td>8.2</td>
<td>2.2</td>
</tr>
<tr>
<td>2016B</td>
<td>33.43°N, 90.93°W</td>
<td>Sharkey very-fine clay</td>
<td>Very-fine, smectitic, thermic Chromic Epiaquerts</td>
<td>Soybean:rice</td>
<td>8.1</td>
<td>2.1</td>
</tr>
<tr>
<td>2017A</td>
<td>33.44°N, 90.90°W</td>
<td>Sharkey very-fine clay</td>
<td>Very-fine, smectitic, thermic Chromic Epiaquerts</td>
<td>Rice:fallow</td>
<td>7.8</td>
<td>2.4</td>
</tr>
<tr>
<td>2017B</td>
<td>33.43°N, 90.90°W</td>
<td>Commerce silty clay loam</td>
<td>Fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquents</td>
<td>Soybean:rice</td>
<td>7.1</td>
<td>1.7</td>
</tr>
<tr>
<td>2018</td>
<td>33.42°N, 90.90°W</td>
<td>Bosket very fine sandy loam</td>
<td>Fine-loamy, mixed, active, thermic Molllic Hapludalfs</td>
<td>Rice:rice</td>
<td>7.9</td>
<td>1.2</td>
</tr>
</tbody>
</table>
Table 4.2  Main effect of paraquat treatment on rice injury 3, 14, and 21 d after paraquat treatment (DA-PT) in the Starter N Fertilizer Study conducted from 2015 to 2018 at Stoneville, MS\textsuperscript{a}.

<table>
<thead>
<tr>
<th>Treatment\textsuperscript{b}</th>
<th>3 DA-PT</th>
<th>14 DA-PT</th>
<th>21 DA-PT</th>
</tr>
</thead>
<tbody>
<tr>
<td>No paraquat</td>
<td>0 b</td>
<td>0 b</td>
<td>0 b</td>
</tr>
<tr>
<td>Paraquat</td>
<td>41 a</td>
<td>46 a</td>
<td>55 a</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Data were pooled over six siteyears and four starter N fertilizer application timings. Means followed by the same letter for each parameter are not different at p ≤ 0.05.

\textsuperscript{b}Paraquat treatments included paraquat at 0 and 84 g ai ha\textsuperscript{-1} applied to rice in the two- to three-leaf (EPOST) stage.
Table 4.3  Main effect of paraquat treatment on rice dry weight prior to flood, height 14 d after paraquat treatment (DA-PT), height, number of d to 50% heading expressed as d after emergence (DAE), dry weight at maturity, rough and total milled rice yields, and in the Starter N Fertilizer Study conducted from 2015 to 2018 at Stoneville, MS.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Dry weight prior to flood</th>
<th>Height</th>
<th>Days to 50% heading</th>
<th>Dry weight maturity</th>
<th>Rough rice yield</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g m$^{-2}$</td>
<td>cm</td>
<td>DAE</td>
<td>g m$^{-2}$</td>
<td>kg ha$^{-1}$</td>
</tr>
<tr>
<td>No paraquat</td>
<td>106 a</td>
<td>28 a</td>
<td>83 a</td>
<td>1,731 a</td>
<td>8,400 a</td>
</tr>
<tr>
<td>Paraquat</td>
<td>24 b</td>
<td>16 b</td>
<td>93 b</td>
<td>1,157 b</td>
<td>5,490 b</td>
</tr>
</tbody>
</table>

aData were pooled over four starter N fertilizer applications and five siteyears for dry weight at maturity, total milled rice yield, and rough rice yields or six siteyears for dry weight prior to flooding, height, and d to 50% heading.

Means followed by the same letter for each parameter are not different at p ≤ 0.05.

bParaquat treatments included paraquat at 0 and 84 g ai ha$^{-1}$ applied to rice in the two- to three-leaf (EPOST) stage.
Table 4.4  Main effect of paraquat treatment on rice injury 3, 14, and 21 d after paraquat treatment (DA-PT) in the Nitrogen Fertilizer Timing Study conducted from 2015 to 2018 at Stoneville, MS\textsuperscript{a}.

