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Rice (Oryza sativa L.) response to sub-lethal concentrations of paraquat at different growth stages

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Rice (Oryza sativa L.) response to sub-lethal concentrations of paraquat at different growth stages

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in Weed Science
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Off-target herbicide movement onto rice is an annual problem in rice-producing areas within Mississippi. In Mississippi, rice is routinely drill-seeded in April to early May. Because these dates often coincide with preplant and/or preemergence (PRE) herbicide applications to corn (Zea mays L.), cotton (Gossypium hirsutum L.), and soybean [Glycine max (L.) Merr.], drift onto neighboring rice crops is likely to occur. Although the effects of off-target movement of paraquat on rice may not be visibly apparent, the potential effect on rough rice yield could be detrimental. Field research was conducted at the Delta Research and Extension Center in Stoneville, MS, in 2019, 2020, and 2021 to characterize rice response to exposure to a range of sub-lethal concentrations of paraquat during the vegetative and reproductive growth phases. Other field experiments characterized rice response to exposure to a sub-lethal concentration of paraquat at different stages of reproductive growth. A final field experiment evaluated rice response and barnyardgrass control with labeled herbicides after exposure to a sub-lethal concentration of paraquat.

DEDICATION

I would like to dedicate this work to my husband, Dion, for always encouraging me to “go for it” and telling me “you got this”. You believed in me when I did not believe in myself. I would also like to dedicate this research to my daughters, K’lynn and Khylee, who have been my “why” throughout this journey. Lastly, I would like to dedicate this research to Dr. Brian R. Lockhart who believed in me in 2012 and told me I would be a PhD one day.

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Also a special acknowledgment of appreciation to the Mississippi Rice Promotion Board for funding my research and allowing me to continue my education. I would like to acknowledge and thank Matt Edwards, Jimmy Peeples, and all the other staff at the Delta Research and Extension Center for the time and effort they allocated towards my research. I would also like to thank Read Kelly, Hunter Bowman, Alex Mangialardi, and Will Eubank, along with the other graduate students at Mississippi State University for their encouragement and friendship.

To all of my family and friends, this journey would not have been possible without your continued love and support. Thank you for prayers and encouragement throughout this journey.

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INTRODUCTION

Rice is a semi-aquatic, annual grass with round, hollow, jointed culms (Moldenhauer et al. 2013). The general life cycle of rice lasts 105 to 120 d. Plant heights typically range from 0.4 to 1.8 m, depending on cultivar and environmental conditions (Buehring 2008; Dunand and Saichuk 2014; Moldenhauer and Gibbons 2003; Moldenhauer et al. 2013). Rice cultivation first began 8000 to 8500 yr ago in the Yangzi Valley and expanded to southern China and southeastern Asia (Higham and Lu 1998). Rice was first introduced to the United States through South Carolina in the late 1600s (Linscombe 2006); however, commercial production in Mississippi did not begin until the mid-1940s in Washington County (Miller and Street 2008). Rice production in the U.S. is centered in the midsouthern states of Arkansas, Louisiana, Mississippi, Missouri, and Texas with additional production in California (Daberkow and Whitener 1986).

Rice morphology is divided into three phases: vegetative, reproductive, and grain filling/ripening (Beighley 2012; Dunand and Saichuk 2014; Moldenhauer and Gibbons 2003; Moldenhauer et al. 2013). The vegetative phase includes germination, seedling establishment, and tillering stages and is characterized by active tillering, a gradual increase in plant height, and leaf emergence at regular intervals (Moldenhauer et al. 2013). The reproductive phase is divided into multiple stages including panicle initiation (PI; formation of panicles on the uppermost node of the culm and with nodes still stacked); internode elongation (IE; nodes elongate and move up the stem); panicle differentiation (PD; panicle inside the stem approximately 0.3 cm in length); booting (panicles swell within the leaf sheath); and several heading (HEAD) stages (Buehring 2008; Moldenhauer et al. 1994; Smith and Dilday 2003). Heading can be characterized as culm elongation, reduced tiller production, flag leaf emergence, head emergence, and spikelet flowering (Moldenhauer et al. 2013; Moldenhauer and Gibbons 2003). Agronomically, HEAD is defined as the time when 50% of booting culms have partially exerted panicles (Smith and Dilday 2003). The ripening period involves several stages including milk (grain exhibits milky consistency), soft dough (grain has soft consistency), hard dough (grain has hard consistency), and maturity (Buehring 2008; Smith and Dilday 2003; Yoshida 1981).

Rice production in Mississippi is limited to the Mississippi and Yazoo river basin, commonly known as the Mississippi Delta, with little production in the state outside this area (Miller and Street 2008). Bolivar, Sunflower, Tunica, and Washington counties have traditionally been the leading rice-producing counties in Mississippi, harvesting 75,300 ha^{-1} of rice in 2020, accounting for 5% of Mississippi's total crop hectarage (USDA-NASS 2021). These counties' clay soils, large and flat fields, available water, and climate are optimum for rice growth (Miller and Street 2008).

Weeds are the primary pest of Mississippi rice and their control costs an estimated $7.5 to $15 million annually (Buehring and Bond 2008). Weeds compete with rice for sunlight, water, nutrients, and other growth requirements (Smith 1988). Factors such as weed species composition, weed density, duration of weed-rice interference, rice cultivar, seeding density, water management, and nutrient availability influence the degree of rice yield loss from weed interference (Odero and VanWeelden 2018). Weed infestations interfere with harvest operations, and weed seed contamination of rice grain lowers quality and may lower the economic value of the crop (Odero and VanWeelden 2018).

Herbicides are the most widely utilized weed management strategy in U.S. crop production (Hill 1982; McWhorter and Shaw 1982). Glyphosate usage rapidly increased following the introduction and widespread adoption of glyphosate-resistant (GR) canola (*Brassica napus* L.), corn (*Zea mays* L.), cotton (Gossypium hirsutum L.), and soybean [*Glycine max* (L.) Merr.] (Shaner 2000). Failure to incorporate multiple herbicide modes of action (MOA), as well as other poor stewardship practices, has resulted in the development of GR weeds (Powles 2008). To combat GR weeds, paraquat plus residual herbicides are recommended preemergence (PR)E in GR cropping systems (Anonymous 2016; Bond et al. 2021).

Paraquat is a fast-acting, nonselective herbicide that rapidly kills a variety of annual and perennial grass and broadleaf weed species upon contact but provides no soil residual activity for control or suppression of these weeds (Bromilow 2004; Dodge 1971; Haley 1979). Paraquat acts by intercepting electrons between the bound ferredoxin acceptors and nicotinamide adenine dinucleotide phosphate ($NADP^+$) and then reducing oxygen to superoxide (O^{2-}) (Calderbank 1968). Hydroxyl radicals are generated that readily oxidize lipid membranes. In full sunlight, exposed vegetation becomes chlorotic within hours and necrotic within 1 to 3 d (Fuerst and Vaughn 1990).

Paraquat is utilized as a herbicide, desiccant, defoliant, and plant growth regulator (USDA-NASS 1997). It can be applied preplant, PRE, or post-directed in corn, cotton, peanut (*Arachis hypogaea* L.), soybean, grain sorghum [*Sorghum bicolor* (L.)], and other vegetable and fruit crops for nonselective weed control. However, paraquat is limited to preplant or PRE applications in rice (Anonymous 2016; Bond et al. 2021).

In Mississippi, rice is routinely drill-seeded in April to early May (Koger et al. 2005). Because these dates often coincide with preplant and/or preemergence (PRE) herbicide applications to corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybean [*Glycine max* (L.) Merr.] (Buehring 2008), drift onto neighboring rice crops is likely to occur (Calhoun et al. 2016). Spray drift, or off-target movement, is the physical movement of a pesticide through air at the time of application, or soon thereafter, to any site other than that intended for application (EPA 2019; Henry et al 2004). Volatilization, tank contamination, and particle drift have been identified as common causes of off-target herbicide movement (Cundiff et al. 2017; Steckel et al. 2010). However, particle drift, which occurs when herbicide carriers evaporate leaving particles of concentrated herbicide that moves to susceptible plants (Fishel and Ferrell 2016; Jordan et al. 2009), is the most preventable form of off-target movement because application methods can be adjusted to minimize off-target movement potential. Environmental conditions, boom height, droplet size, and distance from susceptible vegetation are major factors affecting particle drift (Maybank et al. 1978; Nordby and Skuterud 1975; Thistle 2004; Wolf et al. 1993).

Off-target herbicide movement can injure susceptible crops grown in adjacent fields and negatively affect biodiversity, reproduction, and composition of non-target species (Boutin et al. 2014; Follak and Hurle 2002). Off-target movement can account for a loss of up to 25% of the applied herbicide, which can spread over a distance of a few m to several hundred km. Depending on the herbicide and application method, volatilization may be responsible for as much as 80 to 90% of herbicide loss within a few days of application (Majewski 1995).

To study crop response to off-target herbicide movement, applications ranging from 1/10 to 1/100 of labeled rates are often utilized (Al-Khatib et al. 2003; Lawrence et al. 2017, 2020; Roider et al. 2007; Wolf et al. 1993). Applications within this range are consistent with in-crop exposure to an off-target herbicide movement event, allowing for estimations of crop response (Wolf et al. 1993). Previous research with simulated glyphosate drift reported that injury symptoms in most crops were already detectable at 1 to 6% of the labeled rate (Al-Khatib and Peterson 1999; Hoss et al. 2003). Use of varying or constant carrier volume are two techniques for evaluating the effects of off-target herbicide movement (Banks and Schroeder 2002; Davis et al. 2011; Ellis et al 2002; Lawrence et al. 2020; McCoy et al. 2020; Roider et al. 2008; Webster et al. 2015). Testing off-target movement utilizing variable carrier volume reduces the herbicide concentration in proportion to a specified spray volume; whereas, testing with a constant carrier volume applies reduced herbicide concentrations in a single carrier volume (Hensley et al. 2012; Davis et al. 2011; Lawrence et al. 2017).

Concentrations of herbicides associated with off-target movement can injure plants, causing chlorosis or stunting, depending on susceptibility to the herbicide (Smith et al. 2000). In susceptible crops, injury varies depending on mode of action, distance from the susceptible crop, and level of crop susceptibility (Henry et al. 2004). Glyphosate at 140 g ae ha^{-1} or 12.5% of the labeled rate applied at panicle differentiation (PD) injured rice ≤ 15%; however, yield was reduced 54% (Ellis et al. 2003). Kurtz and Street (2003) reported glyphosate at 140 g ha^{-1} applied during rice booting injured rice ≤ 5%; however, yield was reduced ≥ 63% in 3 of 4 yr. Imazethapyr applied to one-tiller non-Clearfield® rice at 8.7 and to rice at PD at 4.4 g ai ha^{-1} reduced yield to 59 and 75% of the nontreated, respectively (Hensley et al. 2012). A premix of imazethapyr plus imazapyr applied at 7.9 g ai ha^{-1} to non-Clearfield® rice at the two- to three-leaf growth stage reduced plant height 12% and caused 19% injury 28 d after treatment (DAT) (Bond et al. 2006). Imazamox at 2.7 and 5.5 g ai ha^{-1} injured non-Clearfield® rice ≥ 20% 28 DAT regardless of rate (Webster et al. 2016). This research also reported 72 and 60% yield reductions compared to the nontreated following imazamox applied at 2.7 g ha^{-1} to one-tiller and booting rice, respectively (Webster et al. 2016).

Previous research evaluating early-season rice response to off-target movement of paraquat at 84 g ai ha^{-1} reported that rice was injured ≥ 41% regardless of application timing, with ≥ 50% injury following exposure at PD (Lawrence et al. 2020). Rough rice yields were reduced to 8% of the nontreated following rice exposure to paraquat at PD; however, rice exposed at spiking to one-leaf stage produced yield 94% of the nontreated control (Lawrence et al. 2020). Research evaluating rice response following late-season exposure to paraquat reported that paraquat at 70 g ai ha^{-1} injured rice ≥ 40% when applied at early-boot, late-boot, and HEAD stages with the greatest injury (71%) at HEAD (Calhoun et al. 2016). Injury was ≥ 79% following paraquat applied to rice at the soft dough and hard dough stages (Calhoun et al. 2016). Rice yield was reduced ≥ 90% with paraquat at early-boot and late-boot stages and ≥ 55% at the soft dough stage compared with the nontreated control (Calhoun et al. 2016). Paraquat at 28 g ha^{-1} injured rice 5 to 25% when applied at 50% heading (McCoy et al. 2020). This same research reported 2080, 2480, and 2020 kg ha^{-1} yield loss from paraquat applied at 50% heading, 50% heading plus 7 d, and 50% heading plus 14 d, respectively (McCoy et al. 2020). Yield losses were 1280 and 610 kg ha^{-1} following paraquat applied to rice 21 and 28 d after 50% heading, respectively (McCoy et al. 2020).

Off-target herbicide movement onto rice is an annual problem in rice-producing areas within Mississippi (Koger et al. 2005). Although previous research has documented rice response to early- and late-season off-target movement of paraquat (Calhoun et al. 2016; Lawrence et al. 2020; McCoy et al. 2020), research identifying rice response throughout the entire life cycle is lacking. Therefore, research was conducted to (1) characterize the rice response to exposure to a range of sub-lethal concentrations of paraquat during the vegetative and reproductive growth phases, (2) characterize the rice response to exposure to a sub-lethal concentration of paraquat at different stages of reproductive growth, and (3) evaluate rice response and barnyardgrass control with labeled herbicides after exposure to a sub-lethal concentration of paraquat.

