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Mitigating Rice Injury Caused by Florpyrauxifen-Benzyl and Optimizing Florpyrauxifen-benzyl Rate and Timing for use in Furrow-Irrigated Rice

James Winston Beesinger
University of Arkansas, Fayetteville

Mitigating Rice Injury Caused by Florpyrauxifen-Benzyl and Optimizing Florpyrauxifen-benzyl Rate and Timing for use in Furrow-Irrigated Rice

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James Winston Beesinger
University of Tennessee at Martin
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Jason Norsworthy, Ph.D.
Thesis Director

Thomas R. Butts, Ph.D.
Committee Member

Trenton Roberts, Ph.D.
Committee Member

Edward Gbur, Ph.D.
Committee Member

Abstract

Florpyrauxifen-benzyl (synthetic auxin, WSSA Group 4) is a postemergence, broad-spectrum herbicide labeled for use in Mid-South rice (*Oryza sativa* L.) production. Introduction of florpyrauxifen-benzyl to Arkansas rice production led to observations of varying levels of injury caused by the herbicide across cultivars and environments. Findings from previous research indicated hybrid long-grain rice and medium-grain rice were more susceptible to florpyrauxifen-benzyl and hypotheses were formed using this research regarding the impact of environmental conditions on the amount of injury observed. Concerns of yield loss, delay in maturity and loss of groundcover as well as questions regarding the ability of florpyrauxifen-benzyl to be applied with other herbicides that may cause injury led to the necessity for more research across cultivars and hybrids. Prior research also highlighted the benefits of using florpyrauxifen-benzyl in furrow-irrigated rice weed control programs to control problematic weed species such as Palmer amaranth (*Amaranthus palmeri* S. Wats). Florpyrauxifen-benzyl effectively controlled Palmer amaranth in a greenhouse study at lower-than-labeled rates and was found to be an effective alternative site-of-action for use in furrow-irrigated rice. Research conducted included experiments determining the tolerance of popular cultivars and hybrids to florpyrauxifen-benzyl with and without an application of benzobicyclon, isolation of multiple environmental and cultural variables to determine their effect on rice injury, and optimizing the rate and timing of florpyrauxifen-benzyl to best control Palmer amaranth in furrow-irrigated rice. Florpyrauxifen-benzyl reduced yield of rice hybrid XP753 by 17% following sequential applications at 30 g ae ha^{-1} and reduced groundcover of all hybrids tested. However, injury was not compounded by an application of benzobicyclon post-flood. Rice injury caused by florpyrauxifen-benzyl was most severe under 40% soil moisture or saturated conditions. Rice injury was more severe under low light conditions, high temperatures, and when the flood was

introduced before three days and after six days following application. Single applications of florpyrauxifen-benzyl at 15 g ae ha^{-1} controlled Palmer amaranth as well as single applications of the herbicide at the labeled rate of 30 g ae ha^{-1}. Florpyrauxifen-benzyl at 15 g ae ha^{-1} was as effective as 30 g ae ha^{-1} in controlling Palmer amaranth less than 10 cm in height. Sequential applications of florpyrauxifen-benzyl at 8 g ae ha^{-1} were as effective as sequential applications at 30 g ae ha^{-1}. Based on these findings, injury caused by single applications of florpyrauxifen-benzyl at any rate appear superficial, although sequential applications of labeled rates can cause long-term effects on development and yield. Injury to rice can be reduced by timing an application based on soil moisture, solar radiation, temperature, and flood establishment date after application.

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Chapter 1

General Introduction and Review of Literature

Arkansas Rice Production

Rice (*Oryza sativa* L.) was first planted in Arkansas in 1902 (Hardke 2018). Since, rice has become the third largest crop grown in the state in terms of area planted and harvested behind forage and soybean, respectively. Arkansas produces more rice than any other state in the United States, harvesting over 500,000 hectares in 2020, netting more than 3 billion dollars in worth (NASS 2021). Cultural practices dictate the way rice is planted and irrigated for many cropping systems around the world. The most common way rice is grown in Arkansas is using dry seed, delay flood practices in which rice is drill seeded and subsequently flood irrigated beginning at the 5-leaf stage (Hardke 2018; Talbert and Burgos 2007). In most instances, water is pumped from the highest point of the field to the lowest, using systems of levees and levee gates to control the flood depth; however, Arkansas producers also use precision levelling to ensure that floods remain at an equal depth throughout an entire field (Hardke 2018).

Cultivars of rice grown by producers are commonly chosen based on specific needs determined by the grower. The grower's choice is commonly driven by yield requirements, grain quality, and most recently, herbicide tolerance. Rice grown in the United States is non-transgenic or not genetically modified. Rather, it is bred or hybridized for specific traits and tolerances (Hardke et al. 2018). One of the most notable instances of rice being selectively bred is the development of Clearfield® (BASF, Florham Park, NJ 07932) rice in 2002. Clearfield technology allowed for imidazolinone herbicides (imazethapyr and imazamox), those that inhibit acetolactate synthase (ALS), to be sprayed over Clearfield® rice cultivars. Quizalofop-resistant cultivars (Provisia® technology, BASF, Florham Park, NJ 07932) were developed and released in 2018 as another option for control of barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.]. Quizalofop is an acetyl carboxylase (ACCase, WSSA Group 1) herbicide, a member of the aryloxyphenoxy propionate family and is used for control of annual grass weed species (Shaner 2014). Introduction of herbicide-resistant rice cultivars enabled producers to use herbicide sites of action never used in rice production to combat herbicide-resistant weed species.

Weed Control in Rice

The flooded environment in which rice is commonly cultivated provides advantages not commonly available in production of other crops. Implementation of a flood on a rice crop can provide nitrogen retention in the soil as well as weed suppression (Henry 2018). The anaerobic environment provided by the flood does not allow the germination or survival of certain weed species, such as Palmer amaranth (*Amaranthus palmeri* S. Wats.) (Norsworthy et al. 2013). However, weed species able to survive the flooded conditions must be controlled through combinations of cultural practices other than flooding and chemicals to prevent loss in yield or milling quality (Smith and Fox 1973).

Although the flooded environment in a rice field has the ability to suppress some weeds and prevent the emergence of most, other species are still able to thrive in the anaerobic conditions and threaten rice with competition for nutrients. Since the introduction of propanil (WSSA Group 7) to rice in the 1950's, many other herbicides have been developed, tested, and labeled for use in Mid-South U.S. rice production (Talbert and Burgos 2007). Overuse and dependency on these herbicides to control weeds that survive the flood have led to the development of herbicide-resistant weed species. As of 2021, weeds in rice fields have been documented with resistance to bensulfuron methyl, bispyribac-sodium, clomazone, cyhalofop, fenoxaprop, florpyrauxifen-benzyl, halosulfuron-methyl, imazamox, imazethapyr, penoxsulam, propanil, and quinclorac (Heap 2021). Barnyardgrass alone has been documented with multiple resistance to clomazone, imazethapyr, quinclorac, and propanil (Heap 2021).

Florpyrauxifen-benzyl

To combat rapid development of herbicide resistance, florpyrauxifen-benzyl, labeled as Loyant, was released by Corteva Agrosciences in 2018. Florpyrauxifen-benzyl was the first member of the arylpicolinate family of auxin herbicides, closely followed by the release of halauxifen-methyl (Weimer 2015). However, florpyrauxifen-benzyl is not the first auxin used in rice production as it was preceded by 2,4-D, triclopyr, and quinclorac, which have been commonly used for weed control in previous years (Telo 2019).

Florpyrauxifen-benzyl is a broad-spectrum herbicide for use in flooded and upland rice at a labeled rate of 30 g ae ha^{-1} (Anonymous 2018). Greenhouse research has determined that florpyrauxifen-benzyl provides greater than 90% control of susceptible barnyardgrass accessions from Arkansas, equal or greater control than that achieved by fenoxaprop (WSSA Group 1), cyhalofop (WSSA Group 1), and quinclorac (WSSA Group 4) (Miller and Norsworthy 2018b). Florpyrauxifen-benzyl was also found to be effective in controlling Palmer amaranth, hemp sesbania [*Sesbania hederacea* (P. Mill.) McVaugh.], northern jointvetch (*Aeschynomene virginica* L. Britton, Sterns & Poggenb.), rice flatsedge (*Cyperus iria* L.), smallflower umbrellasedge (*Cyperus difformis* L.), and broadleaf signalgrass (*Urochloa platyphylla* Munro ex C. Wright R.D. Webster) (Miller and Norsworthy 2018b).

The introduction of florpyrauxifen-benzyl to U.S. rice production was intended to aid producers in controlling quinclorac-resistant barnyardgrass due to the novelty of the site-of-action of the arylpicolinate family, targeting the *Arabidopsis* auxin receptor F-Box protein 5 (AFB5) indole-3-acetic acid co-receptor instead of the transport inhibitor response 1 (TIR1) co-receptor like most synthetic auxin herbicides. However, failure of florpyrauxifen-benzyl to control barnyardgrass was documented the first year of commercial application and resistance has since been confirmed (Hwang et al. 2021). Resistance to florpyrauxifen-benzyl has thus far been documented as metabolic in barnyardgrass.

Rice injury caused by florpyrauxifen-benzyl has been noted in previous research as well as warnings on the Loyant label (Anonymous 2018). Findings indicate that injury may be cultivar specific with observations of more injury in hybrids and medium-grain cultivars than long-grain cultivars (Wright 2020). Crop and weed response to herbicides vary in response to environmental conditions. Temperature, light, and soil moisture can affect the amount of injury to a crop as well as the level of weed control achieved following herbicide application (Bazzaz and Carlson 1982; Bond and Walker 2012; Burt and Akinsoritan 1976; Ferreira et al. 1990). Rice cultivars can differ in response to herbicides. For example, rice cultivar 'Lemont' exhibited more injury than 'Mars' and 'Tebonnet' following a triclopyr application (Pantone and Baker 1992). Increased tolerance of rice to imazethapyr also led to the isolation and breeding of Clearfield resistant cultivars, indicating that certain lines may be more genetically susceptible to certain herbicides. Although resistance to florpyrauxifen-benzyl has been confirmed in barnyardgrass, utilization of florpyrauxifen-benzyl without fear of severe rice injury could benefit producers attempting to control other susceptible weed species while continuing to rotate herbicide sites of action.

Benzobicyclon

Benzobicyclon is a 4-hydroxyphenylpyruvate dioxygenase-inhibiting herbicide (HPPD, WSSA Group 27) applied post-flood as a pro-herbicide in rice (Anonymous 2021; Komatsubara et al. 2009; Williams and Tjeerderma 2016). Benzobicyclon must be hydrolyzed to convert into the active ingredient benzobicyclon hydrolysate. Without conversion to benzobicyclon hydrolysate, control of target weed species such as weedy rice (*Oryza sativa* L.) is minimal (Brabham et al. 2019). The ability of benzobicyclon to control weedy rice raises concern of cultivar tolerance to the herbicide, particularly when used in conjunction with florpyrauxifen-benzyl and other herbicides known to cause rice injury. Previous research has determined that cultivars of indica origin are susceptible to benzobicyclon hydrolysate, and cultivars of japonica origin are not, leading to the discovery of the HPPD Inhibitor Sensitive Gene (HIS1) in certain rice cultivars (Kwon et al. 2012; Maeda et al. 2019; Young et al. 2017). The ability of producers to apply benzobicyclon and florpyrauxifen-benzyl in a herbicide program could be used to control several of the most troublesome weed species in rice, as well as provide novel sites of action to mitigate further herbicide resistance evolution.

Furrow-Irrigated Rice

The rising popularity of furrow-irrigated rice production has presented new problems for producers to overcome. Instead of being flooded on level land until maturity, furrow-irrigated rice is drill-seeded onto bedded rows to allow irrigation water to travel from the top to the bottom of the field in furrows similar to methods used to grow corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybean (*Glycine max* (L.) Merr.) in the midsouthern U.S. (Norsworthy 2011). Instead of a continuous flood from the V5 growth stage to rice maturity, the crop is irrigated on a scheduled basis. Common practice is to draw a levee at the lowest end of the field and allow a section of the field to remain flooded while the rest of the field receives irrigation in the furrows wicking to the top of the rows. The use of furrow irrigation in rice can reduce time input and save in labor, as the same furrows can be used for subsequent crops, although reduced yields have been recorded when furrow-irrigated rice is compared with delayed flood-irrigated rice (Vories et al. 2002; Tracy et al. 1993). The absence of a flood allows for a moist, aerobic environment in which weeds can germinate and flourish (Henry et al. 2018). While weeds commonly found in flood-irrigated rice fields can still be present in furrow-irrigated fields, weeds commonly problematic in other cropping systems may prevail as well, providing the need for innovation in weed control systems used to maintain furrow-irrigated areas. Current recommendations call for the use of overlapping preemergence residual herbicides to prevent emergence of weed species in the absence of a flood; however, options must be established to control weeds which escape residual herbicides (Norsworthy et al. 2008).

Palmer amaranth Control with Florpyrauxifen-benzyl

Palmer amaranth is one of the most troublesome weeds in Mid-South crop production (Van Wychen 2020). With resistance to seven known sites of action in Arkansas alone, Palmer amaranth has the potential to be difficult to control in furrow-irrigated rice (Heap 2021). Prior to resistance, protoporphyrinogen oxidase inhibitors (PPO, WSSA Group 14) and imazethapyr (acetolactate synthase inhibitor, WSSA Group 2) were used to control Palmer amaranth in preflood rice and on levees; however, current recommendations for control of Palmer amaranth in rice call for applications of 2,4-D or a mixture of triclopyr and propanil or propanil alone. In some areas, local regulations have restricted the use of 2,4-D due to potential for off-target movement of the herbicide, further limiting herbicide options for producers (ASPB 2020).

Previous research has indicated the benefit of using florpyrauxifen-benzyl for control of Palmer amaranth. Greenhouse studies have shown substantial levels of Palmer amaranth control following applications of florpyrauxifen-benzyl at less than labeled rates (30 g ae ha^{-1}) (Miller and Norsworthy 2018b). Experiments in furrow-irrigated rice indicate that the use of florpyrauxifen-benzyl at 30 g ae ha^{-1} in a herbicide program provided greater control of Palmer amaranth than herbicide programs without florpyrauxifen-benzyl (Wright et al 2020). Single Palmer amaranth females are able to produce as many as 600,000 seed per plant when not faced with competition for nutrients or resources and as many as 139,000 seeds when in competition with drill-seeded soybean (Keely et al. 1987; Schwartz et al. 2016). Considering 68.5% of rice hectares in Arkansas are rotated with soybean, the ability to reduce the production of Palmer amaranth seed using sites of action not available for use in soybean could reduce inputs to the soil seedbank while working to mitigate resistance (Bagavathiannan and Norsworthy 2012; Norsworthy et al. 2014).