<table>
<thead>
<tr>
<th>Treatment\textsuperscript{b}</th>
<th>3 DA-PT</th>
<th>14 DA-PT</th>
<th>21 DA-PT</th>
</tr>
</thead>
<tbody>
<tr>
<td>No paraquat</td>
<td>0 b</td>
<td>0 b</td>
<td>0 b</td>
</tr>
<tr>
<td>Paraquat</td>
<td>45 a</td>
<td>50 a</td>
<td>62 a</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Data were pooled over six siteyears and five N fertilizer management strategies. Means followed by the same letter for each parameter are not different at \( p \leq 0.05 \).

\textsuperscript{b}Paraquat treatments included paraquat at 0 and 84 g ai ha\textsuperscript{-1} applied to rice in the two- to three-leaf (EPOST) stage.
Table 4.5 Interaction of paraquat treatment and N fertilizer timing on rice injury 7 and 28 d after paraquat treatment (DA-PT) in the Nitrogen Fertilizer Timing Study conducted from 2015 to 2018 at Stoneville, MSa.

<table>
<thead>
<tr>
<th>N fertilizer timingb</th>
<th>Rate</th>
<th>7 DA-PT</th>
<th>28 DA-PT</th>
<th>7 DA-PT</th>
<th>28 DA-PT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg N ha⁻¹</td>
<td>No paraquatc</td>
<td>Paraquatc</td>
<td>No paraquatc</td>
<td>Paraquatc</td>
</tr>
<tr>
<td>LPOST</td>
<td>168</td>
<td>0 c</td>
<td>48 a</td>
<td>0 c</td>
<td>67 a</td>
</tr>
<tr>
<td>LPOST fbPD</td>
<td>112 fb 56</td>
<td>0 c</td>
<td>47 a</td>
<td>0 c</td>
<td>63 b</td>
</tr>
<tr>
<td>LPOST fb14 DPF fbPD</td>
<td>84 fb 42 fb 42</td>
<td>0 c</td>
<td>48 a</td>
<td>0 c</td>
<td>63 b</td>
</tr>
<tr>
<td>MPOST fb LPOST fb14 DPF fbPD</td>
<td>42 fb 42 fb 42 fb 42</td>
<td>0 c</td>
<td>45 b</td>
<td>0 c</td>
<td>60 b</td>
</tr>
<tr>
<td>LPOST fb14 DPF fb PD fb 5% HD</td>
<td>42 fb 42 fb 42 fb 42</td>
<td>0 c</td>
<td>47 a</td>
<td>0 c</td>
<td>63 b</td>
</tr>
</tbody>
</table>

aData were pooled over six siteyears. Means followed by the same letter for each evaluation are not different at p ≤ 0.05.

bNitrogen fertilizer timings included applications to rice at three- to four-leaf (MPOST), four-leaf to one-tiller (LPOST), panicle differentiation (PD), 14 d postflood (14 DPF), and 5% heading (5% HD) growth stages.

cParaquat treatments included paraquat at 0 and 84 g ai ha⁻¹ applied to rice in the two- to three-leaf (EPOST) stage.

dFollowed by (fb)
Table 4.6  Main effect of paraquat treatment on rice height at 50% heading, number of d to 50% heading expressed as d after emergence (DAE), dry weight at maturity, rough and total milled rice yields in the Nitrogen Fertilizer Timing Study conducted from 2015 to 2018 at Stoneville, MS\(^a\).

<table>
<thead>
<tr>
<th>Treatment(^b)</th>
<th>Height</th>
<th>D to 50% heading</th>
<th>Dry weight</th>
<th>Rough rice yield</th>
<th>Total milled rice</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>cm</td>
<td>DAE</td>
<td>g m(^{-2})</td>
<td>kg ha(^{-1})</td>
<td>%</td>
</tr>
<tr>
<td>No paraquat</td>
<td>108 a</td>
<td>82 b</td>
<td>1,804 a</td>
<td>7,930 a</td>
<td>70 a</td>
</tr>
<tr>
<td>Paraquat</td>
<td>93 b</td>
<td>92 a</td>
<td>1,004 b</td>
<td>4,430 b</td>
<td>69 b</td>
</tr>
</tbody>
</table>

\(^a\)Data were pooled over five N fertilizer timings and five siteyears for dry weight, total milled rice yield, and rough rice yield or six siteyears for rice height and d to 50% heading. Means followed by the same letter for each parameter are not different at \(p \leq 0.05\).