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CHAPTER II

RICE RESPONSE TO SUB-LETHAL CONCENTRATIONS OF PARAQUAT DURING THE VEGETATIVE AND REPRODUCTIVE GROWTH PHASES

Abstract

Off-target herbicide movement onto rice is an annual problem in rice-producing areas within Mississippi. Off-target herbicide movement can injure susceptible crops grown in adjacent fields and negatively affect biodiversity, reproduction, and composition of non-target species. For rice, the magnitude of damage from off-target movement of a paraquat-based herbicide application depends on the concentration that moves to the rice and the growth stage at the time of the off-target event. Two concurrent field studies were conducted in 2019, 2020, and 2021 to characterize the rice response to exposure to a range of sub-lethal concentrations of paraquat during the vegetative (Vegetative Study) and reproductive (Reproductive Study) growth phases. In the Vegetative Study, paraquat was applied at 84, 21, 5.2, 1.3, and 0.65 g ha-1 to rice in the two- to three-leaf (EPOST) growth stage. In the Reproductive Study, paraquat was applied at 28, 7, 1.75, 0.43, 0.21 g ha^{-1} at 7 d after 50% heading. In the Vegetative Study, a linear trend was detected for rice injury 3, 7, 14, 21, and 28 DAT. Rice injury at 84 g ai ha^{-1} increased from 49% 3 DAT to 58% 14 DAT and declined to 48% by 28 DAT. Rough rice yield was reduced with the highest concentration of paraqaut. For every 1 g of paraquat applied to rice, a yield loss of 30 kg ha^{-1} was observed. In the Reproductive Study, a linear trend was detected for rice injury 7 and 14 DAT. At 7 and 14 DAT, the greatest injury was 14 and 16%, respectively, with paraquat at 28 g ai ha^{-1}. No discernible trend was detected for rice injury 21 and 28 DAT. Rough rice yield ranged from 12,600 to 8600 kg ha^{-1} and was reduced as great as 33% following paraquat at 28 g ai ha^{-1}. Although the effects of off-target movement of paraquat on rice may not be visibly apparent, the potential effect on rough rice yield could be detrimental. Therefore, producers should consider strategies to mitigate off-target movement when applying paraquat-based herbicide treatments including making applications during periods of low wind and wind direction away from rice.

Nomenclature: Paraquat; rice, *Oryza sativa* L. ‘CL153’.

Key words: Off-target movement, paraquat exposure

Introduction

Rice is a semi-aquatic, annual grass with round, hollow, jointed culms (Moldenhauer et al. 2013). The general life cycle of rice lasts 105 to 120 d, and plant heights typically range from 0.4 to 1.8 m, depending on cultivar and environmental conditions (Buehring 2008; Dunand and Saichuk 2014; Moldenhauer and Gibbons 2003; Moldenhauer et al. 2013). Rice cultivation first began 8000 to 8500 yr ago in the Yangzi Valley and expanded to southern China and southeastern Asia (Higham and Lu 1998). Rice was first introduced to the United States through South Carolina in the late 1600s (Linscombe 2006); however, commercial production in Mississippi did not begin until the mid-1940s in Washington County (Miller and Street 2008). Rice production in the U.S. is centered in the midsouthern states of Arkansas, Louisiana, Mississippi, Missouri, and Texas with additional production in California (Daberkow and Whitener 1986).

Rice production in Mississippi is limited to the Mississippi and Yazoo river basin, commonly known as the Mississippi Delta, with little production in the state outside this area (Miller and Street 2008). Bolivar, Sunflower, Tunica, and Washington counties have traditionally been the leading rice-producing counties in Mississippi, harvesting 75,300 ha^{-1} of rice in 2020, accounting for 5% of Mississippi's total crop hectarage (USDA-NASS 2021). These counties' clay soils, large and flat fields, available water, and climate are optimum for rice growth (Miller and Street 2008).

In Mississippi, rice is routinely drill-seeded in April to early May (Koger et al. 2005). Because these dates often coincide with preplant and/or preemergence (PRE) herbicide applications to corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybean [*Glycine max* (L.) Merr.] (Buehring 2008), drift onto neighboring rice crops is likely to occur (Calhoun et al. 2016). Spray drift, or off-target movement, is the physical movement of a pesticide through air at the time of application, or soon thereafter, to any site other than that intended for application (EPA 2019; Henry et al 2004). Volatilization, tank contamination, and particle drift have been identified as common causes of off-target herbicide movement (Cundiff et al. 2017; Steckel et al. 2010). However, particle drift, which occurs when herbicide carriers evaporate leaving particles of concentrated herbicide that moves to susceptible plants (Fishel and Ferrell 2016; Jordan et al. 2009), is the most preventable form of off-target movement because application methods can be adjusted to minimize off-target movement potential. Environmental conditions, boom height, droplet size, and distance from sensitive vegetation are major factors affecting particle drift (Maybank et al. 1978; Nordby and Skuterud 1975; Thistle 2004; Wolf et al. 1993).

Off-target herbicide movement can injure susceptible crops grown in adjacent fields and negatively affect biodiversity, reproduction, and composition of non-target species (Boutin et al. 2014; Follak and Hurle 2002). Off-target movement can account for a loss of up to 25% of the applied herbicide, which can spread over a distance of a few m to several hundred km.

Depending on the herbicide and application method, volatilization may be responsible for as much as 80 to 90% of herbicide loss within a few days of application (Majewski 1995).

To study crop response to off-target herbicide movement, applications ranging from 1/10 to 1/100 of labeled rates are often utilized (Al-Khatib et al. 2003; Lawrence et al. 2017, 2020; Roider et al. 2007; Wolf et al. 1993). Applications within this range are consistent with in-crop exposure to an off-target herbicide movement event, allowing for estimations of crop response (Wolf et al. 1993). Previous research with simulated glyphosate drift reported that injury symptoms in most crops were already detectable at 1 to 6% of the labeled rate (Al-Khatib and Peterson 1999; Hoss et al. 2003). Use of varying or constant carrier volumes are two techniques for evaluating the effects of off-target herbicide movement (Banks and Schroeder 2002; Davis et al. 2011; Ellis et al 2002; Lawrence et al. 2020; McCoy et al. 2020; Roider et al. 2008; Webster et al. 2015). Testing off-target movement utilizing variable carrier volume reduces the herbicide concentration in proportion to a specified spray volume; whereas, testing with a constant carrier volume applies reduced herbicide concentrations in a single carrier volume (Hensley et al. 2012; Davis et al. 2011; Lawrence et al. 2017).

Concentrations of herbicides associated with off-target movement can injure plants, causing chlorosis or stunting, depending on sensitivity to the herbicide (Smith et al. 2000). In susceptible crops, injury varies depending on mode of action, distance from the sensitive crop, and level of crop sensitivity (Henry et al. 2004). Glyphosate at 140 g ae ha^{-1} or 12.5% of the labeled rate applied at panicle differentiation (PD) injured rice ≤ 15%; however, yield was reduced 54% (Ellis et al. 2003). Kurtz and Street (2003) reported glyphosate at 140 g ha^{-1} applied during rice booting injured rice ≤ 5%; however, yields were reduced ≥ 63% in 3 of 4 yr. Imazethapyr applied to one-tiller non-Clearfield® rice at 8.7 g ai $ha^{-1}$and to rice at PD at 4.4

reduced yield to 59 and 75% of the nontreated, respectively (Hensley et al. 2012). A premix of imazethapyr plus imazapyr applied at 7.9 g ai ha^{-1} to non-Clearfield® rice at the two- to three-leaf growth stage reduced plant height 12% and caused 19% injury 28 d after treatment (DAT) (Bond et al. 2006). Imazamox at 2.7 and 5.5 g ai ha^{-1} injured non-Clearfield® rice ≥ 20% 28 DAT regardless of rate (Webster et al. 2016). This research also reported 72 and 60% yield reductions compared to the nontreated following imazamox applied at 2.7 g ha^{-1} to one-tiller and booting rice, respectively (Webster et al. 2016).

In previous research evaluating early-season rice response to simulated off-target movement of paraquat at 84 g ai ha^{-1}, rice was injured ≥ 41% 28 DAT regardless of application timing with rough rice yields reduced to 8% of the nontreated following rice exposure to paraquat at PD (Lawrence et al. 2020). Paraquat applied at 28 g ha^{-1} injured rice 5 to 25% when applied at 50% heading, and yield loss was ≥ 12% when paraquat was applied up to the date of draining (McCoy et al. 2020).

Off-target herbicide movement onto rice is an annual problem in rice-producing areas within Mississippi (Koger et al. 2005). Although previous research has documented rice response to early- and late-season off-target movement of paraquat (Lawrence et al. 2020; McCoy et al. 2020), research identifying the paraquat concentration that is least injurious to rice is lacking. Therefore, research was conducted to characterize the effects of sub-lethal paraquat applications on rice when exposed during vegetative and reproductive growth phases.

Materials and Methods

Vegetative Study

Field research was conducted from 2019 to 2021 at the Mississippi State University Delta Research and Extension Center in Stoneville, MS, to evaluate rice response following exposure to a range of sub-lethal concentrations of paraquat during vegetative growth. Global positioning system coordinates, soil series, soil description, soil pH, and soil organic matter (OM) for this study are detailed in Table 2.1. The experimental site included a rice-fallow rotation where rice was seeded every other year. Glyphosate (Roundup PowerMax 4.5 L, 1,120 g ae ha^{-1}, Bayer Cropscience, St. Louis, MO), paraquat (Gramoxone 2.0 SL, 560 g ha^{-1}, Syngenta Crop Protection, Greensboro, NC), and/or 2,4-D (2,4-D Amine 3.8 SL, 1,120 g ae ha^{-1}, Agri Star, Ankeny, IA) were applied in late-March to early-April each year to control emerged vegetation prior to seeding.

Rice cultivar, 'CL153' (Horizon Ag, Memphis, TN) was drill-seeded May 28, 2019, May 12 and 20, 2020, and June 17, 2021 to a depth of 2 cm using a small-plot grain drill (Great Plains 1520, Great Plains Mfg, Inc., Salina, KS) at 356 seed m^{-2}. Plots were 0.6 × 4.6 m and consisted of nine rows of rice bordered on either end by a 1.5-m alley that contained no rice. Nitrogen fertilizer was applied at 168 kg ha^{-1} as urea (46-0-0) immediately prior to flood establishment (Norman et al. 2013). Plots were flooded to an approximate depth of 6 to 10 cm when rice reached the one- to two-tiller stage. Rice was managed throughout the growing season utilizing local guidelines to optimize yield (Buehring 2008).

The experimental design was a randomized complete block with four replications. Paraquat was applied at 84, 21, 5.2, 1.3, and 0.65 g ha^{-1} to rice in the two- to three-leaf (EPOST) growth stage. These concentrations represented 1/10, 1/40, 1/160, 1/640, and 1/1280 times the suggested use rate for preplant paraquat applications (Anonymous 2016; Bond et al. 2021). A nontreated control was included for comparison. All treatments included NIS (Activator 90, 90% non-ionic surfactant, Loveland Products, Greeley, CO) at 0.5% v/v and were applied using a CO_2-pressurized backpack sprayer equipped with flat-fan nozzles (Airmix 11002 nozzle, Greenleaf Technologies, Covington, LA) set to deliver 140 L ha^{-1} at 206 kPa using water as a carrier. Simulated off-target movement was applied with a constant carrier volume to reduce herbicide concentrations and mimic low concentration exposure (Davis et al. 2011; Ellis et al. 2002).

Visible estimates of aboveground rice injury were recorded 3, 7, 14, 21, and 28 DAT on a scale of 0 to 100% where 0 indicated no effect and 100 indicated complete plant death. Rice plant height was determined 14 DAT and at maturity by measuring from the soil surface to the uppermost extended leaf and calculating the mean height of five randomly selected plants in each plot. 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. These data were converted to delay in heading by subtracting d to 50% heading in an individual plot from that in the nontreated. Days to canopy closure was calculated using Canopeo (Oklahoma State University, Stillwater, OK) to measure green leaf area based on a percentage. Images were taken at weekly intervals from the day of the first application until all plots reached 100% green leaf area. Canopeo is based on color ratios of red to green (R/G) and blue to green (B/G) and an excess green index (2G– R–B). Green normalized difference vegetative index (NDVI) was assessed as an indication of plant health using a hand-held crop sensor (GreenSeeker crop sensing system, Trimble Navigation Limited, Sunnyvale, CA) at 28 DAT. Plots were drained approximately 2 wk before harvest maturity. Rice was harvested with a Zurn 150 combine (Zürn Harvesting GmbH & Co. KG., Schöntal-Westernhausen, Germany) at a moisture content of approximately 20% on October 24, 2019, September 15 and 30, 2020, and October 20, 2021. Final rough rice grain yield was adjusted to 12% moisture content.

Subsamples of rough rice were collected at harvest to determine whole and total milled rice yield, grain chalking, length, and width. Whole and total milled rice yields were determined from cleaned 100-g subsamples of rough rice using the procedure outlined by Adair et al. (1972). Rice was mechanically hulled and milled in a Grainman No. 2 miller (Grain Machinery Manufacturing Corp., Miami, FL) for 30 s and size-separated with a No. 12 4.76-mm screen. Whole and total milled rice yields are expressed as a mass fraction of the original 100-g sample of rough rice. Grain characterization was performed utilizing WinSEEDLE^{TM} (Regent Instruments Canada Inc., Régent Guay, QC G2G 1B5, Canada) and grain length, width, and chalking were recorded.

Data were regressed against paraquat rate 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). Data which did not exhibit a significant trend were subjected to ANOVA using the PROC GLIMMIX procedure in SAS 9.4 (Statistical software Release 9.4, SAS Institute, SAS Institute Inc., Cary, NC) with siteyear and replication (nested within experimental run) as random effects parameters (Blouin et al. 2011). Estimates of least square means were utilized for mean separation (α=0.05).

Reproductive Study

Field research similar to that described for the Vegetative Study was conducted from 2019 to 2021 at the Mississippi State University's Delta Research and Extension Center in Stoneville, MS. However, this study evaluated rice exposure to a range of sub-lethal concentrations of paraquat during reproductive growth. Rice was drill-seeded on May 2 and 28, 2019, May 12 and 20, 2020, and June 17, 2021. Coordinates, soil information, site maintenance, and plot size were the same as for the Vegetative Study.

The experimental design was a randomized complete block with four replications. Paraquat was applied at 28, 7, 1.75, 0.43, 0.21 g ha^{-1} at 7 d after 50% heading. These concentrations correspond to 1/10, 1/40, 1/160, 1/640, and 1/1280 times the suggested use rate for paraquat as a harvest aid for soybean desiccation (Anonymous 2016; Bond et al. 2021). Visible estimates of aboveground rice injury, rice height, yield (rough, whole, and total milled rice), grain chalking, and grain characterization were collected as previously described. Rice was harvested with a small-plot combine on October 2, 2019, September 15 and 30, 2020, and October 20, 2021, and final rough rice grain yield was adjusted to 12% moisture content. Data analyses were performed as previously described for the Vegetative Study.