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Chapter 2

Rice Cultivar Tolerance to Multiple Applications of Florpyrauxifen-benzyl and Florpyrauxifen-benzyl followed by Benzobicyclon

Abstract

Varying rice cultivar tolerance in response to florpyrauxifen-benzyl and benzobicyclon applications have been observed. The safe use of florpyrauxifen-benzyl and benzobicyclon in the same herbicide program could provide broad-spectrum weed control and delay the occurrence of resistance in weed species. Two experiments were conducted in 2019 and 2020 near Stuttgart, AR, to test cultivar tolerance to multiple rates of florpyrauxifen-benzyl and applications of florpyrauxifen-benzyl followed by benzobicyclon. The first experiment was designed to determine the tolerance of rice cultivars XP753, CL XL745, Gemini 214CL, Titan, and Diamond to applications of florpyrauxifen-benzyl at 30 and 60 g ae ha^{-1} and sequential applications of 30 g ae ha^{-1}. The second experiment was to determine the effect of benzobicyclon applied post-flood on rice injury following an application of florpyrauxifen-benzyl on the same cultivars used in the previous experiment. Rough rice yield loss of 17% was observed when sequential applications of florpyrauxifen-benzyl at 30 g ae ha^{-1} were made to XP753, and all applications of florpyrauxifen-benzyl besides single applications of 30 g ae ha^{-1} delayed heading of CL XL745 by one day. Single applications of florpyrauxifen-benzyl at 60 g ae ha^{-1} caused a 45% groundcover reduction of XP753 while sequential applications of 30 g ae ha^{-1} reduced groundcover on all hybrid cultivars tested. Applications of benzobicyclon alone never injured rice more than 8% and applying benzobicyclon after an application of florpyrauxifen-benzyl did not increase the injury observed over florpyrauxifen-benzyl alone. However, application of benzobicyclon alone has the potential to cause a one-day delay in maturity. Single applications of florpyrauxifen-benzyl followed by benzobicyclon can be used as part of a herbicide program to control problematic weeds without concern for greater injury than is typically caused by florpyrauxifen-benzyl alone.

Nomenclature: benzobicyclon; florpyrauxifen-benzyl; rice, *Oryza sativa* L.

Keywords: crop tolerance, herbicide injury, rice development

Introduction

The cultivar of rice sown by a producer is chosen based on specific characteristics such as disease tolerance and herbicide resistance, yield potential, and grain milling quality, among other factors. Cultivars of rice are divided into three classes based on grain length: short, medium, and long grain. In 2019, hybrid, long-grain rice cultivar ‘XP753’ was the most popular cultivar chosen by producers in Arkansas, comprising 25.6% of rice hectares planted in the state. Other popular cultivars in Arkansas included the hybrid, long-grain ‘RT Gemini 214CL’ (15%) and ‘RT CL XL745’ (9.7%), pure-line, long-grain ‘Diamond’ (10.9%), and pure-line, medium-grain ‘Titan’ (6.5%) (Hardke 2020). Cultivar specific response to herbicide treatments have been previously identified, and through selective breeding, led to the development of imidazolinone- (Clearfield®, FullPage®) and quizalofop- (Provisia®, Max-Ace®) (BASF, Ludwigshafen, Germany, ADAMA, Airport City, Israel) resistant lines. Varying rice cultivar sensitivity to other herbicides has also been observed, such as triclopyr, a synthetic auxin herbicide (Pantone and Baker 1992).

Florpyrauxifen-benzyl, labeled as Loyant® (Corteva Agriscience, Wilmington, DE 19805) in rice, is a synthetic auxin herbicide made commercially available in 2018 for pre-flood weed control at a rate of 30 g ae ha^{-1}. Florpyrauxifen-benzyl is a member of the arylpicolinate family of auxin herbicides, with one other member being halauxifen-methyl (Weimer et al. 2015). Favoring the *Arabidopsis* auxin receptor F-Box protein 5 (AFB5) indole-3-acetic acid co-receptor as opposed to the transport inhibitor response 1 (TIR1) co-receptor, as well as exhibiting broad-spectrum weed control and selectivity for rice, florpyrauxifen-benzyl provides an alternative herbicide option for control of herbicide-resistant weed species in rice (Bell et al. 2015; Epp et al. 2016). Florpyrauxifen-benzyl is not, however, the first synthetic auxin to be used in rice production. Triclopyr, 2,4-D, and quinclorac have been used for weed control in rice prior to the release of florpyrauxifen-benzyl (Telo 2019).

Florpyrauxifen-benzyl is labeled for control of barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.] and other problematic weed species in rice production. It provides effective control of Palmer amaranth (*Amaranthus palmeri* S. Wats.), hemp sesbania [*Sesbania hederacea* (P. Mill.) McVaugh.], northern jointvetch (*Aeschynomene virginica* L. Britton, Sterns & Poggenb.), rice flatsedge (*Cyperus iria* L.), smallflower umbrellasedge (*Cyperus difformis* L.), and broadleaf signalgrass (*Urochloa platyphylla* Munro ex C. Wright R.D. Webster) (Miller and Norsworthy 2018). Control of the most problematic weeds of rice with florpyrauxifen-benzyl provides benefits to growers using this herbicide.

The florpyrauxifen-benzyl label for rice warns that crop injury can occur when the herbicide is applied to medium-grain and hybrid cultivars (Anonymous 2018). In early research, greater injury in the form of leaf malformation as well as height and biomass reduction were observed on long-grain hybrid cultivar CL XL745 than pure-line, long-grain ‘CL111’ and medium-grain ‘CL272’ (Wright et al. 2020). Other studies conducted showed CL XL745 exhibited 6% injury 28 days after application, while pure-line, long-grain, acetyl-CoA carboxylase-resistant rice was injured up to 10% by florpyrauxifen-benzyl (Sanders et al. 2020). The use of florpyrauxifen-benzyl without fear of causing long-term injury to the rice crop would provide another effective site-of-action to combat herbicide resistance.

Benzobicyclon, a 4-hydroxyphenylpyruvate dioxygenase-inhibiting herbicide (HPPD, WSSA Group 27), is the first HPPD herbicide registered for use in rice production in California and recently receivedwas registered in 2021 in the midsouthern US rice production region (Anonymous 2021; Komatsubara et al. 2009). Benzobicyclon is applied as a pro-herbicide, requiring conversion to the active herbicidal form, benzobicyclon hydrolysate, through hydrolysis (Williams and Tjeerderma 2016). Benzobicyclon hydrolysate controls some weeds resistant to acetolactate synthase-inhibiting herbicides (ALS, WSSA Group 2), including certain weedy rice biotypes (*Oryza sativa* L.) and aquatics such as ducksalad (*Heteranthera limosa* Sw. Wild) and California arrowhead (*Sagittaria montevidensis* Cham. & Schltdl.) (McKnight et al. 2018). Hydrolysis of benzobicyclon in water is necessary to provide sufficient weed control as evident by foliar applications providing 1% weedy rice control, whereas treatment of foliage and water can increase control to 88% (Brabham et al. 2019). Because of the ability of benzobicyclon to control certain weedy rice biotypes, there are concerns for insufficient rice crop tolerance to the herbicide. Rice cultivar tolerance to benzobicyclon is known to differ between cultivars of *japonica* and *indica* origin (Kwon et al. 2012). Cultivars of *japonica* origin show little to no injury after application whereas ones of *indica* descent show as much as 98% injury 6 weeks after application, with eventual death in some instances (Kwon et al. 2012; Young et al. 2017). Cultivar tolerance to benzobicyclon has been attributed to the presence of the HPPD Inhibitor Sensitive 1 Gene (HIS1), which is commonly found in cultivars of *indica* descent (Maeda et al. 2019).

The combination of florpyrauxifen-benzyl and benzobicyclon in a weed control program could result in the effective management of several of the most problematic weedy species in rice, while also adding sites of action never before used in rice production. The following research was conducted to determine rice cultivar sensitivity to applications of florpyrauxifen-benzyl at 30 and 60 g ha^{-1} and sequential applications at 30 g ha^{-1}. Additionally, rice cultivar sensitivity to an application of florpyrauxifen-benzyl at 30 g ha^{-1} followed by benzobicyclon was evaluated.

Materials and Methods

Cultivar Sensitivity to Florpyrauxifen-benzyl. A field experiment was conducted at the Rice Research and Extension Center (RREC) near Stuttgart, Arkansas, in 2019 and 2020 to test rice cultivar sensitivity to florpyrauxifen-benzyl following single and sequential applications of the herbicide. The soil at the site was a DeWitt silt loam (fine, smectic, thermic typic Albaqualf) consisting of 19% clay, 27% sand, and 54% silt with 2% organic matter with a pH of 5.6. The seedbed was prepared using shallow tillage followed by a preplant application of glyphosate at 1,120 g ae ha^{-1}. Rice was drill-seeded on April 2, 2019, and April 11, 2020, at a rate of 36 seeds per meter row for hybrid cultivars and 72 seeds per meter row for pure-line cultivars. A 10-row cone drill with 18-cm row spacing was used to seed rice cultivars according to the plot randomization. Plots measured 5.2 by 1.8 meters, with a 1-meter alley. All plots were maintained weed-free using preemergence applications of clomazone at 560 g ai ha^{-1} (Command 3ME, FMC, Philadelphia, PA 19104) and postemergence applications of propanil at 4,480 g ha^{-1} (Riceshot, UPL, King of Prussia, PA 19406) at 1-leaf rice, and an application of fenoxaprop at 124 g ai ha^{1} (Ricestar HT, Gowan Co., Yuma, AZ 85364) with halosulfuron-methyl at 52 g ai ha^{-1} (Permit 75WG, Gowan Co., Yuma, AZ 85364) at 3-leaf rice for both site years. Potassium and phosphorous were applied preplant based on soil test values, and nitrogen at 135 kg N ha^{-1} in the form of urea (460 g N kg^{-1}) was aerially-applied to the test site at the 5-leaf stage of rice. Levees were constructed, and the test site flooded to a 5-cm depth.

This experiment was designed as a randomized complete block with a two-factor factorial, where the first factor was florpyrauxifen-benzyl treatment (none, single application of 30 g ae ha^{-1}, single application of 60 g ae ha^{-1}, and sequential applications of 30 g ae ha^{-1} (Loyant™ Herbicide, Corteva AgriSciences LLC, 9330 Zionsville Road Indianapolis, IN 46268);

the second factor was rice cultivar. All applications of florpyrauxifen-benzyl included 0.58 L ha^{-1} of methylated seed oil, with the sequential application applied to 2-leaf followed by 4- to 5-leaf rice. The two single applications were applied at the 4- to 5-leaf stage of rice. Three hybrid, long-grain cultivars (CL XL745, XP753, and RT Gemini 214CL; RiceTec Inc., Alvin, TX 77512); one pure-line, long-grain (Diamond; Rice Research and Extension Center, Stuttgart, AR 72160); and one pure-line, medium-grain cultivar (Titan; Rice Research and Extension Center, Stuttgart, AR 72160) were evaluated. The first florpyrauxifen-benzyl application occurred on May 1, 2019and May 12, 2020. All subsequent applications were made on May 17, 2019 and May 22, 2020, 16 and 10 days after the initial application in each year, respectively. All plots were flooded on May 29, 2019, and May 29, 2020, 12 and 8 days after final florpyrauxifen-benzyl application, respectively. Applications were made with a CO_2-pressurized backpack sprayer at 140 L ha^{-1} at 276 kpa using four 110015 AIXR nozzles spaced 48-cm apart (TeeJet Technologies, Springfield, IL 62703).

Cultivar Sensitivity to Florpyrauxifen-benzyl following Benzobicyclon. The second field experiment was also conducted in 2019 and 2020 at the Rice Research and Extension Center near Stuttgart, AR. Soil texture at the site both years was 19% clay, 27% sand, and 54% silt with 2% organic matter and a pH of 6.2. Rice was drill seeded on May 1, 2019, and May 3, 2020, at a rate of 36 seeds per meter row for hybrid cultivars and 72 seeds per meter row for inbred cultivars using a 10-row cone drill with 18 cm row spacing. Plots were kept weed-free using the same herbicide treatments as in the previous experiment. Rice was fertilized with 135 kg N ha^{-1} as urea preflood (5-leaf rice). Other fertilizer applications were made based on soil test values prior to planting.

This experiment was designed as a split-plot randomized complete block with two sub-plot factors. The whole-plot factor was comprised of separate bays with and without benzobicyclon at 371 g ai ha^{-1} applied within one week of flood establishment. Subplot factors were rice cultivar and the application of florpyrauxifen-benzyl at 0 and 30 g ae ha^{-1} applied prior to flooding. Hybrid, long-grain cultivars RT CL XL745,XP753, and RT Gemini 214CL; pure-line, long-grain cultivar Diamond; and pure-line medium-grain cultivar Titan were randomized across blocks with each block hosting nontreated plots and plots receiving applications of florpyrauxifen-benzyl only, benzobicyclon only, and florpyrauxifen-benzyl followed by benzobicyclon.

Applications of florpyrauxifen-benzyl at 30 g ae ha^{-1} with 0.58 L ha^{-1} methylated seed oil were made on 4- to 5-leaf rice on May 29, 2019 and June 1, 2020. The flood was established on May 30, 2019, and June 3, 2020 and applications of benzobicyclon at 371 g ai ha^{-1} were made on June 4, 2019, and June 11, 2020, at 5 and 10 days after florpyrauxifen-benzyl application, respectively. Herbicide treatments were made with a CO_2-pressurized backpack sprayer equipped with 110015 AIXR nozzles (TeeJet Technologies, Springfield, IL 62703) calibrated to deliver 140 L ha^{-1} at 276 kpa.

Data Collection. Visible estimations of rice injury (injury ratings) for both experiments were evaluated on a 0 to 100 scale, where 0 indicates no injury and 100 represents crop death. Injury ratings occurred at 21 and 28 days after the 4- to 5-leaf application for the florpyrauxifen-benzyl alone experiment and 14 and 21days after the florpyrauxifen-benzyl application for the florpyrauxifen-benzyl followed by benzobicyclon experimentdue to maximum injury occurring within the evaluation dates specified. Rice injury ratings were based on visual estimations of leaf malformation, stunting, loss of groundcover, decreased biomass, and chlorosis. Aerial images of all plots were taken 35 days after final florpyrauxifen-benzyl application from a height of approximately 60 meters using a DJI Phantom Pro 4 (Sentera 6636 Cedar Avenue S., Minneapolis, MN 55423) with a 1080p camera. Groundcover of each plot was determined using Field Analyzer (Turf Analyzer, Fayetteville, AR 72702). Dates that rice reached 50% heading in each plot were recorded and reported relative to the nontreated control. Rice grain was harvested with a small-plot combine (Almaco, Nevada IA), and rough rice grain yield was adjusted to 12% moisture.

Data Analysis. Data were analyzed using R Statistical Software v 4.0.3 (R Core Team 2018). If data were found to violate the assumptions of normality, nonparametric assessments were used for analysi (Kniss and Streibig 2018). Shapiro-wilk and Levene's tests were used to confirm the assumption that injury ratings were non-normal data. Similar assumption verifications were performed on groundcover, heading date, and yield data, and thereby ANOVA or equivalent non-parametric tests were used as appropriate. Injury ratings, collected from the split-plot experiment, were analyzed in two steps: 1) using a nonparametric Kruskal-Wallis test for the whole-plot factor being the application of benzobicyclon, and 2) sub-plot factors being the application of florpyrauxifen-benzyl and cultivar used for evaluation (Kruskal and Wallis 1952; Shah and Madden 2004). Non-parametric data from the florpyrauxifen-benzyl cultivar sensitivity study were analyzed using the rankFD function to assess interactions between factors (Brunner et al. 1997, 2019). Due to the inconsistent nature of the injury caused by florpyrauxifen-benzyl, site-years for both trials were analyzed separately. Parametric data from both trials were analyzed using Dunnett's procedure after ANOVA to compare means from each treatment to the nontreated control. Yield data collected from all trials were analyzed using the mass collected but reported as a percent of the nontreated control. All models with yield were subjected to ANOVA and when necessary, means were separated using Tukey's adjustment at $\alpha = 0.05$.