\(^b\)Paraquat treatments included paraquat at 0 and 84 g ai ha\(^{-1}\) applied to rice in the two- to three-leaf (EPOST) stage.
Table 4.7  Main effect of N fertilizer timing on number of d to 50% heading expressed as d after emergence (DAE) and rough rice yield in a study evaluating rice response to different N fertilizer management strategies following exposure of rice in the two- to three-leaf (EPOST) growth stage to a sub-lethal rate of paraquat conducted from 2015 to 2018 at Stoneville, MS\textsuperscript{a}.

<table>
<thead>
<tr>
<th>N fertilizer timing\textsuperscript{b}</th>
<th>Rate</th>
<th>D to 50% heading</th>
<th>Rough rice yield</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg N ha\textsuperscript{-1}</td>
<td>DAE</td>
<td>kg ha\textsuperscript{-1}</td>
</tr>
<tr>
<td>LPOST</td>
<td>168</td>
<td>88 a</td>
<td>6,360 a</td>
</tr>
<tr>
<td>LPOST fb PD</td>
<td>112 fb 56</td>
<td>87 b</td>
<td>6,220 a</td>
</tr>
<tr>
<td>LPOST fb 14 DPF fb PD</td>
<td>84 fb 42 fb 42</td>
<td>87 b</td>
<td>6,120 ab</td>
</tr>
<tr>
<td>MPOST fb LPOST fb 14 DPF fb PD</td>
<td>42 fb 42 fb 42 fb 42</td>
<td>86 c</td>
<td>6,300 a</td>
</tr>
<tr>
<td>LPOST fb 14 DPF fb PD fb 5% HD</td>
<td>42 fb 42 fb 42 fb 42</td>
<td>86 c</td>
<td>5,920 b</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Data were pooled over six siteyears and five N fertilizer applications. Means followed by the same letter for each parameter are not different at \( p \leq 0.05 \).

\textsuperscript{b}Nitrogen fertilizer management strategies included applications to rice at the three- to four-leaf (MPOST), four-leaf to one-tiller (LPOST), panicle differentiation (PD), 14 d postflood (14 DPF), and 5% heading (5% HD) growth stages.

\textsuperscript{c}Followed by (fb)
Literature Cited


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 (2018) 2019 Weed management suggestions for Mississippi row crops. Pages 19-23 in Bond JA. (ed.), Mississippi State Univ Ext Ser and Miss Agric and For Exp Stn Mississippi State, MS Pub 3171


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, 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


Kurtz ME, Street JE (2003) Response of rice (Oryza sativa) to glyphosate applied to simulate drift. Weed Technol 17:234-238


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CHAPTER V
EVALUATION OF RICE EMERGENCE FOLLOWING S-METOLACHLOR APPLIED TO TWO DIFFERENT SOIL SERIES