Results and Discussion

Vegetative Study

A linear trend was detected for rice injury 3, 7, 14, 21, and 28 DAT (Figure 2.1). Data for each of these evaluations were clustered and leveraged by the 1/10 concentration. Rice injury at 84 g ai ha^{-1} concentration increased from 49% 3 DAT to 58% 14 DAT. By 28 DAT, rice injury had declined to 48%. Previous research evaluating early-season rice response to off-target movement of paraquat at 84 g ha^{-1} reported rice was injured $\geq$ 41% 28 DAT regardless of application timing (Lawrence et al. 2020). Injury 14 DAT was greatest following paraquat applied to spiking to one-leaf rice; however, by 28 DAT, injury was greatest following applications to three- to four-leaf rice, 7 d following flood establishment, and at PD, with $\geq$ 50% injury following exposure at PD (Lawrence et al. 2020). The paraquat rate utilized by Lawrence et al. (2020) corresponds with the highest rate utilized in the current work. Ellis et al. (2003) documented $\geq$ 78% rice injury 14 DAT with glyphosate at 140 g ha^{-1} applied to rice in the two-to three- leaf growth stage. By 28 DAT, this same concentration of glyphosate injured rice 98% (Ellis et al. 2003).

A linear trend was detected for delay in heading, rough rice yield, and grain lenth (Figures 2.2, 2.3, and 2.4). Delay in heading was 3 d following exposure to paraquat at 84 g ai ha^{-1} (Figure 2.2). Therefore, every 1 g of paraquat applied to rice EPOST resulted in a delay in 50% heading of approximately 0.03 d. Similar research reported delays in heading increased linearly as paraquat exposure timing was delayed later in the growing season (Lawrence et al. 2020). On average, delays in rice heading increased 0.26 d d^{-1} following paraquat exposure from the one-leaf stage through PD (Lawrence et al. 2020). Rough rice yield was reduced with the highest concentration of paraqaut (Figure 2.3). For every 1 g of paraquat applied to rice, a yield loss of 30 kg ha^{-1} was observed. The greatest yield reduction ($\geq$ 26% of the nontreated) occurred with 84 g ai ha^{-1}. Lawrence et al. (2020) reported rough rice yields were reduced to 8% of the nontreated following rice exposure to paraquat at 84 g ha^{-1} at PD; however, rice exposed at the one-leaf stage produced yields 94% of the nontreated control. Similarly, Ellis et. al (2003) documented rice yield reductions of 67 to 99% when glyphosate at 140 g ha^{-1} was applied to rice in the vegetative phase. Grain length was reduced with the highest concentration of paraquat (Figure 2.4). For every 1 g paraquat applied to rice, a reduction in 0.001 mm of grain length was observed.

Total milled rice yield was greatest (73%) following the lowest concentration of paraquat compared to the least total milled yield (69%) with the nontreated (Table 2.3). Grain width was similar to the nontreated (2.2 mm) following all sub-lethal concentrations of paraquat except paraquat at 1.3 g ha^{-1} which was greater than the nontreated (2.3 mm) (Table 2.2). Whole milled rice yield ranged from 53 to 56 g with the greatest yield following paraquat at 84 and 1.3 g ha^{-1} (>55%). Grain chalking was ≤ 7% for all treatments, including the nontreated (Table 2.2).

To simulate off-target herbicide movement, applications ranging from 1/10 to 1/100 of labeled rates have most often been utilized (Al-Khatib et al. 2003; Lawrence et al. 2017, 2020; Roider et al. 2007; Wolf et al. 1993). In the current study, the lowest paraquat concentration (0.65 g ha^{-1}) was 1/1280 times the suggested rate for preplant paraquat applications; however, visible rice injury still occurred. This suggests that rice is highly sensitive to a sub-lethal concentration of paraquat during vegetative growth. In Mississippi, rice is planted adjacent to corn, cotton, and soybean and is often in early seedling growth stages when preplant and/or PRE herbicides are applied to these crops based on proximity as well as planting dates. Therefore, extreme caution should be taken when applying paraquat-based treatments in close proximity to sensitive rice fields, especially if environmental conditions are conducive for off-target movement.

Reproductive Study

A linear trend was detected for rice injury 7 and 14 DAT (Figure 2.5). At 7 and 14 DAT, the greatest injury was 14 and 16%, respectively, with the 1/10 paraquat concentration. No discernible trend was detected for rice injury 21 and 28 DAT. Injury ranged from 8 to 13% with paraquat at 28 g ai ha^{-1} having the greatest injury 21 and 28 DAT (Table 2.3). Similar research reported paraquat applied at 28 g ha^{-1} injured rice 5 to 18% 3 to 28 DAT, respectively, regardless of application timing (McCoy et al. 2020). The paraquat rate utilized by McCoy et al. (2020) corresponds with the highest rate utilized in the current study. In other research, rice injury 28 d after PD was 19 to 35% from glyphosate at 140 g ha^{-1} (Ellis et al. 2003). Webster et al. (2015)

reported the greatest injury from glufosinate applied to rice at a sub-lethal concentration during boot was 24% 7 DAT.

Linear trends were detected for rough rice yield, whole milled rice yield, and grain chalking (Figures 2.6, 2.7, and 2.8). Rough rice yield ranged from 12,600 to 8600 kg ha^{-1} and was reduced as great as 33% following paraquat at 28 g ai ha^{-1} (Figure 2.6). The lowest whole milled rice yield (50%) occurred following the greatest concentration of paraquat (Figure 2.7). Grain chalking was similar to the nontreated for all paraquat concentrations except 28 g ha^{-1}, which resulted in maximum chalking (12%) (Table 2.4). For every 1 g paraquat applied at 50% heading plus 7 d, chalk content increased 0.12%. Total milled rice yield was greatest (71%) with no paraquat exposure and least (68%) following exposure with 28 g ha^{-1} (Table 2.4). No discernable trend was detected for grain length and grain width. McCoy et al. (2020) reported rough rice yield following paraquat at 28 g ha^{-1} was reduced > 12% following paraquat exposure from 0 to 28 d after heading (DAH). When averaged across glufosinate concentration of 31 and 62 g ai ha^{-1}, applications during late reproductive development reduced primary rice yield to 90% of the nontreated control (Webster et al. 2015). Rough rice yield reductions following glyphosate at the boot growth stage were > 50% (Hensley et al. 2013). Similarly, wheat (*Triticum aestivum* L.) exposure to glyphosate at reproductive growth stages caused similar yield reductions of 54% (Roider et al. 2007). Although rice yield reductions in the Reproductive Study were not as severe as observed in the Vegetative Study, the current study suggests that rice is still sensitive to paraquat exposure during the reproductive growth stage.

Visible injury symptoms from off-target herbicide movement 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). Davis et al. (2011) reported glyphosate applications during the reproductive stages resulted in reduced injury than applications during vegetative stages. Similarly, rice injury following exposure to glyphosate at 140 g ha^{-1} applied at PD was ≤ 15%; however, yield reductions were 54% (Ellis et al. 2003). Ellis et al. (2003) also reported yield reductions ≤ 30% following glufosinate applied at 53 g ha^{-1} at PD. In the current study, rice injury ranged from 5 to 16% following exposure to the greatest concentration of paraquat (28 g ha^{-1}); however, a 33% yield reduction occurred. Based on these data, rice is sensitive to paraquat at 3% its labeled rate during the reproductive growth stage.

The current research demonstrates that, although visible rice injury following paraquat exposure was ≥ 48% during the vegetative stage and ≤ 16% during the reproductive stage, late-season paraquat exposure had a significant effect on rough rice yield. Because paraquat can be utilized as a herbicide, desiccant, defoliant, and plant growth regulator (Anonymous 2016) in Mississippi, application timings for preplant weed control can occur across a broad range of dates in which rice can be in different stages of vegetative growth. Likewise, harvest aid applications can occur over a varied range of dates encompassing a large window of rice reproductive growth. Although the effects of off-target movement of paraquat on rice may not be visibly apparent, the potential effect on rough rice yield could be detrimental. Therefore, producers should consider strategies to mitigate off-target movement when applying paraquat-based herbicide treatments including making applications during periods of low wind and wind direction away from rice.

The objective of this research was to characterize the effects of sub-lethal paraquat applications on rice when exposed during vegetative and reproductive growth phases.To do so, the highest concentrations in both studies (84 and 28 g ha^{-1}) were selected as worst-case-scenarios based on previous research by Lawrence et al. (2020) and McCoy et al. (2020).

Corresponding rates were then chosen as 1/4, 1/16, 1/64, and 1/128 of the highest rate. However, failure to use a log scale resulted in clustered data points for the lower rates. Because no data points existed between the cluster and the highest rate, we were unable to statistically anchor the 1/10X rate. Using a log scale would have allowed for the calculation of a LD10 (rate causing 10% injury) enabling the ability to better pinpoint the rate that is non-injurious to rice.

Table 2.1 Geographic location, soil classification, and agronomic information for field studies evaluating rice response to sub-lethal concentrations of paraquat during the vegetative and reproductive growth phases at the Mississippi State University Delta Research and Extension Center in Stoneville, MS.

Site-year	Coordinates	Soil series	Description	pH	OM
					%
2019	33°26'33.34"N 90°54'19.11"W	Sharkey clay	Very-fine, smectitic, thermic Chromic Eqiaquerts	8.2	2.1
2020 A	33°26'37.19"N 90°54'14.26"W	Sharkey clay	Very-fine, smectitic, thermic Chromic Eqiaquerts	8.2	2.1
2020 B	32°26'10.35"N 90°54'20.11"W	Commerce silty clay loam	Fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts	7.6	1.8
2021	33°26'27.16"N 90°54'20.22"W	Commerce silty clay loam	Fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts	7.6	1.8

Table 2.2 Total and whole milled rice yield, grain chalking, length, and width following exposure to a range of sub-lethal concentrations of paraquat in the Vegetative Study at Stoneville, MS from 2019 to 2021[a].

Concentraion[b]	Total milled yield	Whole milled yield	Grain chalking	Grain length	Grain width
g ai ha^{-1}	%	%	%	mm	mm
0	69 b	53 c	7 b	6.70 a	2.21 b
0.65	73 a	54 b	6 c	6.68 a	2.23 ab
1.3	72 ab	55 a	9 a	6.70 a	2.26 a
5.2	70 b	52 c	5 c	6.63 ab	2.21 b
21	72 ab	54 b	7 b	6.65 ab	2.22 ab
84	72 ab	56 a	7 b	6.57 b	2.21 b

[a] Data were pooled over four siteyears. Means followed by the same letter for each parameter are not different at $p \leq 0.05$.

[b] Rates included 1/10, 1/40, 1/160, 1/640, and 1/1280 times the suggested use rate for preplant paraquat application.

Table 2.3 Rice injury 21and 28 d after treatment (DAT) following exposure to a range of sub-lethal concentrations of paraquat in the Reproductive Study at Stoneville, MS from 2019 to 2021[a].

	Injury	
Concentration[b]	21 DAT	28 DAT
g ai ha^{-1}	——%	——
0	0 c	0 c
0.21	9 b	9 b
0.43	9 b	9 b
1.75	8 b	8 b
7	8 b	8 b
28	13 a	13 a

[a] Data were pooled over five siteyears. Means followed by the same letter for each parameter are not different at $p \leq 0.05$.

[b] Rates included 1/10, 1/40, 1/160, 1/640, and 1/1280 times the suggested use rate for soybean desiccation.

Table 2.4 Total and whole milled rice yield, grain chalking, length, and width following exposure to various rates of paraquat in the Reproductive Study at Stoneville, MS from 2019 to 2021[a].

Concentration[b]	Total milled yield	Whole milled yield	Grain chalking	Grain length	Grain width
g ai ha^{-1}	%	%	%	mm	mm
0	71 a	55 b	9 b	6.77 a	2.54 a
0.21	70 ab	57 a	9 b	6.73 a	2.25 a
0.43	70 ab	57 a	8 b	6.74 a	2.24 a
1.75	70 ab	57 a	9 b	6.68 a	2.22 a
7	69 ab	53 b	8 b	6.69 a	2.22 a
28	68 b	50 c	12 a	6.67 a	2.23 a

[a] Data were pooled over five siteyears. Means followed by the same letter for each parameter are not different at $p \leq 0.05$.
[b] Rates included 1/10, 1/40, 1/160, 1/640, and 1/1280 times the suggested use rate for soybean desiccation.

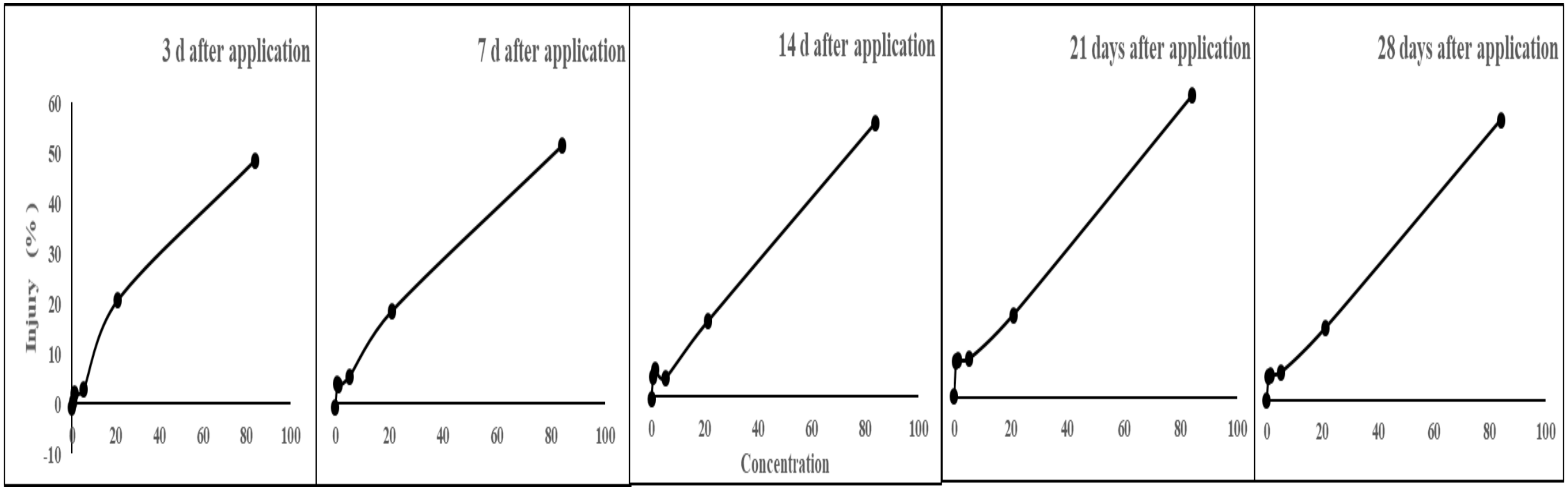

Figure 2.1 Rice injury 3, 7, 14, 21, and 28 d after treatment (DAT) following rice exposure to paraquat with various concentrations in the Vegetative Study at Stoneville, MS, from 2019 to 2021.