Results and Discussion

Cultivar Sensitivity to Florpyrauxifen-benzyl Alone. Rice injury caused by florpyrauxifen-benzyl can be characterized by leaf malformation in the form of rice leaves curled around the midrib and in severe cases, leaf tips trapped inside of leaf sheathes. Injury caused by florpyrauxifen-benzyl can also be identified by an erect appearance of the rice plant and loss of groundcover as well and loss of biomass. Injury caused by florpyrauxifen-benzyl was greater in the experiment occurring in 2020 when compared to injury observed in 2019. Therefore, the experiments were analyzed separately to better determine the interaction of florpyrauxifen-benzyl and rice cultivar. Interactions of florpyrauxifen-benzyl application and cultivar were significant for all visible injury rating dates (Table 2.1). A single application of florpyrauxifen-benzyl at 60 g ae ha^{-1} to 4- to 5-leaf rice caused a similar level of injury as 30 g ae ha^{-1} for all cultivars tested, with the exception of XP753 21 days after application in 2020 (Table 2.2). In 2019, sequential applications of florpyrauxifen-benzyl at 30 g ae ha^{-1} were more injurious to rice than any single application. When CLXL745 was treated with sequential applications of florpyrauxifen-benzyl at 30 g ae ha^{-1}, 29% injury was observed 28 days after application, compared to single applications of 30 and 60 g ae ha^{-1} that caused 1 and 6% injury, respectively (Table 2.2).

Rice injury in 2020 reflects few differences between sequential and single applications (Table 2.2). Rice injury caused by sequential applications of florpyrauxifen-benzyl has been observed to decrease when the number of days between applications increases (Wright et al. 2020). Sequential applications made in 2019 were applied with a 10-day interval, while applications in 2020 were made 16 days apart, explaining the lack of differences observed from injury ratings between sequential and single applications in 2020. Florpyrauxifen-benzyl is known to translocate more in weed species under moist soil conditions, leading to the hypothesis that the herbicide could be more mobile in rice under these conditions, causing increased levels of injury (Miller and Norsworthy 2018). In 2019, rice injury in block one, the highest elevation within the bay, following sequential applications averaged 19% at 28 days after treatment in 2019, while the fourth block with the lowest elevation averaged 31% after sequential applications (data not shown). In 2020, multiple smaller bays were employed, creating less change in elevation from the front to the rear of each bay, reducing the amount of variation among blocks.

While multiple applications of florpyrauxifen-benzyl may increase the risk for injury to rice, the damage caused by florpyrauxifen-benzyl in this trial appeared superficial, as date to 50% heading and rough rice yields were generally not negatively affected (Table 2.3). Groundcover imagery and analysis, however, revealed that the potential for groundcover reduction 35 days after an application of florpyrauxifen-benzyl is possible. Gemini 214CL, CL XL745, and XP753, following sequential applications of florpyrauxifen-benzyl at 30 g ae ha^{-1} in 2019, had a 47, 30, and 45% reduction in groundcover, respectively, compared to the nontreated control for each corresponding cultivar (Table 2.3). Applications of florpyrauxifen-benzyl, no matter the rate, reduced groundcover of XP753. This is not the first rice herbicide for which differences among cultivars has been noted. For example, labeled rates of clomazone injure some rice cultivars more than others, but similar to florpyrauxifen-benzyl, the injury does not generally negatively affect grain yield or the time it takes the rice to mature (Scherder et al. 2004).

Although not agronomically significant, a one-day delay in maturity was observed when florpyrauxifen-benzyl was applied at 30 and 60 g ae ha $^{-1}$ to CL XL745 in 2019. That same year, following sequential applications of florpyrauxifen-benzyl at 30 g ae ha^{-1}, rough rice grain yield collected from XP753 was reduced by 17% (Table 2.3). Neither a reduction in groundcover, grain yield, or delay in maturity was observed in 2020, indicating that conditions causing the yield loss and delays did not occur in both years. While Wright et al. (2020) studied the effects of multiple applications of florpyrauxifen-benzyl at multiple rates on rice at difference growth stages, data reported only encompassed rice with Clearfield resistance, not including hybrids and cultivars produced from differing parent lines and germplasms with possible levels of varying tolerance. Although data collected from these studies coupled with observations made by Wright (2020) indicate that while single florpyrauxifen-benzyl applications cause injury to some cultivars, making more than one application at a labeled rate to hybrid rice has the potential to delay maturity and reduce yield and groundcover under some environmental conditions.

Cultivar Sensitivity to Florpyrauxifen-benzyl followed by Benzobicyclon. The low level of injury observed in 2019 led to few significant main effects or interactions for the parameters evaluated that year (Table 2.4). Although interactions do exist, data were deemed inconclusive due to the low levels of visible rice injury observed as well as the lack of reduction in yield, groundcover, and delay in maturity observed (data not shown). Rice injury caused by florpyrauxifen-benzyl followed by benzobicyclon and both herbicides alone was minimal in 2019, never exceeding 8% (Table 2.5). Environmental differences between years is believed to have contributed to greater injury in 2020 than in 2019 in this trial.Florpyrauxifen-benzyl was applied during dry conditions in 2019 whereas the soil moisture status at application on June 1, 2020, was noted as being “moist” as a result of an irrigation event that occurred prior to application, possibly explaining the differences in injury observed between site-years of the experiment.

Benzobicyclon following florpyrauxifen-benzyl was no more injurious to any cultivar than an application of florpyrauxifen-benzyl alone (Table 2.5). Applications of benzobicyclon alone never resulted in more than 4% visible injury to rice, while visible injury following florpyrauxifen-benzyl alone ranged from 4 to 27% (Table 2.5). All cultivars tested for sensitivity in this study were not in possession of the HIS1 gene; therefore, minimal injury was expected from a stand-alone application of benzobicyclon (Kwon et al. 2012; Young et al. 2017).

Interactions of florpyrauxifen-benzyl and cultivar proved significant 14 days after application in 2020, leading to the conclusion all cultivars tested were susceptible to florpyrauxifen-benzyl to some degree, similar to findings in the earlier trial reported. Visible rice injury was transient in most cases, not affecting rice groundcover 35 days after florpyrauxifen-benzyl treatment and having no effect on reproductive rice via delayed maturity or reduced yield (Table 2.5). Benzobicyclon-only applications reduced groundcover by 6% compared to the nontreated control when applied to XP753 and delayed the heading of Titan by 1 day in 2020, but this effect is unlikely of biological significance (Table 2.5).

Practical Implications

A single florpyrauxifen-benzyl application at a labeled rate of 30 g ae ha^{-1} or in areas of a field where overlap occurs (60 g ae ha^{-1}) will likely result in noticeable injury to the crop if the sensitive cultivars are treated at the 4- to 5-leaf stage. In most cases but not all, the rice was able to recover, causing no reductions in grain yield, groundcover, and delay in maturity. Conversely, sequential florpyrauxifen-benzyl applications of 30 and 60 g ae ha^{-1} should be avoided because of greater risk for injury, loss of groundcover and yield, as well as delays in maturity, as seen here (Table 3) and in previous research (Wright et al. 2020). The addition of benzobicyclon to a weed control program including florpyrauxifen-benzyl does not provide an increased risk for injury compared to florpyrauxifen-benzyl alone on the cultivars tested. The inclusion of a single application of florpyrauxifen-benzyl followed by benzobicyclon in a rice weed control program could provide additional sites of action to mitigate the development of herbicide-resistant weeds while causing minimal long-term crop injury.

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Tables

Table 2.1: P-values derived from ANOVA analyzing the effect of application rate and number of applications and cultivar on injury caused to rice by florpyrauxifen-benzyl

	Visible rice injury ratings[ab]			
	2019		2020	
Sources	21 DAT	28 DAT	21 DAT	28 DAT
	-------------------------------Prob. > F------------------------			
Cultivar	0.0271*	0.0307*	< 0.0001*	< 0.0001*
Application	< 0.0001*	< 0.0001*	< 0.0001*	< 0.0001*
Cultivar * Application	0.0126*	0.0169*	< 0.0001*	< 0.0001*

[a] Abbreviation: DAT, days after treatment

[b] P-values followed by * are significant (α = 0.05)

Table 2.2: Estimations of visible rice injury caused by florpyrauxifen-benzyl application rates on rice cultivars in 2019 and 2020 taken 21 and 28 days after application[abcd]

		Visible crop injury			
		2019		2020	
Cultivar	FPB application	21 DAT	28 DAT	21 DAT	28 DAT
	g ae ha^{-1}	--------------------------------%--------------------------------			
CL XL745	Nontreated	0	0	0	0
	30	1 d	1 d	23 ab	23 a
	60	4 cd	6 cd	13 b-d	9 bc
	30 fb 30	42 a	29 a	17 a-d	12 a-c
XP753	Nontreated	0	0	0	0
	30	9 cd	6 cd	7 de	4 c
	60	3 cd	6 cd	20 a-c	13 a-c
	30 fb 30	34 a	26 ab	14 a-d	8 bc
Gemini 214CL	Nontreated	0	0	0	0
	30	0 d	0 d	10 c-e	9 bc
	60	0 d	1 d	8 de	1 c
	30 fb 30	41 a	34 a	11 c-e	8 bc
Diamond	Nontreated	0	0	0	0
	30	4 cd	5 cd	12 b-e	10 bc
	60	6 cd	10 bcd	23 ab	17 ab
	30 fb 30	15 bc	28 a	24 a	24 a
Titan	Nontreated	0	0	0	0
	30	5 cd	8 cd	6 de	4 c
	60	1 d	1 d	1 e	1 c
	30 fb 30	19 ab	20 abc	7 de	4 c

[a] Applications rates of florpyrauxifen-benzyl applied to 4- to 5-leaf rice

[b] Abbreviation: DAT, days after treatment, FPB, florpyrauxifen-benzyl

[c] Means within the same column followed by the same letter are not different according to Tukey's adjusted HSD (α=0.05)

[d] Nontreated check was not included in analysis

Table 2.3. P-values from t-tests determining differences between treated plots and the nontreated control within cultivars and means associated with relative groundcover, relative heading dates, and relative rough rice grain yield under the same factors.

		Groundcover [b]				Heading date [c]				Yield [d]			
		2019[ef]		2020		2019		2020		2019		2020	
Cultivar	Rate[a]												
	g ae ha^{-1}	(%)	Prob.>F	(%)	Prob.>F	(%)	Prob.>F	(%)	Prob.>F	(%)	Prob.>F	(%)	Prob.>F
CL XL745	Nontreated	100	(93)	100	(100)	0	(80)	0	(81)	100	(10,849)	100	(11,454)
	30	96	0.9242	99	0.8143	1.3	0.6050	1.5	0.5847	102	0.9033	110	0.5911
	60	84	0.1974	98	0.5123	1.3*	<0.0001*	0	0.5847	109	0.2968	99	0.6414
	30 fb 30	70*	0.0120*	99	0.8930	0.8*	<0.0001*	-0.3	0.5847	106	0.6185	86	0.6343
XP753	Nontreated	100	(97)	100	(88)	0	(83)	0	(83)	100	(10,496)	100	(12,110)
	30	71*	0.0205*	109	0.2152	0.5	0.8589	0.8	0.3466	91	0.0538	104*	0.0109*
	60	67*	0.0104*	111	0.1079	-3	0.8589	0.8	0.9999	105	0.2410	107*	0.0033*
	30 fb 30	55*	0.0057*	108	0.8937	0.8	0.9592	0.8	0.9738	83*	0.0009*	109	0.9356
Gemini 214CL	Nontreated	100	(88)	100	(93)	0	(88)	0	(87)	100	(10,647)	100	(10,142)
	30	101	0.9967	98	0.9556	-3	0.7418	0.5	0.8698	101	0.4689	114*	0.0195*
	60	109	0.8074	106	0.6628	-1.3	0.9533	0.8	0.7226	91	0.7535	102	0.8082
	30 fb 30	53*	0.0396*	105	0.7375	-0.8	0.9836	-0.3	0.9679	120	0.6241	105	0.2116
Diamond	Nontreated	100	(77)	100	(95)	0	(80)	0	(79)	100	(11.464)	100	(10,193)
	30	100	0.9999	97	0.2352	-1.8	0.9958	0.5	0.3298	84	0.1969	114	0.9999
	60	84	0.8588	101	0.6904	2.5	0.9958	0.3	0.3298	90	0.1207	102	0.9746
	30 fb 30	74	0.6717	98	0.1456	-0.5	0.9603	-0.3	0.8876	101	0.9974	106	0.5000
Titan	Nontreated	100	(83)	100	(94)	0	(80)	0	(80)	100	(10,193)	100	(8,990)
	30	82	0.4404	106	0.8236	0.3	0.8577	0.8	0.8518	99	0.9999	92	0.9688
	60	111	0.6755	103	0.9893	0.3	0.7242	0.8	0.9631	126	0.5592	108	0.7105
	30 fb 30	84	0.4969	107	0.9436	-0.8	0.9888	0.3	0.9631	100	0.8464	82	0.8849

[a] Applications rates of florpyrauxifen-benzyl applied to 4- to 5-leaf rice

[b] Groundcover analyzed 35 days after final application and reported as relative to nontreated check of each cultivar in each block. Nontreated check = 100%

[c] Heading dates observed when rice was reached 50% emerged head and made relative to nontreated check of each cultivar in each block. Nontreated check = 0 days

[d] Rough rice grain yield made relative to the nontreated check for each cultivar of each block. Nontreated check = 100%

[e] Means followed by* are determined to be different from the nontreated check ($\alpha = 0.05$)

[f] Numbers in parenthesis are exact values collected and averaged across controls in percent, days from emergence to heading, and kg ha^{-1}, respectively.

Table 2.4: P-values derived from ANOVA analyzing the effect of applications of florpyrauxifen-benzyl and benzobicyclon on multiple rice cultivars

	Crop injury			
	2019		2020	
Source	14 DAT[a]	21 DAT	14 DAT	21 DAT
	--------------------Prob. > F-------------------			
Benzobicyclon	0.5881[b]	0.0261*	0.0011*	0.4600
Florpyrauxifen-benzyl	< 0.0001*	< 0.0001*	< 0.0001*	< 0.0001*
Cultivar	0.0618	< 0.0001*	0.0012*	0.0913
Benzobicyclon * Florpyrauxifen-benzyl	0.0690	0.0148*	0.0072*	0.7662
Cultivar * Florpyrauxifen-benzyl	0.1932	0.1497	0.0108*	0.4175
Cultivar * Benzobicyclon	0.0464*	0.0270*	0.3134	0.3373
Cultivar * Benzobicyclon * Florpyrauxifen-benzyl	0.1229	0.0553	0.2612	0.2676

[a] Abbreviation: DAT, days after treatment

[b] P-values followed by * are significant (α = 0.05)

Table 2.5. P-values from t-tests determining differences between treated plots and the nontreated checks within cultivars and means associated with relative groundcover, relative heading dates, and relative rough rice grain yield under the same factors.[abcdefg]

		2020					
Cultivar	Treatment	Groundcover		Heading date		Yield	
		%	Prob.>F[h]	days	Prob.>F	%	Prob.>F
XP753	Nontreated	100	(99)	0	(86)	100	(12,111)
	FPB only	101[f]	0.9658[e]	0.5	0.8715	105	0.9876
	Benzo	94*	0.0393*	1.25	0.4030	95	0.9345
	FPB fb benzo	96	0.1177	1	0.5585	97	0.9786
CL XL745	Nontreated	100	(95)	0	(82)	100	(9840)
	FPB only	107	0.4971	0	0.9999	119	0.9427
	Benzo	101	0.9711	0.25	0.6472	106	0.9536
	FPB fb benzo	102	0.9475	0.25	0.6472	123	0.1048
Gemini 214CL	Nontreated	100	(94)	0	(88)	100	(11,707)
	FPB only	108	0.7632	1.25	0.5518	96	0.9360
	Benzo	104	0.9483	1.75	0.3156	82	0.2976
	FPB fb benzo	104	0.9162	2	0.2275	89	0.6427
Titan	Nontreated	100	(89)	0	(79)	100	(11,808)
	FPB only	104	0.9238	0.25	0.8647	93	0.9205
	Benzo	109	0.7207	1.25*	0.0391*	94	0.9497
	FPB fb benzo	112	0.5248	0.75	0.2584	79	0.4735
Diamond	Nontreated	100	(100)	0	(80)	100	(11,404)
	FPB only	99	0.8361	0.5	0.7934	111	0.6217
	Benzo	95	0.1699	0.5	0.7934	101	0.9969
	FPB fb benzo	98	0.5959	0.25	0.9476	95	0.9334