Abstract
Preplant and/or PRE herbicide applications in soybean, corn, and cotton often include paraquat in mixture with s-metolachlor or prepackaged herbicide mixtures containing s-metolachlor, and rice is often grown in close proximity to these other crops. Considering the s-metolachlor rotation interval for rice, it is plausible to expect off-target movement from preplant and/or PRE herbicide applications containing s-metolachlor may affect rice emergence and crop management decisions. Therefore, a greenhouse study was conducted in Stoneville, MS, in 2018 to evaluate rice emergence across two soil series following applications of s-metolachlor applied at reduced concentration. Rice emergence at the 0X rate was 59, 65, and 66 seedlings 14, 21, and 28 d after treatment (DAT), respectively. By 28 DAT, ≤1 rice seedling emerged in pots treated with a 1X rate of s-metolachlor and concentration from 0 to 1/16X had ≥44 rice seedling emergence. Similar trends to that observed with rice emergence were detected for rice height and fresh weight 28 DAT. Soil concentrations of s-metolachlor 28 DAT were 30, 31, 32, 36, 61, and 488 ppm following exposure to s-metolachlor applied at 0, 1/64, 1/32, 1/16, 1/4, and 1X concentration. Based on these data, a soil analysis would be the best option to determine levels of s-metolachlor prior to planting rice if an off-target herbicide movement containing s-metolachlor occurred. If soil concentrations of s-metolachlor were ≥36 ppm, a cropping system other than rice should be considered to mitigate stand issues.
**Nomenclature:** Rice (*Oryza sativa* L.); *s*-metolachlor 2-chloro-\(N\)-(2-ethyl-6-methylphenyl)-\(N\)-[(1S)-2-methoxy-1-methylethyl]acetamide

**Key words:** Liquid chromatography mass specometry (LC-MS), parts per million (ppm), concentration

### Introduction

Rice production in Mississippi is confined exclusively to the Mississippi and Yazoo river alluvial floodplain, commonly referred to as the Mississippi Delta (Miller and Street 2008; Buehring 2008). This region of Mississippi is ideal for rice production due to its clay-textured soils, environment, and water availability (Miller and Street 2008; Buehring 2008). In 2018, rice production accounted for 5% of hectarage devoted to principle crops in the Mississippi Delta region (USDA-FSA 2018). Top rice-producing counties in 2018 in Mississippi included Bolivar, Tunica, Sunflower, Quitman, and Coahoma; however, these counties devote 48, 34, and 44% of planted ha to soybean [*Glycine max* (L.) Merr.], corn (*Zea mays* L.), and cotton (*Gossypium hirsutum* L.), respectively (USDA-FSA 2018).

Rice is often grown in close proximity to soybean, corn, and cotton. In Mississippi, rice is ideally seeded between April 1 and May 20. These dates often coincide with preplant and/or PRE herbicide applications to neighboring row crops (Anonymous 2019; Buehring 2008). Often these preplant and/or PRE herbicide applications contain paraquat in mixture with residual herbicides representing multiple herbicide MOA to control glyphosate-resistant weed (GR) species (Anonymous 2015, 2018). In Mississippi, nine weed species have evolved resistance to glyphosate (Heap 2019). Of these, only horseweed [*Conyza canadensis* (L.) Cronq.] has evolved resistance to paraquat and none exhibit resistance to *s*-metolachlor (Heap 2019). However, in
2016, a Palmer amaranth biotype from Arkansas was reported resistant to \textit{s}-metolachlor (Heap 2019).

\textit{s}-metolachlor is a member of the chloroacetamide herbicide family and inhibits very long chain fatty acid biosynthesis (VLCFA) (Anonymous 2015; Shaner 2014). \textit{s}-metolachlor is labeled for PPI, PRE, or POST applications in corn, cotton, and soybean (Shaner 2014). However, a 1-yr rotational restriction following \textit{s}-metolachlor applications is recommended for rice production (Anonymous 2018). Applications of \textit{s}-metolachlor alone or prepackaged herbicide mixtures containing \textit{s}-metolachlor are applied PPI and PRE in mixture with paraquat for herbicide-resistant weed control in soybean, corn, and cotton (Anonymous 2018). In recent years, incidents of off-target herbicide movement to rice fields from preplant and/or PRE herbicide applications to neighboring soybean, corn, and cotton fields have increased.