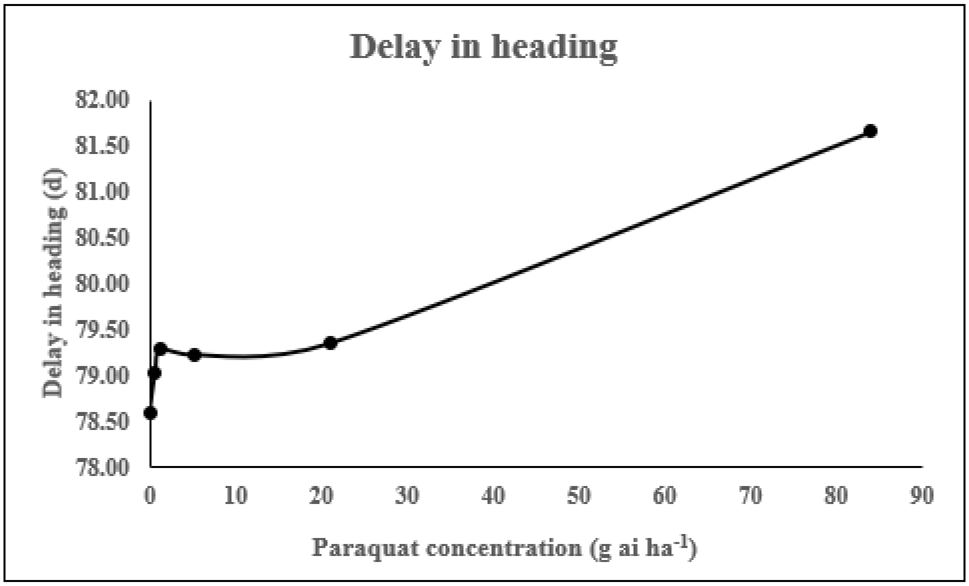

Figure 2.2 Delay in heading following paraquat exposure with various concentrations in the Vegetative Study in Stoneville, MS, from 2019 to 2021.

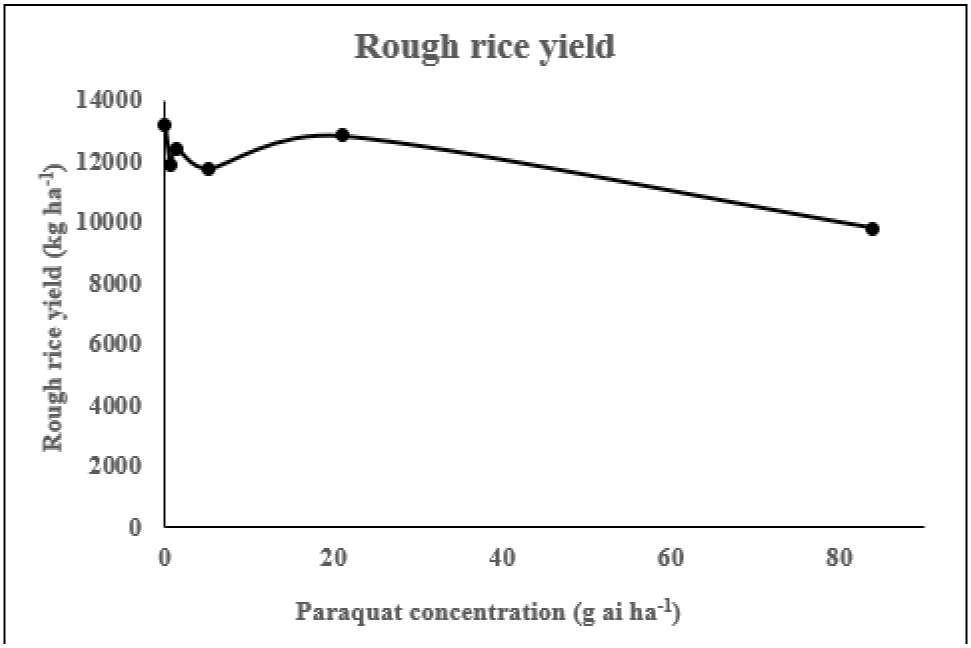

Figure 2.3 Rough rice yield following paraquat exposure with various concentrations in the Vegetative Study in Stoneville, MS, from 2019 to 2021.

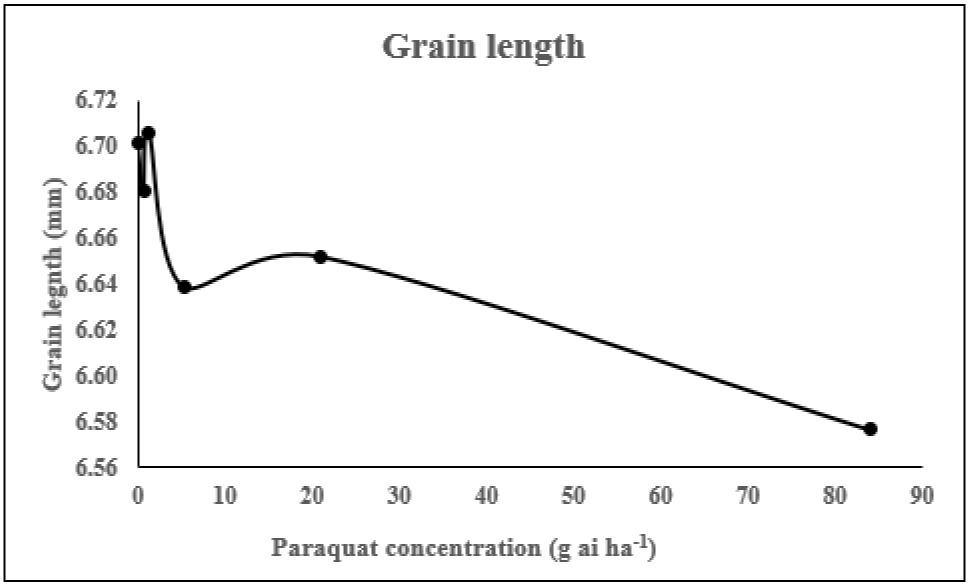

Figure 2.4 Rice grain length following paraquat exposure with various concentrations in the Vegetative Study in Stoneville, MS, from 2019 to 2021.

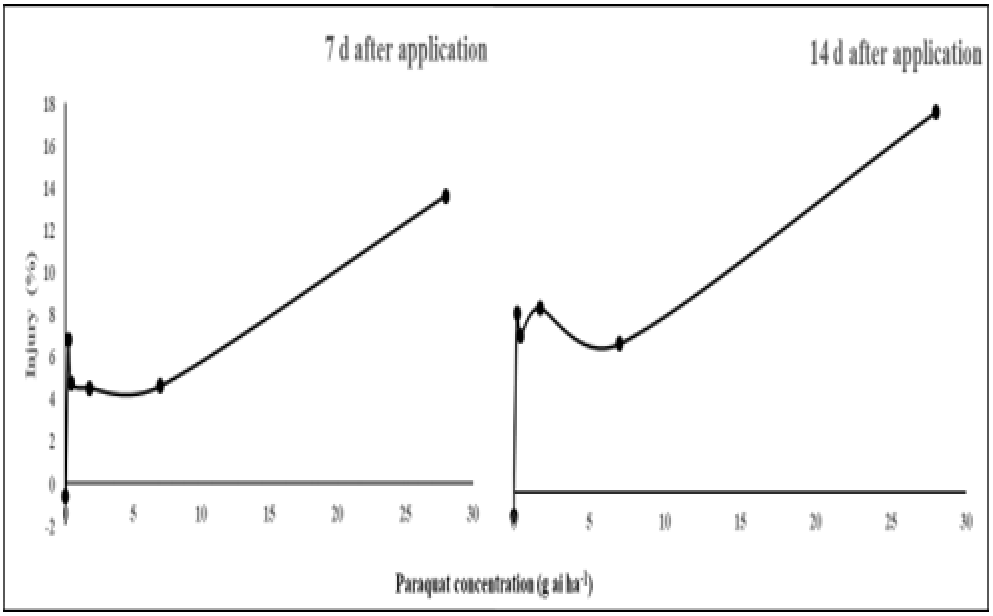

Figure 2.5 Rice injury following paraquat exposure with various concentrations in the Reproductive Study in Stoneville, MS, from 2019 to 2021.

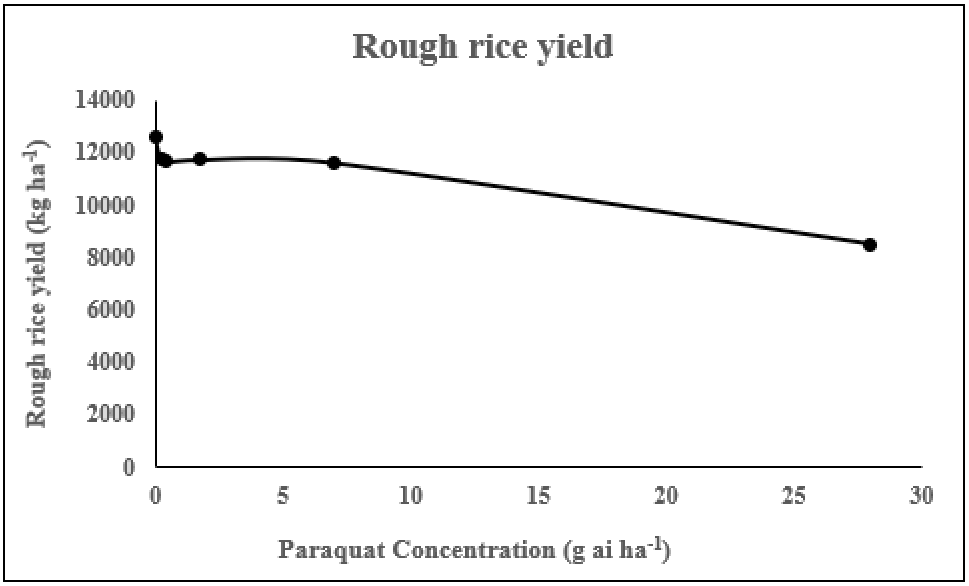

Figure 2.6 Rice injury following paraquat exposure with various concentrations in the Reproductive Study in Stoneville, MS, from 2019 to 2021.

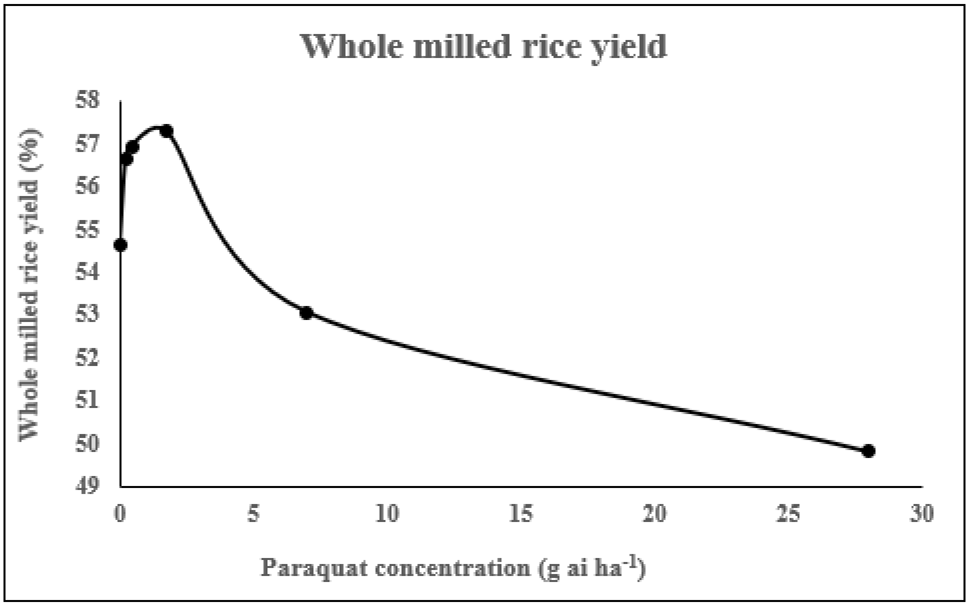

Figure 2.7 Whole milled rice yield following paraquat exposure with various concentrations in the Reproductive Study in Stoneville, MS, from 2019 to 2021.