[a] Applications rates of florpyrauxifen-benzyl at 30 g ae ha^{-1} applied to 4- to 5-leaf rice, benzobicyclon applied at 371 g ai ha^{-1} post-flood

[b] Groundcover analyzed 35 days after final application and reported as relative to nontreated check of each cultivar in each block. Nontreated check = 100%

[c] Heading dates observed when rice was reached 50% emerged head and made relative to nontreated check of each cultivar in each block. Nontreated check = 0

[d] Rough rice grain yield made relative to the nontreated check for each cultivar of each block. Nontreated check = 100%

[e] P-values followed by * are significant (α = 0.05)

[f] Means followed by* are determined to be different from the nontreated check (α = 0.05)

[g] Abbreviation, fb. followed by; FPB, florpyrauxifen-benzyl; benzo, benzobiicyclon

[h] Numbers in parentheses are means collected from the controls in percent, days from emergence to heading, and kg ha^{-1}, respectively

Chapter 3

Impact of Environmental Conditions on Rice Injury Caused by Florpyrauxifen-benzyl

Abstract

Environmental conditions surrounding herbicide applications are known to affect weed control and crop response. Variable levels of rice injury caused by florpyrauxifen-benzyl have been observed across cropping systems and environmental conditions, warranting research in which single environmental and management strategies are isolated to understand the effect of each factor on rice injury and subsequent reductions in rice growth. A field study was conducted to determine the effects of planting date, rice cultivar, and florpyrauxifen-benzyl rate on rice injury, maturity, and yield. Two greenhouse studies were conducted to determine the effect of soil moisture and time of flooding after florpyrauxifen-benzyl application on rice injury caused by the herbicide. Growth chamber experiments were conducted to isolate the effects of temperature and light intensity on rice injury caused by florpyrauxifen-benzyl. In the field study, levels of injury varied across planting dates in both years, indicating the influence of environment on the crop response to florpyrauxifen-benzyl applications. Under dry (40% soil moisture) and saturated (100%) soil conditions, rice injury increased to 36 and 35%, respectively, compared to 27 and 25% at 60 and 80% soil moisture, respectively. Flooding rice 0 to 6 days after florpyrauxifen-benzyl application reduced visible injury; however, a reduction in rice tiller production occurred when the rice was flooded the same day as application. Visible rice injury increased when florpyrauxifen-benzyl was applied under low light intensity (700 μmol m^{-2} s^{-1}) and high temperatures (35/24 C day/night). Based on these findings, applications of florpyrauxifen-benzyl are least likely to cause unacceptable rice injury when applied to soils

having 60 and 80% saturation in high light, low temperature environments, and the crop is flooded three to six days following application.

Nomenclature: florpyrauxifen-benzyl; rice, *Oryza sativa* L.

Key Words: environmental conditions, light intensity, soil moisture, temperature, rice injury

Introduction

Florpyrauxifen-benzyl, labeled under the trade name Loyant (Corteva Agriscience, Wilmington, DE 19805), is a synthetic auxin herbicide (WSSA Group 4) formulated for weed control in rice (Anonymous 2018). Rather than targeting the transport inhibitor response 1 (TIR1) auxin F-box protein like other auxin herbicides, florpyrauxifen-benzyl favors *Arabidopsis* auxin receptor F-Box protein 5 (AFB5) indole-3-acetic acid co-receptor, allowing use of the herbicide to control resistant weed species, such as quinclorac-resistant barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.) (Bell et al. 2015; Miller et al. 2018). Following the commercial release of florpyrauxifen-benzyl in 2018, varying levels of rice sensitivity to the herbicide was noted. Research has since determined rice sensitivity to the herbicide to vary considerably among cultivars. Hybrid-long grain rice cultivars are more susceptible to florpyrauxifen-benzyl than most pureline-long grain cultivars, leading to a varietal sensitivity warning being placed on the label (Anonymous 2018; Wright et al. 2020).

Crop response to herbicides can also vary with environmental conditions. Air temperature affects crop sensitivity to multiple herbicides, with more injury observed during high temperatures in many cases (Burt and Akinsoritan 1976; Ferreira et al. 1990). Light intensity surrounding application influences crop injury as well, as light intensity is known to impact the rate of photosynthesis and other metabolic processes occurring in plants, and the ability of the plant to metabolize herbicides (Bazzaz and Carlson 1982). Translocation and metabolism of quinclorac, another synthetic auxin herbicide used in rice production, is believed to be affected by light intensity because rice grown in low light conditions exhibits greater symptomology than that grown in high light (Bond and Walker 2012). Wright et al. (2020) attributed the varying differences in rice injury caused by florpyrauxifen-benzyl in field experiments compared to those conducted in greenhouses and growth chambers to the amount of light present.

Soil moisture status near herbicide application has been known to affect herbicide efficacy. Applications of clethodim and glyphosate on monocot species were influenced by the soil moisture at the time of application (Boydston 1990; Tanpipat et al. 1997; Waldecker and Wyse 1985). Soil moisture influenced the efficacy of florpyrauxifen-benzyl through increased uptake, translocation, and metabolism of the herbicide in barnyardgrass, hemp sesbania (*Sesbania herbacea* [Mill] McVaugh), and yellow nutsedge (*Cyperus esculentus* L.) (Miller and Norsworthy 2018), leading to recommendations for producers to make applications when soils are saturated and to flood rice paddies immediately after application for maximum herbicide efficacy. However, if translocation, uptake, and metabolism of florpyrauxifen-benzyl into the active florpyrauxifen-acid increases in weed species as soil moisture increases, so should potential for rice injury.

Although rice is well-known to be a flood-tolerant crop, there are plant stresses associated with flooding the crop (Yamauchi et al. 1993). Flood timing of rice can be used as a preventative strategy against many common pests in rice production, and is used as a tool to aid in weed, insect, and disease control (Rice et al. 1997; TeBeest et al. 2012). Due the proven effect of soil moisture on florpyrauxifen-benzyl, it is possible that flood timing could be used to mitigate any potential rice injury caused by the herbicide.

The objective of this research was to determine the impact of environmental conditions surrounding application of florpyrauxifen-benzyl on rice injury. Ambient temperature, light intensity, soil moisture, and flooding have been proven to impact either herbicide efficacy or crop injury caused by herbicides and were specifically examined in this research.

Materials and Methods

Environmental Conditions for Field Study. A field study was conducted in 2019 and 2020 at the Rice Research and Extension Center near Stuttgart, Arkansas to determine the impact of environmental conditions on rice injury caused by application of florpyrauxifen-benzyl. The soil at the test site was a DeWitt silt loam (fine, smectic, thermic typic Albaqualf) consisting of 19% clay, 27% sand, and 54% silt with 2% organic matter with a pH of 5.6. Prior to planting the study in both years, the seed bed was prepared using shallow tillage and a burndown application of glyphosate (Roundup PowerMax II, Bayer CropScience). Rice was planted in 4.7-meter-long plots with 17 cm row spacing, 9 rows wide with a one-meter alley between plots. Pureline rice cultivars were planted at 72 seeds per meter row and hybrid cultivars were planted at 36 seeds per meter row. The trials were maintained weed-free using a preemergence application of clomazone at 560 g ai ha^{-1}(Command 3ME, FMC, Philadelphia, PA 19104) and postemergence applications propanil at 4,480 g ha^{-1} (Riceshot, UPL, King of Prussia, PA 19406) at 1-leaf rice, and an application of fenoxaprop at 124 g ai ha^{1} (Ricestar HT, Gowan Co., Yuma, AZ 85364) with or without halosulfuron-methyl (Permit 75WG, Gowan Co., Yuma, AZ 85364) as needed. Potassium and phosphorus were applied pre-plant based on soil test values. Nitrogen was applied at 135 kg N ha^{-1} in the form of urea (460 g N kg^{-1}) was applied to the test site when rice reached the 5-leaf stage.

The study was designed as a randomized complete block with a split-plot arrangement with two sub-plot factors. The whole-plot factor was planting date which consisted of mid-April, early May, and late May. Actual planting of rice occurred on April 2, May 1, and May 31 in 2019 and April 11, May 2, and June 1 in 2020. The use of staggered planting dates was to ensure that applications of florpyrauxifen-benzyl were made during varying atmospheric temperatures, levels of soil moisture, and other weather conditions. The first subplot factor was rice cultivar. Two cultivars of rice, 'Diamond' (Rice Research and Extension Center, Stuttgart, AR 72160) and 'XP753' (RiceTec Inc., Alvin, TX 77512) were randomized within each planting date. The second sub-plot factor was florpyrauxifen-benzyl rate at 0, 15, 30, and 60 g ae ha^{-1}. All applications of florpyrauxifen-benzyl included methylated seed oil at 0.58 L ha^{-1}. The applications of florpyrauxifen-benzyl were made to 4- to 5-leaf rice. All applications were made using a CO_2-pressurized backpack sprayer equipped with 110015 AIXR nozzles (TeeJet Technologies, Springfield, IL 62703) delivering 140 L ha^{-1} at 276 kpa. Applications in 2019 occurred on May 7, June 6, and June 24. Applications in 2020 occurred on May 21, May 28, and June 24. A levee was constructed between each planting date so that each bay could be fertilized and flooded 5 days after herbicide application.

Impact of Soil Moisture on Rice Injury Caused by Florpyrauxifen-benzyl. A greenhouse experiment was conducted using a complete randomized design at the Altheimer Laboratory in Fayetteville, AR to determine the impact of soil moisture on rice injury caused by florpyrauxifen-benzyl. The treatment structure single factor experiment consisting of four moisture levels (40, 60, 80, and 100% of pore space filled by water). A silt-loam soil, collected from Fayetteville, Arkansas was analyzed using Soil Plant Air Water (SPAW) software. The SPAW software used the percent clay, sand, and organic matter from a soil test conducted at the University of Arkansas Agricultural Diagnostic Lab (Fayetteville, AR) to determine the bulk density and pore space of the sample. The soil was then air dried in the greenhouse until it neared 0% soil moisture. Air dried soil weighing 8,000 g was added to 7.6-liter buckets, and water was added to each bucket based on the weight of the bucket and the determined soil bulk density to achieve the desired soil water content for each treatment. The amount of water to add to each bucket was calculated using the equation:

$$W_w = (F * (V/M)) * W_s$$

where W_w is the amount of the water (g or mL) added to each bucket to reach the desired level of soil moisture (F), V stands for volumetric water content, M represents the matric bulk density of the soil sample (1.44 g cm^{-3}), and W_s is weight of the dried soil placed in each bucket (8,000 g). Rice hybrid XP753 was planted in each bucket. After emergence, rice plants in each bucket were thinned to ensure that there were only 6 plants per bucket. The buckets were watered to the desired field capacity every three days (6 buckets per treatment) using the total weight of the bucket. Florpyrauxifen-benzyl at 30 g ae ha^{-1} plus methylated seed oil at 0.58 L ha^{-1} were applied to three "treated" buckets when rice reached the 4- to 5-leaf stage using TeeJet 1100067 nozzles (TeeJet Technologies, Springfield, IL 62703) using water as a carrier at 187 L ha^{-1} at 276 kpa Three buckets per treatment remained without herbicide application to serve as a nontreated control. As a result, this study had three spatial replicates and two temporal replicates. Moisture levels were maintained until all buckets were flooded to a 5-cm depth 5 days after application. At the time of flooding, nitrogen was applied at 135 kg N ha $^{-1}$ in the form of urea fertilizer (46460 g N kg^{-1}) (46-0-00). The rice remained flooded until termination of the trial. The environmental conditions in the greenhouse were a high daytime temperature of 31 C and a low night temperature of 24 C with humidity at 41%, maintained by the heating and cooling system inside of the greenhouse. Lights were provided at an average of 800 µmol m^{-2} s^{-1} to maintain a 14-hour photoperiod daily. The experiment was conducted twice.

Impact of Flooding Date on Rice Injury Caused by Florpyrauxifen-benzyl. A second experiment was conducted in the same greenhouse in Fayetteville, AR under the same growing conditions. The experiment aimed to determine the impact of flood timing following application of florpyrauxifen-benzyl on rice injury. Rice hybrid XP753 was planted in buckets filled with 8,000 g of soil that were maintained similarly to those used in the previous experiment. However, in these experiments, all buckets were maintained at 100% soil moisture after emergence until flooding. The experiments were conducted as a complete randomized design with treatment structures allowing for analysis as a two-factor factorial. The first factor was florpyrauxifen-benzyl application. Three buckets per treatment received an application of florpyrauxifen-benzyl at 30 g ae ha^{-1} plus methylated seed oil at 0.58 L ha^{-1} and another three buckets remained nontreated to serve as a control. The second factor was application of a 5-cm depth flood established 0, 3, 6, 9, and 12 days following florpyrauxifen-benzyl application (DAT). The experiment had 3 replications spatially and two replications temporally. Nitrogen fertilizer was applied prior to flooding at the same rate as used before. Buckets remained flooded until termination of the experiment.

Impact of Light Intensity and Air Temperature on Rice Injury Caused by Florpyrauxifen-benzyl. A third experiment was conducted in a Conviron Growth Chamber (Controlled Environments LTD., Winnipeg, Manitoba, Canada) at the Altheimer Laboratory to determine the effect of light intensity and temperature on rice injury caused by florpyrauxifen-benzyl. Buckets of soil were filled with 8,000 g of the silt-loam soil, planted to XP753, and maintained at 100% soil moisture using identical methods as those described for the previous experiments. However, buckets used in this experiment were transferred to a growth chamber to create the environment necessary to satisfy the treatments of this experiment. The study was designed as randomized complete block with a split-plot setup with two sub-plot factors. The whole-plot factor was ambient temperature. The growth chamber was programmed to maintain low/high temperatures of 24/35 C (high temperature treatment) and 13/24 C (low temperature treatment) with a 12-hour photoperiod daily. Temperatures used in this experiment were determined by using the average high and low temperature in April, May, and June in Stuttgart, Arkansas with a higher than average treatment and a lower than average treatment determined using data collected from the weather station used in experiment 1. The first sub-plot factor was light intensity with treatments of high light intensity (1100 µmol m^{-2} s^{-1}) and low light intensity (700 µmol m^{-2} s^{-1}), achieved by dividing the growth chamber in half using a curtain and modifying the amount of light output through the removal of bulbs. The second sub-plot factor was with or without an application of florpyrauxifen-benzyl at 30 g ae ha^{-1} plus 0.58 L ha^{-1} methylated seed oil to rice at the 5-leaf stage. All buckets were fertilized using the same rate of nitrogen as in the greenhouse experiments and flooded 5 days after treatment to 5-cm depth. The soil in the buckets remained flooded until the experiment was terminated. The experiment had three replications spatially and two replications temporally.

Data Collection

Environmental Conditions for Field Study. Visual estimations of crop injury (injury ratings) were recorded 21 and 28 DAT. Injury ratings were taken on a 0 to 100% scale where 0 indicates no herbicide injury and 100 represents crop death. Rice injury ratings were based on visual estimations of leaf malformation, stunting, loss of groundcover, decreased biomass, and chlorosis. The date at which 50% of the rice in each plot reached heading was recorded and reported relative to the non-treated control for each cultivar in every block for all three planting dates. Rough rice grain yield was collected using an Almaco plot combine (Almaco, Nevada, IA) and was adjusted to 12% moisture. Temperature, rainfall, and solar radiation were monitored for 7 days prior to the application until 7 days after application using a weather station (Davis

Instrument Corporation, Hayward, California 94545) positioned approximately 25 m from the study in both years. Temperature was reported as an average of daily temperature and average daytime high temperature for the 7-day period spanning either side of the application day, including the day of application. Similarly, solar radiation across this period was reported as a total and average radiation day^{-1}. Rainfall was measured from 7 days before the application until the flood was established 5 days after application and reported as total rainfall over the 12-day period as well as average rainfall day^{-1}. Soil moisture was not directly monitored.