Rice has been documented as sensitive to off-target herbicide movement; however, level of sensitivity is dependent upon herbicide MOA, rate, and application timing (Davis et al. 2011; Lawrence et al. 2017; McCoy et al. 2018; Webster et al. 2015, 2016). Additionally, rice is sensitive to soil applied herbicides in previous cropping seasons (Johnson et al. 1995; Zhang et al. 2000). Braverman et al. (1985) reported that although metolachlor is a viable grass control option in soybean, metolachlor residues can negatively influence rice grown following metolachlor applications. Rice seedling emergence was directly impacted by seeding rate and metolachlor rates (Braverman et al. 1985). Rice seeded to 188 kg ha$^{-1}$ exposed to 0.0 ppmw metolachlor rates had 179 seedling m$^{-2}$ compared to 37 seedling m$^{-2}$ when exposed to metolachlor at 0.8 ppmw. However, when seeding depth was increased from 0.62 cm to 1.25 cm, seedling density was 166 m$^{-2}$ at 0.0 ppmw and 44 m$^{-2}$ at 0.8 ppmw. Additionally, Braverman et al. (1985) reported that rice seedling density and fresh weight were both influenced
by \( s \)-\text{metolachlor} rate in a greenhouse environment. At 0.2 and 0.4 ppmw \text{metolachlor}, seedling densities were reduced 44 and 86\% respectively (Braverman et al. 1985). Averaged across two rates of \( s \)-\text{metolachlor} applied the previous fall, rice injury 14 d after emergence (DAE) was 30\% and yield was reduced to 73\% of the nontreated control (Lawrence et al. 2018). Similar results were observed with pyroxasulfone, which is another VLCFA-inhibiting herbicide.

Previous research has documented rice sensitivity to foliar- and soil-applied herbicides (Braverman et al. 1985; Davis et al. 2011; Johnson et al. 1995; Lawrence et al. 2017, 2018; Webster et al. 2015, 2016; Zhang et al. 2000). \( s \)-\text{metolachlor} is often recommended in preplant and/or PRE herbicide applications in mixture with non-selective herbicides to manage GR weed biotypes, but rotation restrictions can vary across crops planted the following season (Anonymous 2018). However, when off-target movement of these applications occur, an unknown herbicide concentration is left in soil or plant tissue. Considering \( s \)-\text{metolachlor} rotation interval, it is plausible to expect off-target movement from preplant and/or PRE herbicide applications containing \( s \)-\text{metolachlor} may effect rice emergence and subsequent crop management decisions. Therefore, a greenhouse study was conducted to evaluate rice emergence across two soil series following applications of \( s \)-\text{metolachlor} applied at reduced concentration.

**Materials and Methods**

A greenhouse study was conducted in 2018 and 2019 at the Mississippi State University Delta Research and Extension Center in Stoneville, MS (33°25'26.11"N, 90°54'44.16"W), to determine rice seedling emergence following exposure to various \( s \)-\text{metolachlor} concentration across two soil series. Clay and very fine sandy loam soil series were utilized as representative soil series common for rice production in Mississippi (Buehring 2008). Global positioning
system coordinates for soil collection, soil series, soil description, previous crop, soil pH, and soil organic matter (OM) for each study are described in Table 5.1. Both soil series were greenhouse air dried at 48/22 (± 3 C) for 4 wk and homogenized prior to potting (EPA 2014). Both soil series were potted to approximately 1,600 g in 16.5 x 23 cm trays (Small Budget Propagator, Garland Products Ltd, First Avenue Pensnett Estate, Kingswinford, West Midlands, England).

Treatments were arranged in a complete block design, and the study was repeated two times. S-metolachlor (Dual Magnum EC 7.62, P.O. Box 18300 Greensboro, North Carolina 27419) was applied at concentrations of 0 (0X), 4 (1/64X), 17 (1/32X), 67 (1/16X), 266 (1/4X), and 1,064 (1X) to the very fine sandy loam soil series and at 0 (0X), 6 (1/64X), 22 (1/32X), 88 (1/16X), 353 (1/4X), and 1,411 (1X) g ai ha⁻¹ to the clay soil series. All herbicide treatments were applied using a CO₂-pressurized backpack sprayer equipped with flat-fan nozzles (AIRMIX11002, Greenleaf Technologies, 230 E Gibson St., Covington, LA 70433) set to deliver 140 L ha⁻¹ at 206 kPa using water as a carrier. Trays were left undisturbed for 24 h following s-metolachlor applications. Rice cultivar, ‘CL151’ (HorizonAg, 8275 Tournament Dr. Suite 255, Memphis, TN 38125) was seeded at 100 seed across two trays per treatment to a depth of 1.3 cm 24 h following s-metolachlor applications and irrigated with 425 ml of water for herbicide activation (Anonymous 2015). Greenhouse temperatures were 32/25 C (± 3 C) day/night and supplemented with light from sodium vapor lamps set to a 14-h photoperiod. Trays were irrigated with a 425 ml of water as needed.