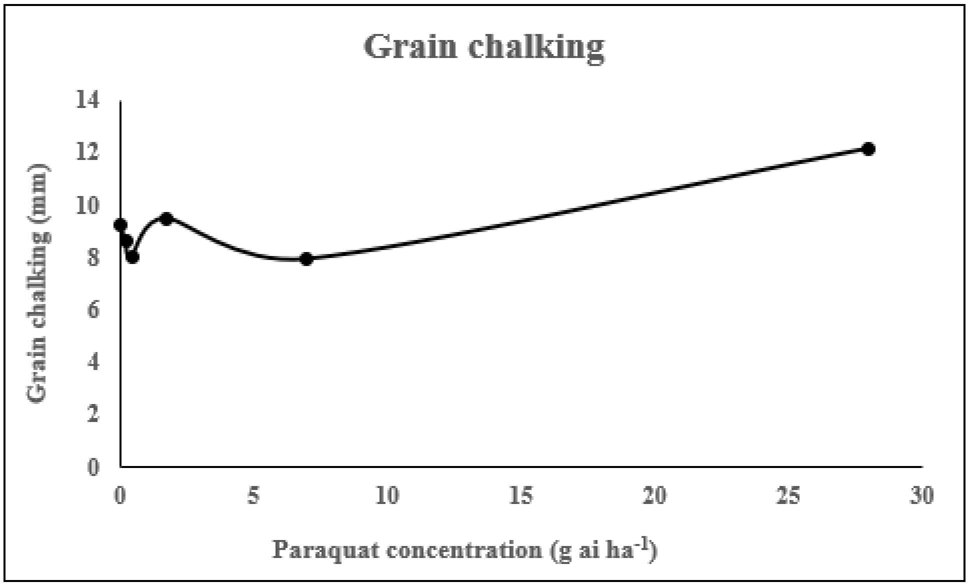

Figure 2.8 Rice grain chalking following paraquat exposure with various concentrations in the Reproductive Study in Stoneville, MS, from 2019 to 2021.

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CHAPTER III

CHARACTERIZATION OF RICE EXPOSURE TO A SUB-LETHAL CONCENTRATION OF PARAQUAT AT DIFFERENT STAGES OF REPRODUCTIVE GROWH

Abstract

Rice reproductive growth and grain filling and ripening often coincide with soybean maturation and harvest throughout Mississippi, creating potential for off-target herbicide movement from desiccants applied to soybean. Field studies were conducted in Stoneville, MS from 2019 to 2021 to characterize rice response to exposure to a sub-lethal concentration of paraquat at different stages of reproductive growth. Paraquat was applied at 28 g ha^{-1} to rice at panicle differentiation (PD), 2.5-cm internode elongation (IE), 7.5-cm IE, 12.5-cm IE, 5% heading, milk, soft dough, hard dough, and 25% moisture content. Quadratic trends were detected for rice injury 7 and 28 DAT. At 7 DAT, injury was < 8% from paraquat exposure at 2352 GDD (milk stage). Maximum rice injury 28 DAT was > 55% with exposure at 1351 GDD (PD); however, rice injury decreased to 19% from exposure at 2551 and 2704 GDD (soft and hard dough). No trend was detected for rice injury 14 DAT, and injury ranged from 13 to 21% across reproductive growth stages. Rice injury 21 DAT decreased linearly as GDD increased. Maximum rice injury of >32% occurred from exposure at 1351 GDD (PD) and minimum injury of 18% with exposure at 2704 GDD (hard dough). Rice yield was most affected following exposure to paraquat during the early compared with later reproductive stages. The greatest yield reduction occurred with exposure at 1688 GDD (7.5-cm IE) where yield was reduced to

19% of the nontreated control. The current research demonstrates that rice is highly sensitive to a sub-lethal concentration of paraquat throughout reproductive growth. Rice exposure to paraquat during early reproductive growth stages led to increased injury over time and had a detrimental effect on rough rice yield compared to exposure during later growth stages.

Nomenclature: Paraquat; rice, *Oryza sativa* L. ‘CL153’.

Key words: Growing degree days, hard dough, heading, internode elongation, milk, moisture content, panicle differentiation, reproductive growth, soft dough

Introduction

Rice morphology is divided into three phases: vegetative, reproductive, and grain filling/ripening (Beighley 2012; Dunand and Saichuk 2014; Moldenhauer and Gibbons 2003; Moldenhauer et al. 2013). The vegetative phase includes germination, seedling establishment, and tillering stages and is characterized by active tillering, a gradual increase in plant height, and leaf emergence at regular intervals (Moldenhauer et al. 2013). The reproductive phase is divided into multiple stages including panicle initiation (PI; formation of panicles on the uppermost node of the culm and with nodes still stacked); internode elongation (IE; nodes elongate and move up the stem); panicle differentiation (PD; panicle inside the stem approximately 0.3 cm in length); booting (panicles swell within the leaf sheath); and several heading (HEAD) stages (Buehring 2008; Moldenhauer et al. 1994; Smith and Dilday 2003). Heading can be characterized as culm elongation, reduced tiller production, flag leaf emergence, head emergence, and spikelet flowering (Moldenhauer et al. 2013; Moldenhauer and Gibbons 2003). Agronomically, HEAD is defined as the time when 50% of booting culms have partially exerted panicles (Smith and Dilday 2003). The ripening period involves several stages including milk (grain exhibits milky consistency), soft dough (grain has soft consistency), hard dough (grain has hardconsistency), and maturity (Buehring 2008; Smith and Dilday 2003; Yoshida 1981).

Rice in the southern U.S. is routinely drill-seeded in the same window when preplant and/or preemergence (PRE) herbicide applications are applied to corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybean [*Glycine max* (L.) Merr.] (Buehring 2008). Paraquat-based herbicide treatments are commonly recommended in these preplant and/or PRE applications (Anonymous 2016; Bond et al. 2021); therefore, off-target movement onto adjacent rice fields may occur. Off-target movement is defined as the physical movement of a pesticide through air at the time of application, or soon thereafter, to any site other than that intended for application (EPA 2019; Henry et al 2004) and can result in visible injury, delayed maturity, and yield losses in sensitive crops in adjacent fields (Boutin et al. 2014). For rice, the magnitude of damage from off-target movement of a paraquat-based herbicide application depends on the concentration that moves to the rice and the growth stage at the time of the off-target event (Lawrence et al. 2020b).

Previous research evaluating rice response following late-season exposure to paraquat reported that paraquat at 70 g ai ha^{-1} injured rice ≥ 40% when applied at early-boot, late-boot, and HEAD stages with the greatest injury (71%) at HEAD (Calhoun et al. 2016). Injury was ≥ 79% following paraquat applied to rice at the soft dough and hard dough stages. Rice yield was reduced ≥ 90% with paraquat at early-boot and late-boot stages and ≥ 55% at the soft dough stage compared with the nontreated. Paraquat at 28 g ha^{-1} injured rice 5 to 25% when applied at 50% heading (McCoy et al. 2020). This same research reported 2080, 2480, and 2020 kg ha^{-1} yield losses from paraquat applied at 50% heading, 50% heading plus 7 d, and 50% heading plus

14 d, respectively. The yield losses were 1280 and 610 kg ha^{-1} following paraquat applied to rice 21 and 28 d after 50% heading, respectively.

Rice reproductive growth and grain filling and ripening often coincide with soybean maturation and harvest throughout Mississippi, creating potential for off-target herbicide movement from desiccants applied to soybean. In recent years, research has demonstrated that rice is especially sensitive to off-target movement of paraquat (Calhoun et al. 2016; Lawrence et al. 2020a, 2020b; McCoy et al. 2020). Lawrence et al. (2020b) reported ≥ 41% injury following early-season exposure to paraquat, with delays in rice maturity > 6 d regardless of growth stage at time of exposure. The extent of injury and yield loss from off-target movement of paraquat is largely influenced by the rice growth stage at the time of exposure and the concentration that moves to the non-target crop (Lawrence et al. 2020b; McCoy et al. 2020). Although previous research has reported rice response following late-season exposure to paraquat beginning at 50% (Calhoun et al. 2016; McCoy et al. 2020), rice response following exposure to paraquat throughout the range of reproductive stages has not been documented. Therefore, research was conducted to evaluate rice response following exposure to a sub-lethal concentration of paraquat applied at different reproductive growth stages.

Materials and Methods

Field research was established at the Mississippi State University Delta Research and Extension Center in Stoneville, MS, from 2019 to 2021 to evaluate rice response following exposure to a sub-lethal concentration of paraquat at different reproductive growth stages. Global positioning system coordinates, soil series, soil description, soil pH, and soil organic matter (OM) are described in Table 3.1. The experimental site included a rice-fallow rotation where rice was seeded every other year. Glyphosate (Roundup PowerMax 4.5 L, 1120 g ae ha^{-1}, Bayer CropScience, St. Louis, MO), paraquat (Gramoxone 2.0 SL, 560 g ha^{-1}, Syngenta Crop Protection, Greensboro, NC), and/or 2,4-D (2,4-D Amine 3.8 SL, 1,120 g ae ha^{-1}, Agri Star, Ankeny, IA) were applied in late-March to early-April each year to control emerged vegetation prior to seeding.

Rice cultivar 'CL153' (HorizonAg, Memphis, TN 38125) was drill-seeded May 2 and 28, 2019, May 12 and 20, 2020, and June 17, 2021, at 356 seed m^{-2} to a depth of 2 cm using a small-plot grain drill (Great Plains 1520, Great Plains Mfg, Inc., Salina, KS). Plots were 0.6 × 4.6 m and consisted of nine rows of rice bordered on either end by a 1.5-m alley that contained no rice. Nitrogen fertilizer was applied at 168 kg ha^{-1} as urea (46-0-0) immediately prior to flooding (Norman et al. 2013). Plots were flooded to an approximate depth of 6 to 10 cm when rice reached the one- to two-tiller stage. Rice was managed throughout the growing season utilizing local guidelines to optimize yield (Buehring 2008).

The experimental design was a randomized complete block with four replications. Paraquat was applied at 28 g ha^{-1} to rice at panicle differentiation (PD), 2.5-, 7.5-, and 12.75-cm IE, 5% HEAD (5% of panicles emerged from bottom of flag leaf), milk, soft dough, hard dough, and 25% moisture content. A nontreated control was included for comparison. All herbicide treatments included NIS (Activator 90, 90% non-ionic surfactant, Loveland Products, Greeley, CO) at 0.5% v/v and were applied using a CO_2-pressurized backpack sprayer equipped with flat-fan nozzles (Airmix 11002 nozzle, Greenleaf Technologies, Covington, LA) set to deliver 140 L ha^{-1} at 206 kPa using water as a carrier. Simulated off-target movement is tested with a constant carrier volume to reduce herbicide concentrations and mimic low concentration exposure (Davis et al. 2011; Ellis et al. 2002).

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 herbicide and 100 indicated complete plant death. Rice plant height was recorded 14 DAT and at maturity 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. Plots were drained approximately 2 wk before harvest maturity. Rice was harvested with a Zurn 150 combine (Zürn Harvesting GmbH & Co. KG., Schöntal-Westernhausen, Germany) at a moisture content of approximately 20% on October 24, 2019, September 15 and 30, 2020, and October 20, 2021. Final rough rice grain yield was adjusted to 12% moisture content.

Subsamples of rough rice were collected at harvest to determine whole and total milled rice yield, grain chalking, length, and width. Whole and total milled rice yields were determined from cleaned 100-g subsamples of rough rice using the procedure outlined by Adair et al. (1972). Rice was mechanically hulled and milled in a Grainman No. 2 miller (Grain Machinery Manufacturing Corp., Miami, FL) for 30 s and size-separated with a No. 12 4.76-mm screen. Whole and total milled rice yields are expressed as a mass fraction of the original 100-g sample of rough rice. Grain characterization was performed utilizing WinSEEDLE^{TM} (Regent Instruments Canada Inc., Régent Guay, QC G2G 1B5, Canada) and grain length, width, and chalking were recorded.

Data were regressed against growing degree days (GDD; heat units used to estimate the growth and development from rice emergence to each reproductive growth stage) (Table 2.2) allowing for both linear and quadratic terms with coefficients depending on GDD, and non-significant model terms were removed sequentially until a satisfactory model was obtained (Golden et al. 2006). Data which did not exhibit a significant trend were subjected to ANOVA using the PROC GLIMMIX procedure in SAS v. 9.4 (Statistical software Release 9.4, SAS Institute, SAS Institute Inc., Cary, NC) with siteyear and replication (nested within experimental run) as random effects parameters (Blouin et al. 2011). Estimates of least square means were utilized for mean separation (α=0.05).

Results and Discussion

Quadratic trends were detected for rice injury 7 and 28 DAT (Figure 3.1). At 7 DAT, injury was ≤ 8% from paraquat exposure at 2352 GDD (milk stage). Maximum rice injury 28 DAT was ≥ 55% with exposure at 1351 GDD (PD); however, rice injury decreased to 19% from exposure at 2551 and 2704 GDD (soft and hard dough). No trend was detected for rice injury 14 DAT, and injury ranged from 13 to 21% across reproductive growth stages. Rice injury 21 DAT decreased linearly as GDD increased. Maximum rice injury of ≥ 32% occurred from exposure at 1351 GDD (PD) and minimum injury of 18% with exposure at 2704 GDD (hard dough). Previous research reported that paraquat injured rice ≥ 50% injury following exposure at PD (Lawrence et al. 2020b). Calhoun et al. (2016) reported rice injury ≥ 40% from paraquat exposure at early- and late-boot stages and at HEAD. McCoy et al. (2020) reported rice injury ranging from 5 to 18% from 50% heading to the day of drain. They attributed less rice injury during the later reproductive growth stages to the natural desiccation of the rice plant, which led to injury symptoms being less apparent (McCoy et al. 2020).

A cubic trend was detected for rough rice yield (Figure 3.2). Rough rice yield was reduced with paraquat exposure at each stage of reproductive growth compared with the nontreated control. Rice yield was most affected following exposure to paraquat during the early compared with later reproductive stages. The greatest yield reduction occurred with exposure at 1903 GDD (12-cm IE) where yield was reduced to 19% of the nontreated. Similarly, Lawrence et al. (2020b) reported paraquat applied at PD reduced rice yield to 8% of the nontreated control. Additionally, rice in the reproductive growth stages from internode elongation to booting was more susceptible to glyphosate, with yields reduced up to 99% following glyphosate exposure in the boot growth stage (Ellis et al. 2003). However, little visible injury was apparent during the boot growth stage. Hensley et al. (2013) reported glyphosate at 54 and 108 g ha^{-1} at one-tiller, PD, and boot growth stages resulted in significant yield reductions while applications to mature rice had no effect. Kurtz and Street (2003) reported visible injury due to glyphosate exposure; however, there was not a correlation to rice yield losses as visible injury decreased at later growth stages while yield reductions increased. On the contrary, the current study demonstrates that rice exposure to paraquat during the early reproductive stages results in the greatest injury and yield reductions compared to later reproductive stages.