Greenhouse and Growth Chamber Experiments. Data collection for the greenhouse and growth chamber experiments occurred 14 and 28 DAT. Data collected from each experiment consisted of visual estimations of rice injury, rice tiller counts, rice height, groundcover analysis, and aboveground rice biomass. Estimations of visible injury were recorded on a similar scale in the early study. The number of rice tillers produced per bucket were counted at each data collection time point. Heights of all rice plants present were recorded. Images were taken above each bucket at a height of 90 cm using a high definition 1080p camera. Rice groundcover was quantified using Canopeo (Oklahoma State University, Stillwater, OK 74078). At 28 days after application, aboveground rice biomass was collected, dried for three days to constant mass, and weighed. Both groundcover and biomass were made relative to the respective nontreated control.

Statistical Analysis. Data were analyzed using R Statistical Software v 4.0.3 (R Core Team, Vienna, Austria). Data that were not deemed normal or heterogeneous through use of a Shapiro-Wilkes and Levene's test were subject to a nonparametric analysis (Kniss and Streibig 2018). All estimations of visible injury from the field study, and all data collected from the growth chamber study were deemed nonparametric and subject to analysis using the Kruskal-Wallis test (Kruskal and Wallis 1952; Shah and Madden 2004). Heading dates and rough rice grain yield were deemed parametric and analyzed using the (nlme) function.

Data from the soil moisture and flood timing greenhouse experiments were analyzed as a two-factor factorial using the RankFD function for nonparametric data (estimations of visible injury) and the (lme) function for parametric variables (height, tiller counts, biomass, and groundcover) (Brunner et al. 1997, 2019). Parametric variables were also assessed using Dunnett's procedure to determine differences from the nontreated control. All means were subject to Tukey's HSD to determine differences between treatments at α= 0.05

Results and Discussion

Environmental Conditions for Field Study. The injury caused to rice by florpyrauxifen-benzyl was characterized by an erect posture of all leaves on the plant and visual appearance of biomass and groundcover loss as well as leaf malformation in the form of leaves cupping around the mid-rib and in severe cases, the leaf tip would remain trapped inside of the leaf sheath. The p-values derived from estimations of visible injury occurring 21 and 28 DAT indicate a strong impact of environmental conditions (planting date) on injury caused by florpyrauxifen-benzyl (Table 3.1). The strong effect of environment on damage to rice is further supported by estimations of visible injury occurring 28 DAT where planting date was significant (Table 3.2). The variable levels of injury observed at 28 DAT among planting dates could possibly be attributed to the weather conditions surrounding times of application. The highest levels of rice injury caused by florpyrauxifen-benzyl occurred when the crop was planted in late May in 2019 and early May in 2020 with 17 and 16% injury, respectively (Table 3.2). The florpyrauxifen-benzyl application to rice planted in late May 2019 was made during a warm period, with an average high temperature of 27 C. The rice planted in early May of 2020 received the greatest amount of rainfall during the period observed, which likely resulted in a high soil moisture content at or near application. Conversely, the lowest injury levels were observed for mid-April planted rice in 2019 (2%) and late May in 2020 (<1%). Average temperature surrounding the application to mid-April planted rice in 2019 was the coolest of the time periods sampled, with an average high temperature of 20 C (Table 3.3).

Based on findings from this study, there is a possible effect of temperature and moisture on the levels of rice injury following a florpyrauxifen-benzyl application. However, there are other factors that can contribute to the levels of injury observed and identification and isolation of these factors could lead to better recommendations on how to minimize rice injury caused by florpyrauxifen-benzyl or injury expectations under certain conditions. Variation of environmental conditions may also be the cause of differences in rice response to florpyrauxifen-benzyl in previously published research. For instance, in one study, hybrid CL XL745 was injured no more than 10% following florpyrauxifen-benzyl at 58 g ae ha^{-1} while in another study as much as 20% injury resulted from the herbicide at the same rate on this hybrid (Sanders et al 2021; Wright et al. 2020).

The rate of florpyrauxifen-benzyl impacted the amount of injury observed 21 and 28 DAT (Table 3.1), but to a less extent than the environmental conditions surrounding the application. Less injury occurred when florpyrauxifen-benzyl was applied at 15 g ae ha^{-1} compared to applications at 60 g ae ha^{-1}. Hybrid XP753 also exhibited a general delay in heading (<1 day) following an application of florpyrauxifen-benzyl at 15 and 60 g ae ha^{-1}. While significant, the delay in maturity is minimal and should not affect production operations. The discovery that florpyrauxifen-benzyl can be applied at 15 g ae ha^{-1} under varying environmental conditions without causing long-term rice injury is significant for producers attempting to use less-than-labeled rates of the herbicide for broadleaf and sedge weed control, which is currently the most widely used rate of this herbicide in Arkansas based on conversations with growers (Norsworthy, personal communication). No relative rice yield reductions were observed following applications of florpyrauxifen-benzyl at any rate under any of the environmental conditions observed.

Impact of Soil Moisture on Rice Injury Caused by Florpyrauxifen-benzyl. Visible injury was affected by soil moisture levels following application of florpyrauxifen-benzyl (Table 3.4). At 14 DAT, florpyrauxifen-benzyl caused the least amount of injury (21%) when soil was maintained at 80% moisture until flooding. At 28 DAT, injury (25 to 27%) was similar when soil moisture was 60 and 80% until flooding. The highest amount of injury (35 to 36%) occurred under 40 and 100% soil moisture, indicating that both stress from drought and extremely wet, saturated soils can solicit more symptomology on rice following an application of florpyrauxifen-benzyl (Table 3.5).

Weed species are known to uptake, translocate, and metabolize the herbicide at higher rates under saturated soil conditions, explaining the interaction of soil moisture with rice injury caused by florpyrauxifen-benzyl (Miller and Norsworthy 2018). However, the excessive visible injury caused under extremely dry conditions could be due to the compounding of drought stress with florpyrauxifen-benzyl further hindering the ability of the rice to grow properly. In order to minimize visible injury caused by florpyrauxifen-benzyl, applications should occur between 60 and 80% field capacity when possible, although applications at all levels of soil moisture elicited injury.

Although injury was observed in the form of leaf malformation, differences were not observed in height, tiller production, groundcover, or biomass production as a result of soil moisture treatment (Table 3.6). T-tests revealed that florpyrauxifen-benzyl alone did cause reductions in rice tiller production and biomass. Rice tiller production was reduced 17% by florpyrauxifen benzyl 14 DAT and the crop did not recover by 28 DAT, with a reduction of 15% averaged across soil moisture treatments at the later assessment. Biomass and groundcover data collected 28 days following florpyrauxifen-benzyl application revealed reductions of 33% and 31%, respectively, across soil moisture treatments (Table 3.6). These findings coincide with previous work that found height, biomass, and groundcover reduction following florpyrauxifen-benzyl applications (Wright et al. 2020). Reduction in groundcover correlates with loss of yield as well as inability of the crop to negatively affect weed emergence and growth (Donald 1998; Norsworthy 2004). The loss of groundcover caused by florpyrauxifen-benzyl, especially in a non-flooded production system like furrow-irrigated rice, could lead to greater weed emergence and the need for a subsequent herbicide application as a result of crop injury and reduced canopy formation. However, considering applications were made to 5-leaf rice, normal practice in a flooded system dictates that flood establishment occurs soon after application, mitigating the need for a residual herbicide, as most terrestrial weed species do not germinate beyond the permanent flood (Henry et al. 2018).

Impact of Flooding Date on Rice Injury Caused by Florpyrauxifen-benzyl. Examination of rice injury caused by florpyrauxifen-benzyl application followed by multiple flood timings revealed that more visible injury occurred when the flood was established 9 or 12 DAT (34 and 28%, respectively) (Tables 3.7 & 3.8). The least amount of visible injury to rice occurred when the flood was established 0 or 3 days after application. The florpyrauxifen-benzyl label for rice recommends that a flood be established within 5 days following application to prevent further emergence of weed species (Anonymous 2020). Therefore, under similar conditions to those maintained in the greenhouse, using current recommendations along with these data, a producer could expect to see 8 to 15% injury 28 days following application of florpyrauxifen-benzyl if flooded within 5 days under the conditions of this study (Table 3.8). However, as previously noted, many factors can affect contribute the level of injury observed. Findings from this experiment indicate that even though there is a lack of visible injury on rice when the flood is established 0 days after treatment with florpyrauxifen-benzyl, there is a reduction in tiller number, indicating that flood establishment should be withheld until 3 to 6 days following application of the herbicide.

As noted in the previous greenhouse experiment, a single florpyrauxifen-benzyl application reduced rice tiller production (17% 14 DAT, 15% 28 DAT), groundcover (30%) and rice biomass (33%), regardless of flooding date (Table 3.9). However, previous research indicates that rice will recover from injury caused by a single application of florpyrauxifen-benzyl at 30 g ae ha $^{-1}$ with no reduction in yield or delay in maturity (Wright et al. 2020). Rice treated with florpyrauxifen-benzyl has been able to compensate for the reductions in tiller production, height, groundcover, and biomass prior to maturity (Wright et al. 2020). However, in order to minimize overall injury, visible or physiological, applications should be made 3 to 6 days prior to flooding.

Impact of Temperature and Light Intensity on Rice Injury Caused by Florpyrauxifen-benzyl. Analysis of the data evaluating the impact of temperature and light intensity on injury caused by florpyrauxifen-benzyl revealed that both factors contribute to the extent of crop damage based on visible rice injury, groundcover, and biomass assessments (Table 3.10). The combination of high temperature and low light caused the greatest injury to rice at 14 and 28 DAT, with 20 and 27% observed, respectively (Table 3.11). Furthermore, no injury was observed at either evaluation for the combination of low temperature and high light. Similarly, for the groundcover and biomass assessments, there was reduction of 44% in groundcover and 19% in biomass caused by florpyrauxifen-benzyl under the high temperature and low light regime (Table 3.11).

Rice tiller production and height 28 DAT was affected by the interaction of temperature and application of florpyrauxifen-benzyl (Table 3.10). Florpyrauxifen-benzyl caused a 9% reduction in rice tiller production and a 5% reduction in rice height under the high temperature regime, averaged over light intensities 28 DAT. Florpyrauxifen-benzyl also induced a 7% reduction in rice tillers, averaged across all temperature and light treatments 14 DAT, like observations from previous experiments (Table 3.11). Findings from this experiment lead to the conclusion that there is increased risk for damage to rice from florpyrauxifen-benzyl in the form of visible injury, stunting, less biomass, and reduced groundcover under prolonged cloudy (low light) periods that are accompanied by warm conditions. While cloudy conditions would be expected to lower air temperature, it is still possible to have air temperatures comparable to those evaluated in this study during summer months when florpyrauxifen-benzyl is being applied in the rice production regions of Arkansas.

Practical Implications. Factors contributing to the amount of injury caused by florpyrauxifen-benzyl have been identified as rate of application, number of applications, rice cultivar receiving the application, preexposure to other herbicides such as quinclorac, as well as environmental conditions and agronomic factors surrounding the application event (Norsworthy personal communication, Wright et al 2020). Understanding the impact of these environmental conditions on the amount of rice injury caused by florpyrauxifen-benzyl observed can allow producers, consultants, and scientists alike to attribute the varying degrees of injury to conditions surrounding the time of application and have a better understanding as to why certain areas appear more susceptible to the herbicide than others, Applicators can also use the findings from these experiments to mitigate rice injury caused by florpyrauxifen-benzyl to the best of their ability. Applications should not be made in extremely dry or saturated conditions. Producers should be mindful that applications shortly followed by saturated conditions because of rainfall or flood establishment will impact the extent of injury to rice. Crop injury can be further exacerbated during periods of above average temperatures, especially if cloudy conditions are present. If florpyrauxifen-benzyl is applied to late-planted rice there will be greater risk for warm conditions surrounding application thus injury to the crop. When deciding to apply florpyrauxifen-benzyl, the weed control benefits should be weighed against the risk for injury, knowing that there are few postemergence options for controlling barnyardgrass and Palmer amaranth, two of the most troublesome weeds of rice in the Mid-south.

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Tables

Table 3.1: P-values derived from analysis of the effect of planting date, rice cultivar, and florpyrauxifen-benzyl rate on rice injury caused by florpyrauxifen-benzyl from a study conducted at the Rice Research and Extension Center near Stuttgart, AR in 2019 and 2020.[ab]

	Rice injury			
Factor	21 DAT	28 DAT	Heading	Yield
Planting Date	< 0.0001*	< 0.0001*	0.4649	0.0970
Rate	< 0.0001*	< 0.0001*	0.1990	0.1480
Cultivar	0.1517	0.1033	0.0675	0.2245
Planting Date X Rate	0.2316	0.0844	0.9899	0.3597
Cultivar X Rate	0.3834	0.4436	0.0209*	0.3283
Planting Date X Cultivar	0.0011*	0.0601	0.5229	0.8362
Planting Date X Rate X Cultivar	0.6784	0.9899	0.8295	0.0760

[a] Abbreviation: DAT, days after treatment

[b] P-values followed by * are significant (α = 0.05)

Table 3.2: Estimations of visible rice injury and date to 50% heading as relates to injury caused by florpyrauxifen-benzyl by planting date, cultivar, and application rate from a study conducted at the Rice Research and Extension Center near Stuttgart, AR in 2019 and 2020. [abcd]

Factor			Cultivar	Rate	Injury 21 DAT	Injury 28 DAT	Heading
				g ae ha^{-1}	--------%--------		days
Planting Date X Cultivar	2019	Mid-April	Diamond		5 de	2	-1
			XP753		5 de	2	0
		Early May	Diamond		4 e	7	0
			XP753		5 de	4	3
		Late May	Diamond		14 bc	16	1
			XP753		22 a	18	1
	2020	Mid-April	Diamond		13 bc	9	0
			XP753		8 c-e	4	0
		Early May	Diamond		17 ab	15	0
			XP753		12 b-d	17	-1
		Late May	Diamond		0 e	1	0
			XP753		0 e	0	0
Cultivar X Rate			Diamond	15	5	5	0 a
				30	8	8	0 a
				60	13	12	0 a
			XP 753	15	5	5	<1 ab
				30	7	7	0 a
				60	14	11	1 b
Planting Date	2019	Mid-April			5	2 b	0
		Early May			4	6 ab	1
		Late May			17	17 a	1
	2020	Mid-April			10	7 ab	0
		Early May			15	16 a	0
		Late May			0	<1 b	1
Rate				15	5 b	6 b	0
				30	8 b	8 ab	0
				60	13 a	11 a	1

[a] Abbreviation: DAT, days after treatment

[b] Means within the same column and grouping followed by the same letter are not significantly different according to Tukey's adjusted HSD (α=0.05)

[c] Heading is days before or after the nontreated check reached 50% heading. Average days from emergence to heading for Diamond were 80 in both 2019 and 2020 and 83 and 85 for XP753 in 2019 and 2020, respectively.