Data was collected and analyzed as a single composite sample from both trays representing each treatment. Across both trays, rice seedling emergence was recorded 7, 14, 21, and 28 d after treatment (DAT). At 28 DAT, plant heights were determined by measuring from
the soil surface to the uppermost extended leaf and calculating the mean height of five randomly selected plants. Aboveground rice fresh weight was collected 28 DAT and weighed to obtain fresh weight. Fresh tissue and soil samples collected from each treatment were frozen until liquid chromatography-mass spectrometry (LC-MS) was conducted to determine s-metolachlor concentrations in tissue and soil. S-metolachlor residues in soil and foliar plant tissue were extracted and analyzed using Mississippi Chemistry Lab modified QuEChERS methodology outlined by Anastassiades et al. (2003).

Data were averaged over two soil series and s-metolachlor concentration. Models to test data included log-logistic, inverse first order polynomial, Gompertz, and a single parameter exponential decay. Data were analyzed using a single parameter exponential decay model in SAS v. 9.4 (SAS Institute Inc. 100 SAS Campus Drive Cary, NC 27513-2414, USA) due to model trends in the data which were most representative of an exponential decay curve.

**Results and Discussion**

Exponential decay trends were detected for rice emergence at all evaluation intervals, height, fresh weight, and soil concentration 28 DAT (Table 5.2). However, no trend was detected for s-metolachlor concentration in foliar plant tissue (Table 5.2). No rice was emerged by 7 DAT (data not presented). Similar trends in rice emergence occurred at all evaluation intervals. Rice emergence at the 0X rate was 59, 65, and 66 seedlings 14, 21, and 28 DAT, respectively (Table 5.2 and Figure 5.1). At 14 DAT, seedling emergence decreased from 58 to 0 as s-metolachlor rate increased from 1/64X to 1X (Table 5.2 and Figure 5.1). A similar trend was observed 21 DAT (Figure 5.2). Regardless of emergence evaluation interval ≤1 rice seedling emerged following 1X rate of s-metolachlor, and seedling emergence was ≥44 following concentration from 0 to 1/16X (Table 5.2 and Figure 5.1).
Similar trends to those observed for rice emergence were detected for rice height and fresh weight 28 DAT (Table 5.2 and Figure 5.1). Averaged across soil series and s-metolachlor application concentration, rice height was 18 cm at 0 and 1/64X and decreased to 17, 16, 10, and 2 cm following s-metolachlor at 1/32, 1/16, 1/4, and 1X, respectively (Figure 5.1). Rice fresh weight following concentration ≤1/16X were ≥2,224 mg (Figure 5.1). Fresh weight was ≤928 mg following s-metolachlor concentration ≥1/4X (Figure 5.1). Inversely, soil concentration of s-metolachlor increased exponentially to the 1X from the 0X rate (Figure 5.1). Soil concentrations of s-metolachlor were 30, 31, 32, 36, 61, and 488 ppm following exposure to s-metolachlor applied at 0, 1/64, 1/32, 1/16, 1/4, and 1X, respectively (Figure 5.1).

These data indicate that s-metolachlor will have an effect on rice emergence, height, and fresh weight (Figure 5.1). However, level of effect would be rate dependent. In the current research, four of six concentrations were considered within the range of an off-target event (Al-Khatib and Peterson 1999). The 1/4 and 1X concentration were outside the bounds of an off-target herbicide movement event; therefore, it is expected that rice emergence, height, and fresh weight would be most severely impacted following these concentrations. Additionally, a two-and 13-fold increase in s-metolachlor concentration was observed following the 1/4 and 1X s-metolachlor concentration compared with concentration ≤1/16X.