Total and whole milled rice yield ranged from 53 to 70% and 50 to 63%, respectively (Table 3.3); however, there was no biological trend to fit the data. Rice exposed to paraquat at 1903 GDD (12.5-cm IE) exhibited the greatest reduction in milling quality at 53 and 50% whole and total milled rice yield, respectively. Whole milled yield was reduced at least 10% with paraquat exposure at each reproductive stage. Koger et al. (2005) reported rice exposure to a sub-lethal concentration of glyphosate was characterized by fewer kernels, blanked kernels, panicle deformation, and the malformation of kernels; however, no differences were observed in rice milling yield.

No discernable trends for grain chalking, width, and length were detected (Table 3.3). Following paraquat exposure, chalking from exposure at 2551 GDD (soft dough) was 8% with as much as 14% chalk from exposure at 1903 GDD (12.5-cm IE) compared to the nontreated with 7% chalk. Grain width and length were approximately 6.7 and 2.2 mm, respectively (Table 3.3).

Traits of grain quality dictate market value and are a determining factor in economic returns for a grower. The length:breadth ratio (L/B) falling between 2.5 and 3.0 has been considered acceptable as long as the length is more than 6 mm (Kaul 1970). Chalkiness is influenced by both genetic background and the environment (Krishnan and Rao 2005) including temperature and soil water status (Dingkuhn and Gal 1996). Based on the length:breadth ratio and chalking observed in the current study, rice would be expected to have high market acceptability following paraquat exposure.

The use of paraquat as a soybean desiccant in Mississippi is recommended at a use rate of 140 to 280 g ha^{-1} when soybeans are fully developed with at least half of the leaves dropped and remaining leaves turning yellow, and a pre-harvest interval of 15 d is required after application (Bond et al. 2021). Rice reproductive growth and grain filling and ripening often coincide with soybean maturation and harvest throughout Mississippi, creating potential for off-target herbicide movement from desiccants applied to soybean. McCoy et al. (2020) reported paraquat applications inhibited the ability of the rice plant to complete proper reproduction as evidenced by reductions in rough rice yield, total seed weight, total number of seed, and seed $panicle^{-1}$ (McCoy et al. 2020). Proper grain-fill during ripening was also inhibited due to paraquat applications, as indicated by the reductions of 1,000-grain weight and head rice yield (McCoy et al. 2020). The objective of the current research was to characterize rice response to exposure to a sub-lethal concentration of paraquat at different stages of reproductive growth. This research demonstrates that rice is highly sensitive to a sub-lethal concentration of paraquat throughout reproductive growth. Rice exposure to paraquat during early reproductive growth stages led to increased injury over time and had a detrimental effect on rough rice yield compared to exposure during later growth stages. Although the effect of off-target movement of paraquat on rice may not be apparent by visible observation, the potential effect on yield could be devastating. Therefore, caution should be taken when applying paraquat as a desiccant near rice that is undergoing reproductive growth, especially when making applications when rice is in the early reproductive growth states.

Table 3.1 Geographic location, soil classification, and agronomic information for field studies evaluating rice response to a sub-lethal concentration of paraquat at different stages of reproductive growth at the Mississippi State University Delta Research and Extension Center in Stoneville, MS.

Site-year	Coordinates	Soil series	Description	pH	OM
					%
2019 A	33°26'31.17"N 90°54'20.04"W	Sharkey clay	Very-fine, smectitic, thermic Chromic Eqiaquerts	8.2	2.1
2019 B	33°26'04.34"N 90°54'25.22"W	Commerce silty clay loam	Fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts	7.6	1.8
2020 A	33°26'35.39"N 90°54'20.11"W	Sharkey clay	Very-fine, smectitic, thermic Chromic Eqiaquerts	8.2	2.1
2020 B	32°26'01.17"N 90°54'30.30"W	Commerce silty clay loam	Fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts	7.6	1.8
2021	33°26'24.44"N 90°54'28.16"W	Commerce silty clay loam	Fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts	7.6	1.8

Table 3.2 Mean growing degree days (GDD) from rice emergence to each reproductive growth stage in an experiment evaluating rice response to a sub-lethal concentration of paraquat during reproductive growth at Stoneville, MS from 2019 to 2021[a].

Reproductive stage	GDD[b]
Panicle Differentiation (PD)	1351
2.5-cm internode elongation (IE)	1481
7.5-cm internode elongation (IE)	1688
12.5-cm internode elongation (IE)	1903
5% head	2137
Milk	2352
Soft dough	2551
Hard dough	2704
25% moisture	2884

[a] Data were pooled over five experiments.

[b] GDD calculated by adding daily temperatures from rice emergence to each reproductive growth stage.

Table 3.3 Total and whole milled rice yield, grain chalking, length, and width for different reproductive growth stages following paraquat exposure at 28 g ai ha^{-1} at Stoneville, MS from 2019 to 2021a.

Growing degree days	Reproductive Stage	Total Milled Yield	Whole milled yield	Chalking	Length	Width
		g	g	%	mm	mm
Control	Control	72 a	72 a	7 e	6.65 ab	2.24 ab
1351	PD	66 b	61 b	13 a	6.65 ab	2.20 d
1481	2.5-cm IE	66 b	65 b	12 b	6.64 ab	2.23 b
1688	7.5-cm IE	57 d	57 b	13 a	6.66 ab	2.23 b
1903	12.5-cm IE	53 d	50 c	14 a	6.66 ab	2.22 c
2137	50% head	67 b	58 b	13 a	6.59 b	2.23 b
2352	Milk	63 c	56 b	12 b	6.72 a	2.26 a
2551	Soft dough	69 a	60 b	8 d	6.60 b	2.21 cd
2704	Hard dough	68 ab	63 b	10 c	6.72 a	2.24 ab
2884	25% moisture	70 a	63 b	10 c	6.66 ab	2.21 cd

[a] Data were pooled over five experiments. Means followed by the same letter for each parameter are not different at $p \leq 0.05$.

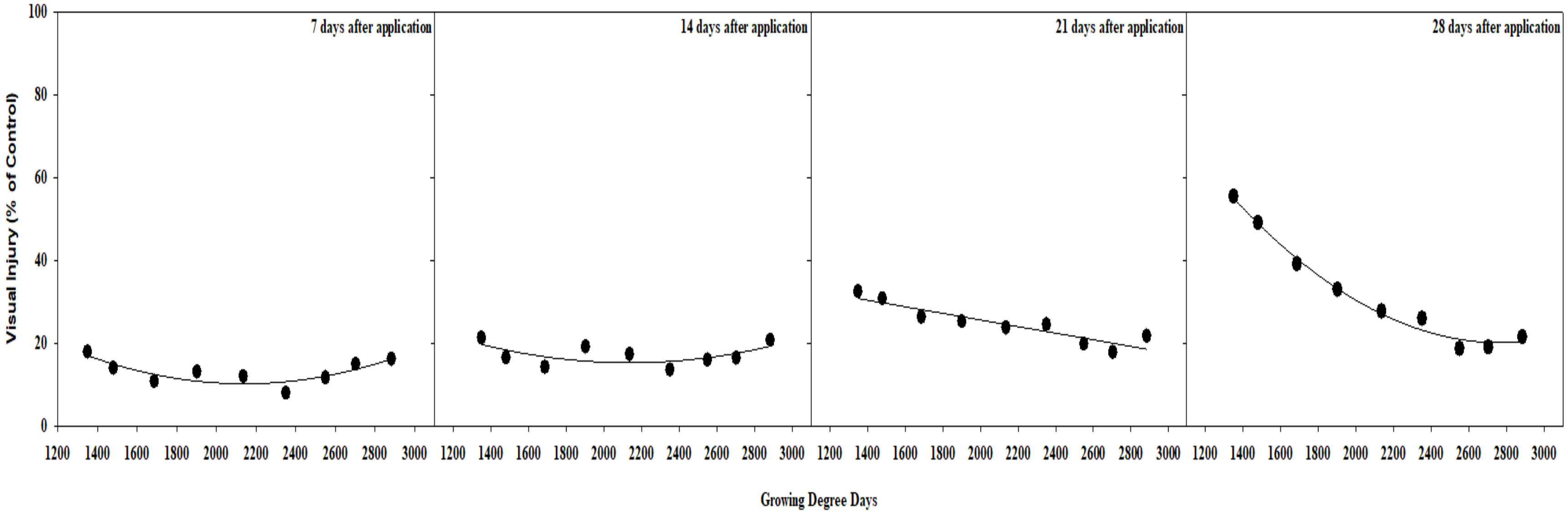

Figure 3.1 Rice injury 7, 14, 21, and 28 d after treatment (DAT) following rice exposure to paraquat at 28 g ai ha-1 for different GDD at Stoneville, MS, from 2019 to 2021

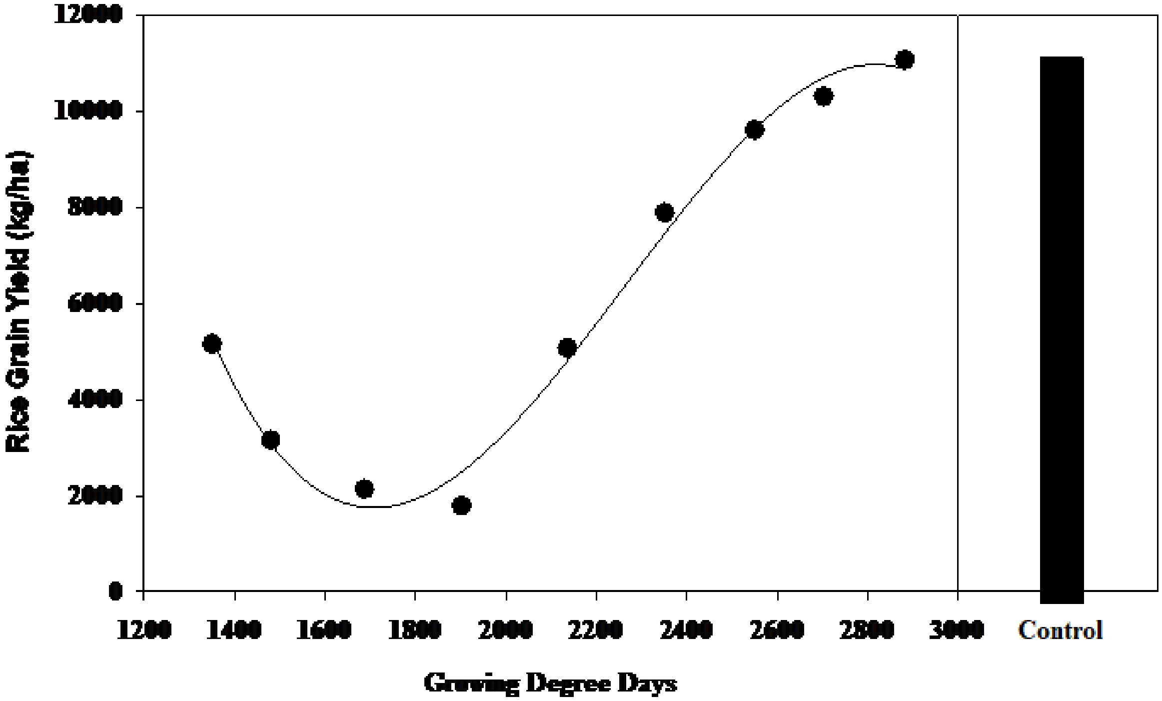

Figure 3.2 Rough rice yield following exposure to paraquat at 28 g ai ha-1 for different GDD at Stoneville, MS, from 2019 to 2021

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CHAPTER IV

BARNYARDGRASS (ECHINOCHLOA CRUS-GALLI) CONTROL AND RICE RESPONSE TO LABELED HERBICIDES FOLLOWIG EXPOSURE TO A SUB-LETHAL CONCENTRATION OF PARAQUAT

Abstract

In Mississippi, rice is often in early seedling growth stages when paraquat-based herbicide treatments are commonly applied to corn, cotton, and soybean; therefore, off-target movement onto adjacent rice fields may occur. After an off-target movement event has occurred, weed management is still necessary. Field studies were conducted in 2019, 2020, and 2021 at Stoneville, MS, to evaluate rice injury and barnyardgrass control with labeled herbicides after exposure to a sub-lethal concentration of paraquat. Labeled herbicide treatments were no herbicide treatment and imazethapyr at 105 g ai ha^{-1}, quinclorac at 420 g ai ha^{-1}, propanil at 3363 g ai ha^{-1}, bispyribac-sodium at 28 g ai ha^{-1}, cyhalopfop at 31 g ai ha^{-1}, and florpyrauxifen-benzyl at 29 g ai ha^{-1}. Rice injury was detected 7 and 28 days after treatment (DAT) with injury $\geq$ 35 and 14%, respectively, for all labeled herbicide. Florpyrauifen-benzyl and imazethapyr injured rice the greatest ($\geq$20%) 28 DAT. Following paraquat exposure, barnyardgrass control was similar for all labeled herbicide treatments 7, 14, and 28 DAT except with florpyrauxifen-benzyl (87%) and no labeled herbicide (paraquat alone) (84%) 7 DAT. Across all evaluations, barnyardgrass control was at least 12% greater following paraquat exposure and labeled herbicide treatments than no paraquat exposure. The current research demonstrates that labeled herbicides applied following exposure to a sub-lethal concentration of paraquat resulted in <

36% injury and provided as much as 95% control of barnyardgrass, depending on the herbicide treatment. Therefore, the labeled herbicides choice should be based on weed spectrum.

0Nomenclature: Paraquat; imazethapyr, quinclorac, propanil, bispyribac-sodium, cyhalofop, florpyrauxifen-benzyl; Barnyardgrass, *Echinochloa crus-galli* L. Beauv. ECHCG; rice, *Oryza sativa* L. 'CL153'.