[d] Application rates of florpyrauxifen-benzyl applied to 4- to 5-leaf rice

Table 3.3: Weather data collected near experiment site at the Rice Research and Extension Center near Stuttgart, AR[ab]

Planting date		Injury 28 DAT	Temperature Average	Temperature Average high	Rainfall Average day^{-1}	Rainfall Total	Solar radiation Average day^{-1}	Solar radiation Total
		%	------ C --------		------ cm ------		-------- W m^{-2} --------	
2019	Mid-April	2 b	20	20	0.48	5.8	48196	674738
	Early May	6 ab	25	26	0.49	5.9	68532	959447
	Late May	17 a	26	27	0.36	4.3	70790	991054
2020	Mid -April	7 ab	23	24	0.31	3.7	68255	955564
	Early May	16 a	24	25	0.45	5.4	78310	1096341
	Late May	<1 b	23	23	0.48	5.8	60770	850784

[a] Data recorded from 7 days prior to application to 7 days past application.
[b] Total rainfall was recorded from 7 days prior to application until flooding 5 days after application.

Table 3.4: P-values determined using ANOVA from a greenhouse experiment conducted to determine the impact of soil moisture on rice injury from a greenhouse study conducted at the Altheimer Lab in Fayetteville, AR.[ab]

Assessment date	Assessment	P-value
14 DAT	Rice injury	0.0424*
	Tiller count	0.8951
	Rice height	0.8951
28 DAT	Rice injury	0.0389*
	Tiller count	0.1332
	Rice height	0.7907
	Groundcover	0.9356
	Biomass	0.8083

[a] Abbreviation: DAT, days after treatment
[b] P-values followed by * are significant (α = 0.05)

Table 3.5: Estimations of visible rice injury caused by applications of florpyrauxifen-benzyl at differing soil moistures from a greenhouse study conducted at the Altheimer Laboratory in Fayetteville, AR.[abc]

Factor		Rice injury 14 DAT	Rice injury 28 DAT
	--------------------(%)-------------------		
Soil Moisture	40	32 a	36 a
	60	22 b	27 bc
	80	21 b	25 c
	100	26 ab	35 ab

[a] Abbreviation: DAT, days after treatment
[b] Means within the same column followed by the same letter are not significantly different according to Tukey’s adjusted HSD (α=0.05)
[c]Applications rates of florpyrauxifen-benzyl applied to 4- to 5-leaf rice

Table 3.6: Impact of florpyrauxifen-benzyl at 30 g ae ha^{-1} on rice height and tiller production at 14 and 28 days after treatment (DAT) and rice groundcover and biomass at 28 DAT averaged over soil moisture regimes in a greenhouse experiment at the Altheimer Laboratory in Fayetteville, AR. [abc]

Factor	Rate	Rice height		Tiller production		Groundcover	Biomass
		14 DAT	28 DAT	14 DAT	28 DAT	28 DAT	28 DAT
	g ae ha^{-1}	---------- Prob. > F ----------					
Florpyrauxifen-benzyl application	0 vs 30	0.1864	0.2319	0.0249	0.0041	0.0453	0.0011
		---------- % of nontreated ----------					
	30	95	102	83*	85*	70*	67*

[a] Abbreviation: DAT, days after treatment
[b] Applications rates of florpyrauxifen-benzyl applied to 4-5 leaf rice
[c] Means displayed as percent of nontreated check are compared to the nontreated with significant differences indicated using an asterisk

Table 3.7: P-values determined using ANOVA on data from experiment determining the impact of flood timing on florpyrauxifen-benzyl injury observed.

Assessment date[a]	Assessment	p-value[b]
14 DAT	Rice Injury	<0.0001*
	Tiller Count	0.3308
	Rice Height	0.5167
28 DAT	Rice Injury	<0.0001*
	Tiller Count	0.0463*
	Rice Height	0.5262
	Groundcover	0.3951
	Biomass	0.7154

[a] Abbreviation: DAT, days after treatment
[b] P-values followed by * are significant ($\alpha = 0.05$)

Table 3.8: Impact of flood establishment timing following florpyrauxifen-benzyl application at 30 g ae ha^{-1} in the greenhouse on visible estimates of rice injury and rice tiller counts.[abc]

		Rice injury		Tiller count
Factors		14 DAT	28 DAT	28 DAT
Flood Timing	0	4 c	8 b	79 b
	3	5 c	8 b	93 a
	6	15 b	15 b	94 a
	9	28 a	27 a	97 a
	12	34 a	31 a	104 a

[a] Abbreviation: DAT, days after treatment
[b] Means within the same column followed by the same letter are not different according to Tukey's adjusted HSD (α=0.05)
[c] Applications rates of florpyrauxifen-benzyl applied to 4- to 5-leaf rice

Table 3.9: Impact of florpyrauxifen-benzyl at 30 g ae ha^{-1} on rice height and tiller production at 14 and 28 days after treatment (DAT) and rice groundcover and biomass at 28 DAT averaged over flooding timings in a greenhouse experiment at the Altheimer Laboratory in Fayetteville, AR. [abc]

		Rice height		Tiller production		Groundcover	Biomass
Factor	Rate	14 DAT	28 DAT	14 DAT	28 DAT	28 DAT	28 DAT
	g ae ha^{-1}	-- Prob. > F --					
Florpyrauxifen-benzyl application	0 vs. 30	0.1971	0.0907	0.0393	0.1529	0.0497	0.0029
		----------------------------------- % of nontreated -----------------------------------					
	30	97	96	86*	93	81*	81*

[a] Abbreviation: DAT, days after treatment
[b] Application rate of florpyrauxifen-benzyl applied to 4- to 5-leaf rice
[c] Means displayed as percent of nontreated check are compared to the nontreated with significant differences indicated using an asterisk

Table 3.10: P-values derived from ANOVA in a growth chamber experiment investigating the effect of light and temperature on rice injury caused by florpyrauxifen-benzyl conducted at the Altheimer Lab in Fayetteville, AR.[ab]

	14 DAT			28 DAT				
Factor	Injury	Height	Tillers	Injury	Height	Tillers	GC[c]	Biomass
Temperature	<0.0001*	0.1674	0.7656	<0.0001*	<0.0001	0.0464	<0.0001	0.5870
Light	<0.0001*	0.5875	0.9075	<0.0001*	0.8777	0.8808	<0.0001	0.0114
Temp X Light	<0.0001*	0.7566	0.0812	<0.0001*	0.7583	0.3684	<0.0001	0.1400
Temp X Loyant	<0.0001*	0.1674	0.7656	<0.0001*	<0.0001	0.0464	<0.0001	0.5870
Light X Loyant	<0.0001*	0.5875	0.9075	<0.0001*	0.8777	0.8808	<0.0001	0.0114
Temp X Light X Loyant	<0.0001*	0.7566	0.0812	<0.0001*	0.7583	0.3684	<0.0001	0.1400

[a] Abbreviations: DAT, days after treatment; GC, groundcover
[b] P-values followed by * are significant (α = 0.05)

Table 3.11: Rice injury, tiller production, height, groundcover, and biomass following florpyrauxifen-benzyl at 30 g ae ha^{-1} in high or low temperature and light regimes in an experiment conducted at the Altheimer Laboratory in Fayetteville, AR[abcdef]

				14 DAT		28 DAT				
Factor	Temp	Light	Application	Injury	Tillers	Injury	Tillers	Height	Groundcover	Biomass
			g ae ha^{-1}	---%--						
Temperature * Light * Application	Low	Low	0	0 b	100	0 c	100	100	100 a	100 a
			30	6 bc	106	3 c	105	104	81 bc	71 b
		High	0	0 c	100	0 c	100	100	100 a	100 a
			30	1 c	86	0 c	99	106	111 a	96 a
	High	Low	0	0 c	100	0 c	100	100	100 ab	100 a
			30	20 a	84	27 a	87	91	56 c	81 b
		High	0	0 c	100	0 c	100	100	100 ab	100 a
			30	10 b	97	14 b	94	98	84 ab	90 ab
Temperature * Application	Low		0	0	100	0	100 a	100 ab	100	100
			30	3	96	2	101 a	105 a	96	86
	High		0	0	100	0	100 a	100 ab	100	100
			30	15	95	20	91 b	95 b	70	83
Application			0	0	100 a	0	100	100	100	100
			30	9	93 b	11	96	100	83	85

[a] Abbreviation: DAT, days after treatment

[b] Means within the same column followed by the same letter are not different according to Tukey's adjusted HSD (α=0.05)

[c] Data reported relative to nontreated check.

[d] Applications rates of florpyrauxifen-benzyl applied to 4- to 5-leaf rice

[e] Low and high light regimes were 700 µmol m^{-2} s^{-1} and 1100 µmol m^{-2} s^{-1}, respectively

[f] Low and high temperature regimes were 13/24 C and 24/35 C (night/day), respectively

Chapter 4

Palmer amaranth Control in Furrow-Irrigated Rice with Florpyrauxifen-benzyl

Abstract

Palmer amaranth is a common weed on levees in rice fields but has become increasingly problematic with adoption of furrow-irrigated rice and the lack of an established flood. Florpyrauxifen-benzyl has previously been found effective for controlling Palmer amaranth in rice, but the efficacy of low rates of florpyrauxifen-benzyl and the effect of Palmer amaranth size on control is unknown. The objective of this research was to find the level of Palmer amaranth control expected with single and sequential applications of florpyrauxifen-benzyl at varying weed heights. The first study was conducted at the Lon Mann Cotton Research Station near Marianna, AR, in 2019 and 2020 to determine the effect of florpyrauxifen-benzyl rate on control of <10 cm (labeled size) and 28- to 32-cm tall (larger-than-labeled size) Palmer amaranth. The second experiment was conducted in 2020 at Pine Tree Research Station and Lon Mann Cotton Research Station to compare single applications of florpyrauxifen-benzyl at low rates to sequential applications at the same rates with a 14-day interval on 20- and 40-cm tall Palmer amaranth. Results revealed that florpyrauxifen-benzyl at 15 g ae ha^{-1} was as effective as 30 g ae ha^{-1} in controlling <10-cm tall Palmer amaranth (92% and 95% mortality in 2019). Sequential applications of florpyrauxifen-benzyl at 8 g ae ha^{-1} was as effective as single or sequential applications at 30 g ae ha^{-1}. However, no rate of florpyrauxifen-benzyl applied to 20- or 40-cm tall Palmer amaranth was sufficient to provide season-long control of the weed, with the escaping female plants producing as many as 6,120 seed per plant following a single application.

Nomenclature: florpyrauxifen-benzyl; Palmer amaranth, *Amaranthus palmeri* S. Watson; rice, *Oryza sativa* L.

Key Words: furrow-irrigated rice, weed control

Introduction

In Arkansas, 10.5% of rice hectares produced in 2019 were furrow-irrigated (Hardke 2020). Furrow-irrigation is an agronomic practice in which rice is drill-seeded on elevated beds, similar to popular methods used in Mid-South corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybean [*Glycine max* (L.) Merr.] production (Norsworthy et al. 2011). While flood-irrigated rice necessitates a continuous flood from V5 until rice maturity, furrow-irrigated rice utilizes irrigation water that is distributed throughout fields using the furrows between beds via polypipe on the elevated end of a field (Counce et al. 2020). Although yields from traditionally direct-seeded, delayed-flood rice typically surpass those of furrow-irrigated rice, there are advantages to producing rice without a continuous flood (Tacker 2007; Vories et. al 2002). Depending on soil texture, cropping systems, and other factors faced by a producer, furrow-irrigating rice can reduce water use and other input costs such as field preparation between crop rotations (Vories et al. 2002; Tracy et al. 1993).

The act of flooding rice provides more benefits to producers than irrigation alone. While flooded rice creates the anaerobic conditions used to stop germination of certain weed species buried in the soil seedbank, furrow-irrigated rice supplies weed species with enough moisture and oxygen to germinate and grow (Henry et al 2018). Terrestrial weeds found to be problematic in flooded rice such as barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.], sprangletops, (*Leptochloa* ssp.), and sedges (*Cyperus* ssp.) can still emerge and thrive in furrow-irrigated rice because of the moist environment. However, furrow irrigation also allows an aerobic environment that is conducive to typical upland crop pests such as Palmer amaranth (Norsworthy et al. 2011), which was recently found to be the second most problematic weed of furrow-irrigated rice in Arkansas in a 2020 survey (Butts and Norsworthy, non-published data).

Palmer amaranth is the most problematic weed in cotton (*Gossypium ssp.*) and soybean (*Glycine max ssp.*) production in the Mid-South and was the fifth most troublesome weed in rice production, prior to the rapid increase in popularity of furrow-irrigated rice (Van Wychen 2020; Riar 2013). Palmer amaranth has historically been a nuisance on levees but shifting from flood irrigation to furrow irrigation increases the likelihood of Palmer amaranth as a problematic pest. The impact of Palmer amaranth on cotton and soybean in the southern U.S. has been documented (Rowland et al. 1999; Klingaman and Oliver 1994). Little is known about the consequences of Palmer amaranth on rice yields because historically the crop has been grown in the southern U.S. with a flood established at the V5 growth stage, leading to conditions unsuitable for season-long survival of Palmer amaranth. However, as the acreage planted to furrow-irrigated rice continues to increase along with the prevalence of Palmer amaranth in this system, there is a need to develop strategies to remove the weed from rice and understand the impact of its presence on the crop.

Herbicide options for Palmer amaranth control in rice are limited. Palmer amaranth has already developed resistance to seven known sites of action in the state of Arkansas alone, further limiting effective herbicide options for rice producers (Heap 2021). Among the herbicides no longer effective for controlling Palmer amaranth are protoporphyrinogen oxidase inhibitors (PPO, WSSA Group 14) and acetolactate synthase inhibitors (ALS, WSSA Group 2), formerly common options for control of Palmer amaranth in rice. Applications of 2,4-D were previously recommended for Palmer amaranth control on levees; however, some regulations restrict the use of 2,4-D in certain areas due to the risk for off-target movement of the herbicide and the susceptibility of other prominent crops in the area (ASPB 2020).

Florpyrauxifen-benzyl (Loyant) is a synthetic auxin herbicide (WSSA Group 4) released by Corteva Agriscience in 2018 for pre-flood control of grass and broadleaf weed species in rice (Anonymous 2018). Florpyrauxifen-benzyl at the labeled rate of 30 g ae ha^{-1} has been shown to be effective for controlling Palmer amaranth in furrow-irrigated rice with greater than 97% control (Wright et al. 2020). In greenhouse studies, florpyrauxifen-benzyl at 10 g ae ha^{-1}, 1/3rd of the labeled use rate in rice, controlled Palmer amaranth 84%, indicating that applications under the labeled rate may provide effective control if applied to small weeds or used sequentially as part of a herbicide program (Miller and Norsworthy 2018). The objective of the studies conducted in this research were to (1) determine the level of Palmer amaranth control that could be expected following a single application of florpyrauxifen-benzyl to labeled and larger-than-labeled weed sizes and (2) determine the efficacy, crop injury, and impact on weed-seed production of single versus sequential applications of florpyrauxifen-benzyl at varying rates on larger-than-labeled Palmer amaranth.