Averaged over soil series and application concentration under greenhouse conditions, s-metolachlor concentration ranging from 1/16 to 1X had the greatest impact on rice emergence, height, and fresh weight (Figure 5.1). Soil concentration at the 1/16X rate was 36 ppm compared with 32, 31, and 30 ppm observed in the 1/32, 1/64, and 0X concentration, respectively. Additionally, the 1/16X rate was half of that observed in the 1/4X rate; therefore, soil
concentration could be indicative of severity of potential rice injury when seeding rice into soil with an unknown concentration of s-metolachlor.

In the current research, foliar tissue did not exhibit a trend in s-metolachlor concentration accumulated from the soil (data not presented). A curve could not be generated in part due to the lack of plant material collected following the 1X rate; however, foliar levels of s-metolachlor concentration at concentration ≤1/4X were inconsistent (data not presented). Based on this observation, a soil analysis would be the best option to determine levels of s-metolachlor prior to seeding rice if an off-target herbicide movement event containing s-metolachlor occurred previously. If soil concentrations were ≥36 ppm, a cropping system other than rice should be considered to mitigate stand issues.
Table 5.1  Coordinates, soil series, soil description, previous crop, soil pH, and soil organic matter (OM) in a greenhouse study evaluating rice emergence following soil applied s-metolachlor at various applications across two soil series at Stoneville, MS.

<table>
<thead>
<tr>
<th>Siteyear</th>
<th>Coordinates</th>
<th>Soil series</th>
<th>Description</th>
<th>Previous crop</th>
<th>pH</th>
<th>OM</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018</td>
<td>33.24°N, 90.56°W</td>
<td>Sharkey very-fine clay</td>
<td>Very-fine, smectitic, thermic Chromic Epiaquerts</td>
<td>Soybean:rice</td>
<td>8.1</td>
<td>2.1</td>
</tr>
<tr>
<td>33.24°N, 90.54°W</td>
<td>Bosket very fine sandy loam</td>
<td>Fine-loamy, mixed, active, thermic Mollic Hapludalfs</td>
<td>Rice:rice</td>
<td>7.9</td>
<td>1.2</td>
<td></td>
</tr>
</tbody>
</table>


Table 5.2  Exponential decay models for rice emergence 14, 21, and 28 d after treatment (DAT) and rice height, fresh weight, soil and foliar concentration 28 DAT in a greenhouse study evaluating rice emergence following soil applied $s$-metolachlor at various applications across two soil series at Mississippi State University Delta Research and Extension Center in Stoneville, MS$^a$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emergence</td>
<td></td>
</tr>
<tr>
<td>14DAT</td>
<td>$y = 59.323\left(-7.6591 \times X\right)$</td>
</tr>
<tr>
<td>21 DAT</td>
<td>$y = 65.613\left(-6.6882 \times X\right)$</td>
</tr>
<tr>
<td>28 DAT</td>
<td>$y = 66.281\left(-6.3487 \times X\right)$</td>
</tr>
<tr>
<td>Height</td>
<td>$y = 17.889\left(-2.1990 \times X\right)$</td>
</tr>
<tr>
<td>Fresh weight</td>
<td>$y = 2,276.360\left(-4.6598 \times X\right)$</td>
</tr>
<tr>
<td>Soil concentration (ppm)</td>
<td>$y = 30.4084\left(2.7761 \times X\right)$</td>
</tr>
<tr>
<td>Foliar concentration (ppm)</td>
<td>n/s</td>
</tr>
</tbody>
</table>

$^a$All data were pooled over two soil series at six $s$-metolachlor concentration and two experiments.

$^b$Not significatnt (n/s)
Figure 5.1 Rice emergence 14 (a), 21 (b), and 28 (c) days after treatment (DAT) and rice height (d), fresh weight (e), and soil concentration (f) 28 DAT following soil applied s-metolachlor at various concentrations across two soil series.
Literature Cited

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 (2018) 2019 Weed management suggestion for Mississippi row crops. Pages 16-23 in Bond JA. (ed.), Mississippi State Univ Ext Ser and Miss Agric and For Exp Stn Mississippi State, MS Pub 3171