Key words: Labeled herbicides, off-target movement, paraquat exposure

Introduction

Weeds are the primary pest of Mississippi rice and their control costs an estimated $7.5 to $15 million annually (Buehring and Bond 2008). Weeds compete with rice for sunlight, water, nutrients, and other growth requirements (Smith 1988). Factors such as weed species composition, weed density, duration of weed-rice interference, rice cultivar, seeding density, water management, and nutrient availability influence the degree of rice yield loss from weed interference (Odero and VanWeelden 2018). Weed infestations interfere with harvest operations, and weed seed contamination of rice grain lowers quality and may lower the economic value of the crop (Odero and VanWeelden 2018). Barnyardgrass is the most troublesome weed in Mississippi rice production (Webster 2012). Barnyardgrass is highly competitive with rice due to its adaptation to flooded environments, prolific seed production, and rapid growth (Marambe and Amarasinghe 2002).

Herbicides are the most widely utilized weed management strategy in U.S. crop production (Hill 1982; McWhorter and Shaw 1982). Glyphosate usage rapidly increased following the introduction and widespread adoption of glyphosate-resistant (GR) canola (*Brassica napus* L.), corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybean [*Glycine* *max* (L.) Merr.] (Shaner 2000). Failure to incorporate multiple herbicide modes of action (MOA), as well as other poor stewardship practices, has resulted in the development of GR weeds (Powles 2008). To combat GR weeds, paraquat plus residual herbicides are recommended preemergence (PRE) in GR cropping systems (Anonymous 2016; Bond et al. 2021).

Paraquat is a fast-acting, nonselective herbicide that rapidly kills a variety of annual and perennial grass and broadleaf weed species upon contact but provides no soil residual activity for control or suppression of these weeds (Bromilow 2004; Dodge 1971; Haley 1979). Paraquat acts by intercepting electrons between the bound ferredoxin acceptors and nicotinamide adenine dinucleotide phosphate ($NADP^+$) and then reducing oxygen to superoxide (O^{2-}) (Calderbank 1968). Hydroxyl radicals are generated that readily oxidize lipid membranes. In full sunlight, exposed vegetation becomes chlorotic within hours and necrotic within 1 to 3 d (Fuerst and Vaughn 1990).

Paraquat is utilized as a herbicide, desiccant, defoliant, and plant growth regulator (USDA-NASS 1997). It can be applied preplant, PRE, or post-directed in corn, cotton, peanut (*Arachis hypogaea* L.), soybean, grain sorghum [*Sorghum bicolor* (L.)], and other vegetable and fruit crops for nonselective weed control. However, paraquat is limited to preplant or PRE applications in rice (Anonymous 2016; Bond et al. 2021).

In Mississippi, rice is often in early seedling growth stages when preplant and/or PRE herbicides are applied to corn, cotton, and soybean. Paraquat-based herbicide treatments are commonly applied preplant and/or PRE in these crops; therefore, off-target movement onto adjacent rice fields may occur. Off-target movement is defined as the physical movement of a pesticide through air at the time of application, or soon thereafter, to any site other than that intended for application (EPA 2019; Henry et al 2004) and can result in crop damage, including visible injury, delayed maturity, and yield losses to sensitive crops in adjacent fields (Boutin et al. 2014).

For rice, the magnitude of damage from an off-target herbicide movement event depends upon the herbicide MOA, the herbicide rate, and the rice growth stage of the rice at the time of the event (Bond et al 2006; Ellis et al. 2003; Kurtz and Street 2003; Lawrence et al. 2020b; McCoy et al. 2020). Previous research evaluating early-season rice response to off-target movement of paraquat at 84 g ai ha^{-1} reported that rice was injured ≥ 41% regardless of application timing with ≥ 50% injury following exposure at panicle differentiation (PD) (Lawrence et al. 2020b). Delays in rice maturity were > 6 d regardless of growth stage at time of exposure with delays in maturity up to 2 wk following PD treatments. Rough rice yields were reduced to 8% of the nontreated following rice exposure to paraquat at PD (Lawrence et al. 2020b). Paraquat applied at 28 g ha^{-1} injured rice 5 to 25% when applied at 50% heading (McCoy et al. 2020). This same research reported 2,080, 2,480, and 2,020 kg ha^{-1} yield loss from paraquat applied at 50% heading, 50% heading plus 7 d and 14 d, respectively (McCoy et al. 2020).

After an off-target herbicide movement event has occurred, weed management is still necessary. However, no published work on rice response or weed control with labeled herbicides applied following exposure to sub-lethal concentrations of paraquat is available. Therefore, research was conducted to evaluate rice injury (Rice Response Study) and barnyardgrass control (Barnyardgrass Control Study) with labeled herbicides after exposure to a sub-lethal concentration of paraquat.

Materials and Methods

Rice Response Study

Field research was conducted from 2019 to 2021 at the Mississippi State University Delta Research and Extension Center in Stoneville, MS, to evaluate rice response to labeled herbicides after exposure to a sub-lethal concentration of paraquat. Global positioning system coordinates, soil series, soil description, soil pH, and soil organic matter (OM) for this study are listed in Table 4.1. The experimental site included a rice-fallow rotation where rice was seeded every other year. Glyphosate (Roundup PowerMax 4.5 L, 1,120 g ae ha^{-1}, Bayer CropScience, St. Louis, MO), paraquat (Gramoxone 2.0 SL, 560 g ha^{-1}, Syngenta Crop Protection, Greensboro, NC), and/or 2,4-D (2,4-D Amine 3.8 SL, 1,120 g ae ha^{-1}, Agri Star, Ankeny, IA) were applied in late-March to early-April each year to control emerged vegetation prior to seeding.

Rice cultivar, 'CL153' (HorizonAg, Memphis, TN) was drill-seeded at 356 seed m^{-2} on May 28, 2019, May 12 and 20, 2020, and June 17, 2021, to a depth of 2 cm using a small-plot grain drill (Great Plains 1520, Great Plains Mfg, Inc., Salina, KS). Plots were 0.6 by 4.6 m and consisted of 9 rows of rice bordered on either end by a 1.5-m alley that contained no rice. Nitrogen fertilizer was applied at 168 kg ha^{-1} as urea (46-0-0) immediately prior to flood establishment (Norman et al. 2013). Plots were flooded to an approximate depth of 6 to 10 cm when rice reached the one- to two-tiller stage. Rice was managed throughout the growing season utilizing local guidelines to optimize yield (Buehring 2008).

Treatments were arranged as a two-factor factorial within a randomized complete block design and four replications. Factor A was labeled herbicide treatment and consisted of no herbicide treatment and the herbicide products listed in Table 4.2 applied to rice in the three- to four-leaf (MPOST) growth stage. Factor B was paraquat exposure and consisted of paraquat applied at 0 and 84 g ha^{-1} applied to rice in the spiking to one-leaf (VEPOST) stage. Simulated off-target movement tested with constant carrier volume utilizes reduced herbicide rates to simulate low concentration exposure (Davis et al. 2011; Ellis et al. 2002; Lawrence et al. 2020b; McCoy et al. 2020). Paraquat treatments included NIS (Activator 90, 90% non-ionic surfactant, Loveland Products, Greeley, CO) at 0.5% (v/v). Imazethapyr and quinclorac treatments included petroleum oil surfactant (Herbimax, 83% petroleum oil, Loveland Products, Greeley, CO) at 1.67 % (v/v). Bispyribac-sodium treatments included surfactant – deposition aid (Phase II, 80% arbamides, alcohol ethoxylates, methylated esters of fatty acids and organosilicone surfactant, Loveland Products, Greeley, CO) at 1% (v/v). Cyhalofop treatments included methylated seed oil surfactant (MSO concentrate with Leci-Tech, 100% methylated seed oil, Loveland Products, Greeley, CO) at 1.67% (v/v). Florpyrauxifen-benzyl treatments included MSO at 0.42% (v/v). All treatments were applied using a CO_2-pressurized backpack sprayer equipped with flat-fan nozzles (Airmix 11002 nozzle, Greenleaf Technologies, Covington, LA) set to deliver 140 L ha^{-1} at 206 kPa using water as a carrier. Simulated off-target movement is tested with a constant carrier volume to reduce herbicide concentrations and mimic low concentration exposure (Davis et al. 2011; Ellis et al. 2002).

Visible estimates of aboveground rice injury were recorded 3, 7, 14, 21, 28 and 42 d after labeled herbicide treatment (DAT) on a scale of 0 to 100% where 0 indicated no visible effect of herbicide and 100 indicated complete plant death. Rice plant height was recorded 21 d after labeled herbicide treatment and at maturity 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. The number of days to 50% heading were 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. Days to canopy closure were calculated using Canopeo (Oklahoma State University, Stillwater, OK) to measure green leaf area as a percentage between rows. Images were collected at weekly intervals from the day of the first application until all plots reached 100% green leaf area. Canopeo is based on color ratios of red to green (R/G) and blue to green (B/G) and an excess green index (2G– R–B). Green normalized difference vegetative index (NDVI) was assessed as an indication of plant health using a hand-held crop sensor (GreenSeeker crop sensing system, Trimble Navigation Limited, Sunnyvale, CA) at 28 DAT. Plots were drained approximately 2 wk before harvest maturity. Rice was harvested with a small-plot combine (Zürn Harvesting GmbH & Co. KG., Schöntal-Westernhausen, Germany) at a moisture content of approximately 20% on October 24, 2019, September 15 and 30, 2020, and October 20, 2021. Final rough rice grain yield was adjusted to 12% moisture content.

Subsamples of rough rice were collected at harvest to determine whole and total milled rice yield. Grain characterization was performed using WinSEEDLE^{TM} (Regent Instruments Canada Inc., Régent Guay, QC G2G 1B5, Canada) and grain length, width, and chalking were recorded. Whole and total milled rice yields were determined from cleaned 100-g subsamples of rough rice using procedure outlined by Adair et al. (1972). Rice was mechanically hulled and milled in a Grainman No. 2 miller (Grain Machinery Manufacturing Corp., Miami, FL) for 30 s and size-separated with a No. 12 4.76-mm screen. Whole and total milled rice yields are expressed as a mass fraction of the original 100-g sample of rough rice.

Arcsine transformations of the square roots of rice injury were performed to improve homogeneity of variances. The transformation did not improve homogeneity of variance based on visual inspection of plotted residuals; therefore, nontransformed data were used in analyses. Nontransformed data were subjected to analysis of variance (ANOVA) utilizing the PROC GLIMMIX procedure with in SAS 9.4 (Statistical software Release 9.4, SAS Institute, SAS

Institute Inc., Cary, NC). Siteyear and replication (nested within siteyear) were random effect parameters (Blouin et al. 2011). Type III Statistics were used to test the fixed effects of labeled herbicide treatment and paraquat exposure for rice injury, height, delays in maturity, canopy closure, NDVI, grain length, width, chalking, and yield. Means and standard deviations were determined utilizing the PROC MEANS procedure in SAS 9.4. Estimates of least square means were utilized for mean separation (α=0.05).

Barnyardgrass Control Study

Field research similar to that described for the Rice Response Study was conducted in 2020 (33°26’32.26” N 90°54’18.10” W) and 2021 (33°26’29.35” N 90°54’18.20” W) at the Mississippi State University Delta Research and Extension Center in Stoneville, MS. However, this study evaluated barnyardgrass control with labeled herbicides after exposure to a sub-lethal concentration of paraquat. Rice was drill-seeded on May 20, 2020, and May 25, 2021. Soil was a Sharkey clay (very-fine, smectitic, thermic Chromic Eqiaquerts) with a pH of 8.2 and an organic matter content of 2.1%. Site maintenance and plot size were the same as for the Rice Response Study.

The experimental design and treatment structure for the Barnyardgrass Control Study was the same as that for the Rice Response Study. Visible estimates of aboveground rice injury and rice plant height was recorded as previously described. Visible estimates of barnyardgrass control were recorded 7, 14, and 28 DAT utilizing the same scale. Rice was harvested with a small-plot combine on October 1, 2020, and October 5, 2021, and final rough rice grain yield was adjusted to 12% moisture content. Data analyses were performed as previously described for the Rice Response Study.

Results and Discussion

Rice Response Study

Rice injury 7, 14, 21, 28, and 42 DAT and rice height 21 DAT were influenced by a main effect of paraquat exposure ($p=0.0001$) at each evaluation. Pooled across labeled herbicide treatments, rice injury following paraquat exposure ranged from 26 to 62% 7 to 42 DAT. Rice injury prior to labeled herbicide treatments (paraquat alone) ranged from 30 to 50% (data not presented). Injury in plots with no paraquat was $\leq$ 8% at each evaluation interval. Symptoms of paraquat injury included water-soaked lesions, yellowing of leaves, necrosis, and stunted plant growth. Pooled across labeled herbicide treatments, rice height 21 DAT was reduced 20.6% following paraquat exposure (Table 4.3).

A main effect of labeled herbicide treatment was detected for rice injury 7 ($p=0.0001$) and 28 DAT ($p=0.0036$) (Table 4.4). Pooled across paraquat exposure, rice injury was $\geq$ 35 % for all labeled herbicide treatments 7 DAT (Table 4.4). Rice injury 28 DAT was $\geq$ 14% for all labeled treatments. Florpyrauifen-benzyl and imazethapyr injured rice the greatest ($\geq$ 20%) 28 DAT.

Main effects of paraquat exposure ($p=0.207$ to 0.3944) and labeled herbicide treatment ($p=0.412$ to 0.6272) and the interactions ($p=0.449$ to 0.6752) of these variables were not significant for rice maturity, d to canopy closure, green NDVI, mature rice height, grain length, width, and chalking (data not presented).

An interaction of labeled herbicide treatment and paraquat exposure was detected for rough, total, and whole milled rice yield. Rough rice yield was reduced 22% following paraquat exposure in the absence of a labeled herbicide treatment (Table 4.5). With no prior exposure to paraquat, rough rice yield with labeled herbicide treatments was $\geq$ 8460 kg ha^{-1} with the greatest yield from plots with no labeled herbicide (9,840 kg ha^{-1}). Following paraquat exposure, florpyrauxifen-benzyl, quinclorac, and imazethapyr produced yields that were similar and $\geq$ 8,430 kg ha^{-1}. Rough rice yield for the other labeled herbicide treatments were similar and $\geq$ 8,140kg ha^{-1}.