Materials and Methods

Optimizing the Rate and Timing of Florpyrauxifen-benzyl on Palmer Amaranth. A field experiment with a randomized complete block design with four replications was initiated to determine the efficacy of single applications of florpyrauxifen-benzyl on multiple sizes of Palmer amaranth at the Lon Mann Cotton Research Station in Marianna, Arkansas, in 2019 and 2020. The soil at the site of both experiments was a Convent silt loam consisting of 9% sand, 80% silt, 11% clay, and 1.8% organic matter with a pH of 6.5. Hybrid, long-grain rice cultivar ‘Gemini 214CL’ (RiceTec Inc., Alvin, TX 77512) was planted in 2019. Due to discontinuation and subsequent shortages of Gemini 214CL, hybrid, long-grain rice cultivar ‘Full Page RT 7521FP’ (RiceTec Inc., Alvin, TX 77512) was sown in 2020. The ground was tilled prior to planting, hipped into 96-cm wide beds and received a preemergence burndown application of glyphosate at 4.5 kg ha $^{-1}$ (Roundup PowerMax II, Bayer CropScience, RTP, NC 27709). Following ground preparation, rice was planted at a rate of 36 seeds per meter row with an 18-cm row spacing. Plot dimensions were established as 3.6 m wide (four 96 cm wide beds) by 6 m long, totaling 21 m^2. Native populations of Palmer amaranth were allowed to germinate following the planting of the rice. The experiment was kept free of weeds other than Palmer amaranth using applications of cyhalofop-butyl (Clincher SF, Corteva Agriscience, Wilmington, DE 19805) and hand weeding if necessary. Once rice reached the 2-leaf stage, it was irrigated every three days unless rainfall occurred and irrigation was deemed unnecessary. Nitrogen was applied at 135 kg N ha^{-1} as urea (460 kg N ha^{-1}) in three split applications with intervals of one week following 5-leaf rice. Other nutrients were applied preplant based on soil test values.

The experiment was set up as a two-factor factorial with a randomized complete block design, with the first factor being application rate of florpyrauxifen-benzyl at 8, 15, 23, and 30 g ae ha^{-1} and the second factor being Palmer amaranth height at application. All applications of florpyrauxifen-benzyl included methylated seed oil at 0.58 L ha^{-1} and pendimethalin at 363 g ai ha^{-1} to minimize further Palmer amaranth emergence throughout the trial. Applications were made to 5- to 7.5- and 28- to 32-cm tall Palmer amaranth, as the former is within the labeled size requirement, and the latter is a larger-than-labeled size (Anonymous 2020). All herbicide applications were made using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} at 276 kPa using four 110015 AIXR nozzles spaced 48 cm apart (TeeJet Technologies, Springfield, IL 62703). A nontreated control was included in the design as well as a treatment that was maintained weed free via hand weeding throughout the growing season.

Prior to application, two, m^2 quadrats were established per plot and Palmer amaranth densities were recorded from each quadrat (Table 4.1). Visible estimations of Palmer amaranth control (control ratings) were taken 21 and 28 days after final treatment (DAT) on a 0 to 100 scale, with zero indicating no plant symptomology and 100 representing plant death. Before the plots were harvested, Palmer amaranth plants in each designated quadrat were counted to determine the percent mortality achieved by the herbicide application, based on the assumption that no Palmer amaranth emerged following application, with suppression of further emergence provided by the pendimethalin application and rice canopy cover. The center of each plot was harvested once the rice had matured using an Almaco (Almaco, Nevada, IA) plot combine with a 1.7 m width. Yields from each plot were adjusted to 12% moisture and reported relative to the corresponding weed-free check to determine the percent reduction in yield caused by the presence of Palmer amaranth.

Salvage Applications of Florpyrauxifen-benzyl on Palmer Amaranth. An experiment was conducted in 2020 at the Lon Mann Cotton Station in Marianna, Arkansas (Convent silt loam, 9% sand, 80% silt, 11% clay, and 1.8% organic matter and pH of 6.5) and at the Pine Tree Research Station near Colt, Arkansas (Calhoun silt loam, 10% sand, 69% silt, 21% clay, and 1.3% organic matter and pH of 7.5) to determine the efficacy of variable rates of florpyrauxifen-benzyl applied once and in sequential applications on 20- and 40-cm tall Palmer amaranth. The trials were planted and maintained similarly to the previously described experiment; however, in both trials, hybrid rice 'Full Page RT 7521FP' (RiceTec Inc., Alvin, TX 77512) was planted at 36 seeds per meter row on 96-cm-wide beds at Marianna and 76-cm-wide beds at Colt. Plots were four hip-rows wide and 6 m long at both locations making plots 21 m^2 at Marianna and 18.24 m^2 at Colt. An application of clomazone (Command 3ME, FMC Corporation, Philadelphia, PA 19104) at 560 g ha^{-1} was made at planting to minimize emergence of weed species other than Palmer amaranth. Clomazone has no activity on Palmer amaranth, as indicated by the label of Command 3ME (Anonymous 2019). The experiment was again kept free of grass weeds using fenoxaprop, cyhalofop, and hand weeding when necessary. Three applications of nitrogen at 56 kg N ha^{-1} as urea (460 g N kg^{-1}) were applied at one-week intervals following the 5-leaf rice growth stage, and the test area was irrigated every three days following the 2-leaf stage of rice unless rainfall occurred.

The experiment was conducted as a randomized complete block design with a three-factor factorial treatment structure. The first factor was florpyrauxifen-benzyl rates of 8, 15, 23, and 30 g ae ha^{-1}. All applications included 0.58 L ha^{-1} of methylated seed oil and pendimethalin at 363 g ai ha^{-1} to minimize further weed emergence. The second factor was Palmer amaranth size: 20- and 40-cm tall plants. The third factor was number of applications made. Single applications of the aforementioned rates were used as well as sequential applications of the same rates at a 14-day interval. A weedy nontreated control and a hand-weeded weed-free control were included.

Before application, two, m^2 quadrats were established in each plot, and Palmer amaranth densities were recorded in each meter square before the initial application at each size (Table 4.2). Visual estimations of Palmer amaranth control (control ratings) were rated 21 and 28 days after final application on the same 0 to 100 scale as described previously. All Palmer amaranth in each plot were counted at the time of harvest. All female Palmer amaranth plants in each plot were counted and harvested by hand, dried to constant mass, and ground. A 0.5-g subsample of the ground plant matter from each plot was weighed, and the number of Palmer amaranth seeds in each subsample was recorded (Schwartz et al. 2016). The average seed production per female

Palmer amaranth plant was calculated by dividing the total seeds produced by the number of female Palmer amaranth per plot. The number of seeds m^{-2} was calculated using the total number of Palmer amaranth seeds produced and the area of the plot. Rough rice grain yield was determined by harvesting the center two hip-rows and beds of each plot using an Almaco small-plot combine (Almaco Nevada, IA) with a 1.7 m wide header. Grain yield was adjusted to 12% moisture.

Data Analysis. Data were analyzed using R Statistical Software v 4.0.3 (R Core Team, Vienna, Austria). Data were checked to determine whether the assumptions of normality and homogeneous variance were met using the Shapiro-Wilkes test and Levene's test. The test result suggested that non-parametric analysis (Kniss and Streibig 2018) was appropriate. Specifically, weed control ratings from both experiments, as well as live Palmer amaranth counts, seed production per female Palmer amaranth plant, and seed m^{-2} estimates were analyzed using the '*RankFD*' package in R (Brunner et al. 1997, 2018), which is known to be useful to evaluate the interaction effect in factorial models. Rough rice grain yield data from both trials were reported and analyzed as a percent of the nontreated control. Site-year was originally included as a factor in the model for both experiments and was found to be highly significant ($p < 0.0001$) in most interactions due to differing levels of efficacy observed by site-year in both experiments; therefore, the experiments were analyzed separately by site-year to simplify results.

Results and Discussion

Optimizing the Rate and Timing of Florpyrauxifen-benzyl on Palmer Amaranth. Florpyrauxifen-benzyl rate and Palmer amaranth size were significant ($p < 0.05$) for estimations of visible control recorded 21 and 28 days after treatment in both site years, and florpyrauxifen-benzyl rate was significant when analyzing mortality in 2020 (Table 4.3). Weed control ratings from 21 and 28 DAT in 2019 and 2020 lead to the conclusion that Palmer amaranth control was maximized over the rates tested when florpyrauxifen-benzyl was applied at 23 or 30 g ae ha^{-1}, averaged over Palmer amaranth sizes (82 to 89% control, 28 days after treatment in 2019) (Table 4.4). Observations from mortality data indicated that florpyrauxifen-benzyl at 15 g ae ha^{-1} was as effective at 23 or 30 g ae ha^{-1}, albeit there is a 19-percentage point numerical decrease in mortality in 2020 as florpyrauxifen-benzyl rate decreases from 23 to 15 g ae ha^{-1}averaged across Palmer amaranth size. The difference in results from percent mortality versus weed control ratings can be attributed to Palmer amaranth being injured, malformed, and stunted by applications of florpyrauxifen-benzyl at 15 g ae ha^{-1} and eventually succumbing to the rice canopy. Based on the mortality data, it appears that florpyrauxifen-benzyl applied at lower-than-labeled rates can achieve similar control to labeled applications. These findings are comparable to those by Miller and Norsworthy (2018) in which florpyrauxifen-benzyl at 20 g ae ha^{-1} controlled 20-cm-tall Palmer amaranth 84%, whereas 23 g ae ha^{-1} achieved 82% control in this experiment. However, applications of florpyrauxifen-benzyl at any rate tested did not achieve 100% Palmer amaranth control or mortality, with the surviving plants producing seed. Thus, there is a need for sequential applications of florpyrauxifen-benzyl or its use with other herbicides as noted elsewhere (Wright et al. 2020).

For herbicides labeled for Palmer amaranth control in other crops, such as dicamba (WSSA Group 4), it is recommended that applications be made before plants reach 10 cm in height (Anonymous 2020). Palmer amaranth control ratings from our studies show the importance of florpyrauxifen-benzyl being applied timely to labeled-sized weeds to maximize control, which should translate into higher mortality of the weed and possibly crop yield although statistical differences in these latter two assessments could not be detected (Table 4.4).

Rough rice grain yield, averaged across Palmer amaranth size, ranged from 66 to 72% of the weed-free check in 2019 and 63 to 76% in 2020, but no differences were determined via florpyrauxifen-benzyl rate or Palmer amaranth size (Table 4.4). End-of-season mortality ratings of Palmer amaranth also never exceeded 95%. At the Palmer amaranth densities present in this study, rice yields were often reduced by more than 25% relative to the weed-free check, even when florpyrauxifen-benzyl was applied (Table 4.4). The yield losses caused by Palmer amaranth in these studies further strengthen the recommendation of beginning with an effective residual herbicide at planting and overlaying residual herbicides in furrow-irrigated rice, with postemergence herbicides like florpyrauxifen-benzyl only used to control the few escapes not controlled by the residual herbicides (Bagavathiannan et al. 2011). The significant seed production from Palmer amaranth plants escaping the florpyrauxifen-benzyl application also justifies the need for a zero-tolerance approach for management of Palmer amaranth in furrow-irrigated rice, especially considering that the crop will most likely be rotated to soybean where auxin herbicides are now heavily relied upon for control of this troublesome, resistance-prone weed.

Salvage Applications of Florpyrauxifen-benzyl on Palmer Amaranth. Findings indicated the importance of florpyrauxifen-benzyl rate, Palmer amaranth size, and the number of applications made when attempting to control Palmer amaranth in furrow-irrigated rice (Table 4.5). Weed control ratings collected from this study again lead to the conclusion that when using single applications of florpyrauxifen-benzyl, control of 20-cm tall Palmer amaranth is maximized using florpyrauxifen-benzyl at 23 to 30 g ae ha^{-1}; however, sequential applications of florpyrauxifen-benzyl at as little as 8 g ae ha^{-1} with a 14-day interval are equally as effective (Table 4.6). When applied to 20-cm-tall Palmer amaranth, single applications of florpyrauxifen-benzyl at 23 g ae ha^{-1} achieved 79% Palmer amaranth control while sequential applications of 8 g ae ha^{-1} reached 76% by 28 DAT (Table 4.6). Once Palmer amaranth reached an average height of 40 cm, single applications of florpyrauxifen-benzyl were less effective, providing 55% control when applied as a single application at 30 g ae ha^{-1}. Consequently, sequential applications of florpyrauxifen-benzyl at 23 or 30 g ae ha^{-1} provided the most effective control of the treatments evaluated on 40-cm tall Palmer amaranth. When averaged over rate and Palmer amaranth size, sequential applications proved more effective than single applications at Colt 21 DAA, providing 67 and 52% control, respectively. Observations from the same weed control ratings from Colt at 21 DAT led to the conclusion that, when averaged over Palmer amaranth size and number of applications, florpyrauxifen-benzyl at 15 to 30 g ae ha^{-1} was most effective, ranging from 55 to 67% Palmer amaranth control (Table 4.6).

Differences determined in yield data from these studies can again be attributed to Palmer amaranth density throughout the growing season. Rice yield in Marianna never surpassed 71% of the nontreated control and rice grown in Colt had a maximum of 41% yield reduction (Tables 4.2 & 4.6). Palmer amaranth interference with rice appears to be a factor of weed density and the majority of the interference occurred prior to the applications of florpyrauxifen-benzyl or from the remaining Palmer amaranth following florpyrauxifen-benzyl application. Yield loss as a result of Palmer amaranth density has been reported in other crops (Klingaman and Oliver 1994; Massinga et al. 2001; Morgan et al. 2001; Rowland et al. 1999). Therefore, it is most likely that the yield loss observed in this study can be attributed to the Palmer amaranth density throughout the field or possible rice injury caused by multiple applications of florpyrauxifen-benzyl.

The number of live Palmer amaranth plants per ha^{-1} at rice maturity was reduced by applications of florpyrauxifen-benzyl at 15 to 30 g ae ha^{-1} at both locations, averaged over size and number of applications. Applications of florpyrauxifen-benzyl at 23 and 30 g ae ha^{-1}, respectively, allowed an average of 530 and 606 Palmer amaranth plants per hectare to survive at the Colt location, respectively, and 47 and 135 plants ha^{-1} at the Marianna site, respectively (Table 4.7). The remaining Palmer amaranth in plots point to the importance of using sequential applications, as a single application left >2,400 remaining plants ha^{-1} in both Marianna and Colt, while sequential applications allowed <1,400 plants ha^{-1} to survive in each location. However, as in the previous study, Palmer amaranth that survived applications were still able to reproduce.

Female Palmer amaranth plants are prolific reproducers and are known to produce as many as 600,000 seed having 7 to 40% germination if not faced with any competition for nutrients and 11,000 to 60,000 seeds per female when competing with soybean (Keeley et al. 1987; Schwartz et al. 2016). When in competition with soybean on 97- and 19-cm row spacing, Palmer amaranth produced 211,000 and 139,000 seeds m^{-2}, respectively, indicating the influence of crop spacing on Palmer amaranth seed production (Jha et al. 2008). Considering the vast differences of seed produced by Palmer amaranth in different cropping scenarios, it is important to quantify the number of Palmer amaranth seeds being produced by Palmer amaranth following herbicide application to determine the number of seeds returned to the soil seedbank. Generally, applications of florpyrauxifen-benzyl at 23 and 30 g ae ha^{-1} reduced seed production at both locations, only allowing the production of 47 to 135 seeds m^{-2} (Table 4.7). Palmer amaranth (20-cm) that survived applications produced more seeds (6,120 seed female^{-1}) than those treated at a 40 cm height (623 seed female^{-1}). These findings indicate that if applications of florpyrauxifen-benzyl are made early, Palmer amaranth that survives the application has enough time to recover, producing more seed than larger Palmer amaranth, that was still possibly injured while entering or during reproductive stages. These findings are similar to those for crops injured by herbicide drift, where early-season exposure often has less impact on grain yield than later exposures (Castner et al. 2020).

Sequential applications also provided an advantage over single applications in reducing Palmer amaranth seed production. Sequential applications reduced the number of seed female^{-1} and m^{-2} when averaged over florpyrauxifen-benzyl rate and Palmer amaranth size. While there was a reduction in viable Palmer amaranth seed returned to the soil seedbank, the fact that seed was seed production points to the importance of a zero-tolerance approach to managing Palmer amaranth, a strategy that has been widely promoted for management of this weed in other cropping systems. Exhaustion of the soil seedbank and prevention of seed production are necessary for preserving the effectiveness of florpyrauxifen-benzyl for controlling Palmer amaranth long-term (Bagavathiannan and Norsworthy 2012; Norsworthy et al. 2014).