Total milled rice yield was similar and $\geq$ 68% following all labeled herbicide treatment with no prior paraquat exposure, including no labeled herbicide, except following quinclorac where total milled rice was only 65% (Table 4.5). Among plots treated with paraquat, the cyhalofop treatment had greater total milled rice yield (69%) than florpyrauxifen-benzyl (67%). Imazethapyr had lower total milled rice yield (65%) than other labeled herbicide treatments. Bispyribac-sodium and quinclorac produced the greatest whole milled rice yield (55%) compared to other labeled herbicide treatments in the absence of paraquat exposure. Following paraquat exposure, whole milled yield with cyhalofop was 59% and greatest among other labeled herbicide treatments. Bispyribac-sodium and plots with no labeled herbicide had the lowest (50%) whole milled rice yield. Rice exposed to paraquat resulted in $\geq$ 35% reductions in total and whole milled rice yield regardless of labeled herbicide treatment.

Previous research reported rice injury following paraquat exposure at 84 g ha^{-1} applied to rice at the two- to three-leaf (EPOST) growth stage (Lawrence et al. 2020a). Lawrence et al. (2020b) reported > 42% injury following paraquat exposure 3 DAT with the greatest injury (56%) 28 DAT. It was also reported that rice did not recover from paraquat exposure at EPOST at 10% of the recommended use rate even after adding starter N or altering N fertilizer. In contrast, the current work demonstrates that rice injury with labeled herbicides following paraquat exposure was 65% 7 DAT; however, there appeared to be some recovery from this injury as rice matured as evidenced by $\leq$ 26% injury 42 DAT. Lawrence et al. (2020b) further suggested that paraquat exposure along with additional herbicide MOAs can induce rough rice yield losses. In this study, rough rice yields following the labeled herbicides evaluated following paraquat exposure were equal to or greater than rough rice yield with paraquat exposure alone. This data indicates that labeled herbicide treatments have little to no impact on rough rice yield following paraquat exposure. Therefore, the labeled herbicides treatments evaluated in this study can be safely utilized for weed management following rice exposure to paraquat.

Barnyardgrass Control Study

Interactions between labeled herbicide treatments and paraquat exposure were detected for barnyardgrass control 7 (p=0.001), 14 (p=0.001), and 28 DAT (p=0.001). Barnyardgrass control 7 DAT with labeled herbicides in the absence of paraquat exposure was greater with quinclorac and imazethapyr than other labeled herbicide treatments. Barnyardgrass control 14 and 28 DAT was greater ($\geq$ 79%) with imazethapyr and propanil alone compared to other labeled herbicide treatments (Table 4.6). In constrast, Miller and Norsworthy (2018a) documented that barnyardgrass control with florpyrauxifen-benzyl provided the highest level of control at 14 DAT (97%) with cyhalofop (83%) and quinclorac (80%) providing less control. Masson et al. (2001) reported >90% barnyardgrass control with imazethapyr 28 DAT. Following paraquat exposure, barnyardgrass control was similar for all labeled herbicide treatments 7, 14, and 28 DAT except with florpyrauxifen-benzyl (87%) and no labeled herbicide (paraquat alone) (84%) 7 DAT. Across all evaluations, barnyardgrass control was at least 12% greater following paraquat exposure and labeled herbicide treatments than no paraquat exposure (Table 4.6).

A main effect of paraquat exposure was detected for barnyardgrass control 42 DAT (p=0.0001), rice height 21 DAT (p=0.0001), and rough rice yield (p=0.001). Pooled across labeled herbicide treatments, barnyardgrass control 42 DAT was 29% greater following paraquat exposure compared to no paraquat exposure (Table 4.7). Rice plant height and rough rice yield was reduced 15 and 20, respectively, following paraquat exposure (Table 4.7).

A main effect of labeled herbicide treatment was detected for barnyardgrass control 42 DAT (p=0.001). Pooled across paraquat exposure treatments, imazethapyr and propanil provided the greatest control ($\geq$ 83%) compared with other labeled herbicide treatments (Table 4.8). Barynyardgrass control was < 78% with bispyribac-sodium, quinclorac, cyhalofop, and florypyrauxifen-benzyl.

A main effect of labeled herbicide treatment was also detected for rough rice yield (p=0.001). Pooled across paraquat exposure treatments, rough rice yield was greater following imazethapyr (9,300 kg ha^{-1}) than all other labeled herbicide treatments and lower with floryprauxifen-benzyl and no labeled herbicide (paraquat alone) ($\leq$ 6,700 kg ha^{-1}) (Table 4.8). Rough rice yield with bispyribac-sodium, propanil, cyhalofop, and quinclorac was similar and 8,800, 8,600, 8,4000, 7,800 kg ha^{-1}, respectively.

Compared with other labeled herbicide treatments in this study, florpyrauxifen-benzyl provided the least barnyardgrass control 7 DAT in the presence of paraquat. Florpyrauxifen-benzyl is a synthetic auxin from the herbicide family, the arylpicolinates (Epp et al. 2016; Miller and Norsworthy 2018b). Auxinic herbicides are typically more efficacious on broadleaf weeds and rarely display activity on grass species (Grossmann 2010); however, florpyrauxifen-benzyl has activity on some grass weed species (Epp et al. 2016). Previous research indicated that in order for florpyrauxifen-benzyl to display its full herbicidal benefits, soil moisture should be near or above field capacity close to the time of application (Miller and Norsworthy 2018b). Likewise, Calhoun et al. (2016) suggested that the ideal application timing to achieve effective control of common rice weeds, including barnyardgrass, is to apply florpyrauxifen-benzyl within

5 d of flooding. In this study, labeled herbicide applications were applied to rice at the three- to four-leaf growth stage (MPOST) on June 17, 2020, and June 23, 2021. A flood was not established until June 25, 2020, and July 6, 2021. As a result, the decrease in activity from florpyrauxifen-benzyl on barnyardgrass control may be attributed to the lack of soil moisture at the time of application. Barnyardgrass is highly competitive with rice due to its adaptation to flooded environments, prolific seed production, and rapid growth (Marambe and Amarasinghe 2002). Therefore, interference from barnyardgrass resulted in reduced rough rice yields with florpryauxifen-bezyl.

The objective of the current study was to evaluate rice injury and barnyardgrass control with labeled herbicides after exposure to a sub-lethal concentration of paraquat. This research demonstrates that barnyardgrass control following paraquat exposure was $\geq$ 87% 7 DAT from the labeled herbicides evaluated with >89% control 14 and 21 DAT. Labeled herbicide choice should be based on weed spectrum; however, to optimize barnyardgrass control and rice yield with florypyrauxifen-benzyl, soil moisture should be near or above field capacity close to the time of application (Calhoun et al. 2016; Miller and Norsworthy 2018b). Although previous research documented that additional herbicide MOA with paraquat can affect rice injury and rough rice yield losses following exposure (Lawrence et. al 2020a), the current research demonstrates that labeled herbicides applied following exposure to a sub-lethal concentration of paraquat resulted in < 36% injury and provided as much as 95% control of barnyardgrass, depending on the herbicide treatment. Therefore, the labeled herbicides choice should be based on weed spectrum.

Table 4.1 Geographic location, soil classification, and agronomic information for the Rice Response Study conducted at Mississippi State University Delta Research and Extension Center in Stoneville, MS, from 2019 to 2021.

Site-year	Coordinates	Soil series	Description	pH	OM
					%
2019	33°26'33.35"N 90°54'19"W	Sharkey clay	Very-fine, smectitic, thermic Chromic Eqiaquerts	8.2	2.1
2020 A	33°26'37.94"N 90°54'14.75"W	Sharkey clay	Very-fine, smectitic, thermic Chromic Eqiaquerts	8.2	2.1
2020 B	32°26'10.16"N 90°54'20.60"W	Commerce silty clay loam	Fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts	7.6	1.8
2021	33°26'27.22"N 90°54'20.60"W	Commerce silty clay loam	Fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts	7.6	1.8

Table 4.2 Herbicide common and tradenames, application rates, and herbicide manufacturer information for the Rice Response and Barnyardgrass Control studies conducted at the Mississippi State University Delta Research and Extension Center in Stoneville, MS, from 2019 to 2021.

Common name	Trade name	Rate	Manufacturer
		g ai ha^{-1}	
Imazethapyr	Newpath	105	BASF Corporation, Research Triangle Park, NC,
Quinclorac	Facet L	420	BASF Corporation, Research Triangle Park, NC,
Propanil	Stam M4	3363	RiceCo LLC, Suite 2428, Memphis, TN
Bispyribac-sodium	Regiment	28	Valent U.S.A, Walnut Creek, CA
Cyhalofop	Clincher SF	31	Corteva AgriSciences, LLC, Indianapolis, IN
Florpyrauxifen-benzyl	Loyant	29	Corteva AgriSciences, LLC, Indianapolis, IN

Table 4.3 Influence of paraquat exposure on rice injury 7, 14, 21, 28, and 42 d after exposure (DAE) and rice plant height 21 DAT in the Rice Response Study conducted at Stoneville, MS, from 2019 to 2021[a].

	Injury					Height
Paraquat exposure[b]	7 DAE	14 DAE	21 DAE	28 DAE	42 DAE	21 DAE
	%					cm
No paraquat	8 b	7 b	5 b	5 b	3 b	63 b
Paraquat	62 a	51 a	39 a	31 a	26 a	50 a

[a] Data were pooled over seven labeled herbicide treatments and four experiments. Means followed by the same letter for each parameter are not different at $p \leq 0.05$.

[b] Paraquat exposure included paraquat at 0 and 84 g ai ha^{-1} applied to rice in the spiking to one-leaf stage.

Table 4.4 Influence of labeled herbicide treatment on rice injury 7 and 28 d after treatment (DAT) in the Rice Response Study conducted at Stoneville, MS, from 2019 to 2021[a].

Labeled herbicide	Rate	7 DAT	28 DAT
	g ai ha^{-1}	%	
No herbicide	-	30 b	15 d
Bispyribac-sodium	28	36 a	17 c
Cyhalofop	31	35 a	14 d
Florpyrauxifen-benzyl	29	37 a	20 a
Imazethapyr	105	38 a	21 a
Propanil	3,363	36 a	19 b
Quinclorac	420	36 a	18 b

[a] Data were pooled over two paraquat exposure treatments and four experiments. Means followed by the same letter for each evaluation are not different at $p \leq 0.05$.

Table 4.5 Interaction of labeled herbicide treatment and paraquat exposure on rice yield (rough, whole, total milled) in the Rice Response Study conducted in Stoneville, MS, from 2019 to 20201[a,b].

		Rough rice		Whole milled rice		Total milled rice	
Labeled herbicide	Rate	No paraquat	Paraquat	No paraquat	Paraquat	No paraquat	Paraquat
	g ai h^{-1}	Kg ha^{-1}		%			
No herbicide	-	9840 a	7620 e	53 cd	50 e	68 ab	68 ab
Bispyribac-sodium	28	8910 c	7760 e	55 b	50 e	69 a	68 ab
Cyhalofop	31	8990 bc	7640 e	54 c	59 a	69 a	69 a
Florpyrauxifen-benzyl	29	9470 b	8830 c	54 c	53 cd	68 ab	67 b
Imazethapyr	105	8460 cd	8430 d	53 cd	53 cd	69 a	65 c
Propanil	3,363	8490 cd	8140 e	53 cd	53 cd	70 a	68 ab
Quinclorac	420	8600 cd	8520 cd	55 b	51 d	65 c	68 ab

[a] Data were pooled over four experiments. Means followed by the same letter for each parameter are not different at $p \leq 0.05$.

[b] Paraquat exposure included paraquat at 0 and 84 g ai ha^{-1} applied to rice in the spiking to one-leaf stage.

Table 4.6 Barnyardgrass control 7, 14, and 28 d after treatment (DAT) with labeled herbicide treatments in the Barnyardgrass Control Study at Stoneville, MS, in 2020 and 2021[a,b].

		7 DAT		14 DAT		28 DAT	
Labeled herbicide	Rate	No paraquat	Paraquat	No paraquat	Paraquat	No paraquat	Paraquat
	g ai ha^{-1}	%					
No herbicide	-	0 h	84 c	0 f	86 b	0 e	88 a
Bispyribac-sodium	28	69 e	93 ab	68 d	94 a	59 cd	90 a
Cyhalofop	31	59 g	92 ab	60 e	90 ab	56 d	87 a
Florpyrauxifen-benzyl	29	52 g	87 c	54 e	89 b	50 d	86 a
Imazethapyr	105	76 d	93 ab	80 c	94 a	79 b	88 a
Propanil	3,363	62 f	95 a	83 c	95 a	82 a	89 a
Quinclorac	420	79 d	91 b	69 d	92 ab	66 c	91 a

[a] Data were pooled over two experiments. Means followed by the same letter for each parameter are not different at $p \leq 0.05$.

[b] Paraquat exposure included paraquat at 0 and 84 g ai ha^{-1} applied to rice in the spiking to one-leaf stage.

Table 4.7 Influence of paraquat exposure on barnyardgrass control 42 d after exposure (DAE), rice height 21 DAT, and rough rice yield in the Barnyardgrass Control Study at Stoneville, MS, in 2020 and 2021[a,b].

Paraquat exposure	Barnyardgrass control	Rice plant height	Rough rice yield
	%	cm	kg ha^{-1}
No paraquat	57 b	59 a	8800 a
Paraquat	86 a	50 b	7000 b

[a] Data were pooled over seven herbicide treatments and two experiments. Means followed by the same letter for each parameter are not different at $p \leq 0.05$.

[b] Paraquat exposure included paraquat at 0 and 84 g ai ha^{-1} applied to rice in the spiking to one-leaf stage.

Table 4.8 Main effect of labeled herbicide treatment on barnyardgrass control 42 d after treatment (DAT) and rough rice yield in the Barnyardgrass Control Study at Stoneville, MS, in

Labeled herbicide	Rate	Control	Yield
		%	kg ha^{-1}
No herbicide	-	47 d	5700 c
Bispyribac-sodium	28	78 b	8800 ab
Cyhalofop	31	70 c	7800 b
Florpyrauxifen-benzyl	29	65 c	6700 c
Imazethapyr	105	84 a	9300 a
Propanil	3,363	83 a	8600 ab
Quinclorac	420	74 bc	8400 b

[a] Data were pooled over two experiments. Means followed by the same letter for each parameter are not different at $p \leq 0.05$.

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