Practical Implications. Findings from these studies indicate that early, timely removal of Palmer amaranth is necessary to maintain yield potential of rice. Although the critical period of weed removal cannot be determined using these data, it is obvious that interference of Palmer amaranth with rice at the densities present in these trials was sufficient to cause yield loss even when florpyrauxifen-benzyl was applied to plants averaging 5 to 7.5 cm in height. Adequate control of labeled Palmer amaranth (< 10 cm height) can be achieved by applications of florpyrauxifen-benzyl at 15 to 30 g ae ha^{-1}; however, some Palmer amaranth plants, especially at the high densities that occurred in these trials, will likely survive, and reproduce, indicating the need for sequential applications of florpyrauxifen-benzyl or another effective herbicide to maintain a high level of control (Miller and Norsworthy 2018). If Palmer amaranth plants escape control and are present at harvest, these plants are likely to make significant contributions to the soil seedbank, making management of this weed in subsequent crops an ever-increasing challenge.

If Palmer amaranth is allowed to remain in the field until it reaches a height of 20 cm, sequential applications of florpyrauxifen-benzyl at 8 to 30 g ae ha^{-1} will provide equal levels of control. However, results from Colt indicated a tendency for greater seed production at the low rate (8 g ha^{-1}) of florpyrauxifen-benzyl and greater seed production when a single rather than sequential applications are employed. Florpyrauxifen-benzyl is better able to control smaller Palmer amaranth (~20 cm tall) than larger (~40 cm tall) plants; however, smaller Palmer amaranth plants treated earlier in the growing season that survive an application have the propensity to produce more viable seed than Palmer amaranth injured closer to reproduction. These results indicate that lower-than-labeled rates can be successfully used for the management of Palmer amaranth, but more than one application will often be needed and additional measures may be warranted to ensure that Palmer amaranth does not successfully produce seed in a furrow-irrigated rice system.

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Tables

Table 4.1: Palmer amaranth densities and average heights from experiment analyzing single applications of multiple rates of florpyrauxifen-benzyl conducted at the Lon Mann Cotton Research Station near Marianna, AR, in 2019 and 2020.

		2019		2020	
Species	Application timing	Height	Density	Height	Density
		cm	# m^{-2}	cm	# m^{-2}
Palmer amaranth	First	5	61	7.5	80
	Second	28	102	32	104

Table 4.2: Palmer amaranth heights and densities collected from studies determining the optimum rate and number of applications of florpyrauxifen-benzyl on large Palmer amaranth conducted at the Lon Mann Cotton Research Station near Marianna, AR, and Pine Tree Research Station near Colt, AR, in 2020.

	Marinna 2020		Colt 2020	
Species	Height	Density	Height	Density
	cm	# m^{-2}	cm	# m^{-2}
Palmer amaranth	20	22	20	4
	40	48	40	4

Table 4.3: P-values derived by factor of Palmer amaranth control ratings, rough rice grain yield, and Palmer amaranth mortality by site year from the experiment conducted at the Lon Mann Cotton Station near Marianna, AR, in 2019 and 2020.[ab]

	2019				2020			
	Palmer amaranth control				Palmer amaranth control			
Factor	21 DAT	28 DAT	Yield	Mortality	21 DAT	28 DAT	Yield	Mortality
	---Prob. > F---							
Rate	0.0013*	0.0073*	0.1062	0.0802	0.0019*	0.0003*	0.5147	0.0001*
Timing	< 0.0001*	0.0002*	0.8076	0.0669	< 0.0001*	< 0.0001*	0.1689	0.1004
Rate X Timing	0.0692	0.4008	0.1891	0.3034	0.1282	0.7062	0.2937	0.0771

[a] Abbreviation: DAT, days after treatment

[b] P-values followed by * are significant (α = 0.05)

Table 4.4: Palmer amaranth control 21 and 28 day after treatment, percent mortality of Palmer amaranth, and rough rice grain yield as affected by florpyrauxifen-benzyl rate and Palmer amaranth size at application at the Lon Mann Cotton Research Station near Marianna, AR, in 2019 and 2020.[abcdef]

		2019				2020			
		PA Control				PA Control			
Factor		21 DAT	28 DAT	Yield	Mortality	21 DAT	28 DAT	Mortality	Yield
Rate	(g ha^{-1})	----------------------------------	------------	----------	---------- % ----------	----------	------------	----------	----------
	8	68 b	76 b	66	82	49 b	44 b	35 b	63
	15	70 ab	79 b	72	92	54 b	53 b	63 ab	64
	23	72 ab	82 ab	72	91	65 ab	72 a	84 a	70
	30	87 a	89 a	71	95	75 a	66 a	88 a	76
Timing	(cm)								
	5-7.5	84 a	87 a	74	97	71 a	79 a	73	70
	28-32	64 b	76 b	66	89	51 b	38 b	63	66

[a] Abbreviations: PA, Palmer amaranth; DAT, days after treatment

[b] Rough rice grain yield as a percentage of weed-free check.

[c] Mortality represented as percentage of Palmer amaranth population at time of harvest divided by density at time of application.

[d] All applications included 0.58 L ha^{-1} methylated seed oil and pendimethalin at 363 g ai ha^{-1}.

[e] Means within the same column followed by the same letter are not different according to Tukey's adjusted HSD (α=0.05); if no letter is present, no statistical difference was observed

[f] Rice in weed-free control produced 8,790 kg ha^{-1}in 2019 and 9,280 kg ha^{-1} in 2020

Table 4.5: P-values derived by factor from control ratings, rough rice grain yield, Palmer amaranth mortality and seed production by site year from the experiments conducted at the Lon Mann Cotton Station near Marianna, AR, and Pine Tree Research Station near Colt, AR, in 2020.[abcde]

Location	Variable	Rate	Size	App	Rate X Size	Rate X App	Size X App	Rate X Size X App
		-------------------	-------------------	-------------------	Prob. > F	-------------------	-------------------	-------------------
Marianna	PA Control 21 DAT	< 0.0001*	< 0.0001*	0.0493*	0.0170*	0.3958	0.3912	0.0150*
	PA Control 28 DAT	< 0.0001*	< 0.0001*	< 0.0001*	0.0023*	0.9931	0.0295*	< 0.0001*
	Yield	0.2804	0.6809	0.1139	0.3432	0.0002*	0.0118*	0.0707
	Live counts ha^{-1}	0.0011*	0.0202*	< 0.0001*	0.1997	0.4582	0.5649	0.6342
	Seed per female plant	0.1838	0.0024*	< 0.0001*	0.2294	04288	0.3247	0.3157
	Seed m^{-2}	0.0476*	0.0006*	< 0.0001*	0.6366	0.4842	0.8642	0.7768
Colt	PA control 21 DAT	0.0002*	0.4041	< 0.0001*	0.2558	0.9937	0.9731	0.7707
	PA control 28 DAT	< 0.0001*	< 0.0001*	< 0.0001*	0.0297*	0.0251*	0.1439	0.0029*
	Yield	0.0247*	0.0031*	0.0191*	0.1306	0.4735	0.1758	0.0281*
	Live counts ha^{-1}	0.0021*	0.1472	0.0009*	0.4853	0.4160	0.8319	0.5257
	Seed per female plant	0.0047*	0.0184*	0.0031*	0.9759	0.9326	0.3247	0.3157
	Seed m^{-2}	0.0088*	0.0289*	0.0026*	0.0939	0.8586	0.3330	0.3347

[a] Rate of florpyrauxifen-benzyl (8, 15, 23, 30 g ae ha^{-1})

[b] Height of Palmer amaranth at time of application (20 and 40 cm), number of applications made (1 versus 2 with 14-day interval)

[c] P-values followed by * are significant ($\alpha = 0.05$)

[d] Abbreviations: PA, Palmer amaranth; DAT, days after treatment

Table 4.6: Palmer amaranth control 21 and 28 days after treatment and rough rice grain yield as affected by florpyrauxifen-benzyl rate, number of applications, and Palmer amaranth size at application at the Lon Mann Cotton Research Station near Marianna, AR, and Pine Tree Research Station near Colt, AR, in 2020.[abcdefg]

				Marianna			Colt		
				Control			Control		
Factor				21 DAT	28 DAT	Yield	21 DAT	28 DAT	Yield
	cm	#	g ae ha^{-1}	----------------	----------------	----------------	%----------------	----------------	
Size X Appl X Rate	20	Single	8	40 c	44 d-f	64	23	22 H	79 ab
			15	58 bc	61 cd	53	62	62 d-f	69 b
			23	74 ab	78 a-c	54	70	85 ab	94 ab
			30	85 a	91 ab	70	85	88 ab	78 ab
		Sequential	8	73 ab	76 a-c	51	73	90 ab	93 ab
			15	78 ab	84 ab	69	86	92 ab	94 ab
			23	86 a	84 ab	74	98	94 ab	111 a
			30	88 a	94 a	53	99	98 a	92 ab
	40	Single	8	39 c	33 f	62	41	45 fg	58 b
			15	40 c	36 ef	59	72	42 g	73 ab
			23	44 c	38 ef	65	75	55 e-g	84 ab
			30	40 c	31 f	70	73	55 e-g	76 ab
		Sequential	8	41 c	46 d-f	55	79	60 d-g	85 ab
			15	44 c	53 de	67	96	65 c-e	59 b
			23	74 ab	74 bc	55	93	83 a-c	69 b
			30	56 bc	74 a-c	48	96	77 b-d	95 ab
Size X Appl	20	Single		64	68	61 ab	60	64	80
		Sequential		81	84	67 a	89	93	95
	40	Single		40	34	62 ab	65	49	72
		Sequential		53	62	57 b	91	71	77
Rate X Appl		Single	8	39	38	63 a-c	32	33	68
			15	48	49	61 a-c	67	52	71
			23	58	58	60 a-c	73	73	89
			30	62	61	71 a	79	71	76
		Sequential	8	57	61	52 bc	77	75	84
			15	61	69	69 ab	91	78	77
			23	80	79	65 a-c	95	89	90
			30	72	84	51 c	98	87	94
Rate			8	48	50	58	55 b	54	76
			15	55	59	64	79 a	65	74
			23	69	68	63	83 a	82	89
			30	67	73	62	88 a		85
Appl		Single		52	51	64	62 b	56	76
		Sequential		67	73	60	90 a	82	86

[a] Abbreviations: Appl., Application; DAT, days after treatment
[b] Rough rice grain yield as percentage of weed free control
[c] Height of Palmer amaranth at time of application (20 and 40 cm)
[d] Number of applications made (1 versus 2 with 14-day interval)
[e] Florpyrauxifen-benzyl rate plus 0.58 L ha^{-1} methylated seed oil plus 363 g ai ha^{-1} pendimethalin
[f] Means within the same column followed by the same letter are not different according to Tukey's adjusted HSD (α=0.05)
[g] Rice in weed free control produced 9,175 kg ha^{-1} in Marianna and 6,806 kg ha^{-1} in Colt

Table 4.7: Palmer amaranth counts and seed production after treatment by florpyrauxifen-benzyl rate, number of applications, and Palmer amaranth size at application at the Lon Mann Cotton Research Station near Marianna, AR, and Pine Tree Research Station near Colt, AR, in 2020.[abcdef]

		Marianna			Colt		
Factor		Count	Palmer amaranth seed		Count	Palmer amaranth seed	
Rate	(g ha^{-1})	# ha^{-1}	# female^{-1}	# ha^{-1}	# ha^{-1}	# female^{-1}	# ha^{-1}
	8	3,780 a	2,720 a	249 ab	3,370 a	3,720 a	656 a
	15	3,490 ab	6,820 a	874 a	2,050 ab	3,060 a	331 a
	23	1,360 b	350 a	47 b	606 b	1,310 b	126 ab
	30	2,300 ab	2,990 a	135 ab	530 b	1,740 b	74 b
Size	(cm)						
	20	3,510 a	6,120 a	578 a	1,893 a	3,370 a	438 a
	40	1,960 b	623 b	51 b	1,382 a	1,550 b	156 b
Applications	(#)						
	Single	3,980 a	5,675 a	599 a	2,420 a	3,690 a	470 a
	Sequential	1,490 b	1,024 b	67 b	852 b	1,230 b	124 b

[a] Living Palmer amaranth counted at the time of rice harvest in each plot (23 m^2 in Marianna and 18.4 m^2 in Colt, adjusted to ha^{-1})
[b] Average Palmer amaranth seed produced by each female per hectare.
[c] Average Palmer amaranth seed produced per square meter.
[d] Rate of florpyrauxifen-benzyl (8, 15, 23, 30 g ae ha^{-1}); all applications included 0.58 L ha^{-1} methylated seed oil and 363 g ai ha^{-1} pendimethalin.
[e] Height of Palmer amaranth at time of application (20 and 40 cm)
[f] Number of applications made (1 versus 2 with 14-day interval)

General Conclusions

Florpyrauxifen-benzyl is a synthetic auxin herbicide (WSSA Group 4) used for postemergence, broad-spectrum week control in Mid-South rice (*Oryza sativa* L.) production. Observations following applications of florpyrauxifen-benzyl led to discoveries of variable levels of rice injury caused by the herbicide. Previous research led to the discovery of cultivar sensitivity and that hybrid rice is more sensitive than pureline-cultivars, however, there were also indications of environmental and cultural practices influencing crop injury.

Experiments were conducted to determine the sensitivity of commonly used cultivars and hybrids to florpyrauxifen-benzyl with and without a subsequent application of the herbicide benzobicyclon, isolation and testing of multiple environmental and cultural variables to identify their role in injury caused by florpyrauxifen-benzyl, and optimization of the application rate and timing of florpyrauxifen-benzyl in furrow-irrigated rice to control Palmer amaranth (*Amaranthus palmeri* S. Wats.).

Yield reduction of rice hybrid XP753 by 17% following sequential applications of florpyrauxifen-benzyl at 30 g ae ha^{-1} occurred in 2019 as well as reduced groundcover of all hybrid cultivars tested. The introduction of benzobicyclon to the field following florpyrauxifen-benzyl application did not cause more injury than an application of florpyrauxifen-benzyl alone on the hybrids tested. Dry soil (40% soil moisture) and saturated soil (100% soil moisture) led to an increase in visible injury caused by florpyrauxifen-benzyl compared to soils at 60 and 80% soil moisture. Low light intensity and high temperature conditions also caused more injury to rice following florpyrauxifen-benzyl. When rice was flooded before three days and after six days following florpyrauxifen-benzyl application, increased levels of injury to rice were observed. A reduced rate application of florpyrauxifen-benzyl at 15 g ae ha^{-1} was as effective as 30 g ae ha^{-1}

in controlling less than 10-cm tall Palmer amaranth. Applying florpyrauxifen-benzyl sequentially with a two-week interval at a rate of as low as 8 g ae ha^{-1} was as effective as sequential applications at 30 g ae ha^{-1}.

Based on these findings, florpyrauxifen-benzyl can be applied at the applicators discretion in flood-irrigated rice production to control labeled weeds at a single rate without fear for long term agronomic injury. Using environmental conditions, variations in rice injury caused by florpyrauxifen-benzyl can be explained as well as potentially mitigated by avoiding applications on saturated or dry soils, during extended periods of hot temperatures or heavy overcast or shade, and by being flooded within 3-6 days after application. Although, applications of florpyrauxifen-benzyl can reduce groundcover and biomass, indicating the need for the use of a preemergence herbicide like pendimethalin to reduce weed emergence caused by the lack of groundcover. Florpyrauxifen-benzyl was also determined to be an effective option for controlling Palmer amaranth in furrow-irrigated rice production at lower than labelled rates, allowing producers to help mitigate the development of resistance and giving them an alternative tool when local regulations restrict the use of herbicides like 2,4-D and quinclorac.