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Florpyrauxifen-benzyl Use in Arkansas Rice (Oryza sativa L.)

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Florpyrauxifen-benzyl Use in Arkansas Rice (*Oryza sativa* L.)

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by

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Abstract

Florpyrauxifen-benzyl is a synthetic auxin herbicide which was commercially released in 2018 to combat troublesome grass, broadleaf, and sedge weed species in rice. Many factors may influence cultivar response to a new herbicide; hence, it is important to understand factors contributing to crop sensitivity to an herbicide in order to make appropriate recommendations. Prior to the onset of this study, research had been conducted on florpyrauxifen-benzyl in a flooded environment; however, none had been executed in a non-flooded environment. Experiments were conducted to evaluate the response of a long-grain variety 'CL111', a medium-grain variety 'CL272', and a long-grain hybrid 'CLXL745' to florpyrauxifen-benzyl as influenced by herbicide rate, environmental conditions, growth stage, days between sequential applications, and applications with an acetolactate (ALS)-inhibiting herbicide and a cytochrome P450-inhibiting insecticide. Additionally, weed control experiments were conducted to evaluate florpyrauxifen-benzyl as part of a full-season herbicide program in furrow-irrigated rice and in mixtures with other herbicides on rice levees. Generally, florpyrauxifen-benzyl at the field rate of 30 g ae ha^{-1} did not cause excessive injury or yield loss. However, the hybrid CLXL745 was most sensitive to florpyrauxifen-benzyl, especially sequential applications made at the labeled rate, resulting in yield loss. Data from these tolerance studies indicate the long-grain variety CL111 is most tolerant to florpyrauxifen-benzyl, while CLXL745 is most sensitive, thus caution should be exercised when applying florpyrauxifen-benzyl to this cultivar. Florpyrauxifen-benzyl applied at mid-season provided 96 to 98% control of Palmer amaranth in a furrow-irrigated rice system. Comparable levels of Palmer amaranth control were observed between florpyrauxifen-benzyl and a standard treatment of 2,4-D, offering another herbicide to control weeds on rice levees in areas where 2,4-D use is restricted. Results from these experiments indicate florpyrauxifen-benzyl will provide a valuable weed management tool for rice farmers.

Nomenclature: florpyrauxifen-benzyl; 2,4-D; Palmer amaranth, *Amaranthus palmeri* S. Wats.; rice, *Oryza sativa* L.

Key words: Rice tolerance, furrow-irrigated rice, rice levees.

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Dedication

This thesis is dedicated to my late, great-uncle Carl E. Smith, who instilled a love for agriculture in me when I was young. I’m grateful for his inspiration that pushed me towards a career in crop science.

Table of Contents

List of Tables

Chapter 2. Use of Florpyrauxifen-benzyl in Non-flooded Rice Production Systems

Chapter 3. Rice Cultivar Response to Florpyrauxifen-benzyl when Applied with Imazethapyr and a Cytochrome P450 Inhibitor

Chapter 4. Characterization of Rice Cultivar Response to Florpyrauxifen-benzyl

List of Figures

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Chapter 4. Characterization of Rice Cultivar Response to Florpyrauxifen-benzyl

General Introduction

Rice production

Arkansas is the top producer of rice in the country, producing nearly half of all rice grown in the United States, with nearly 600,000 hectares harvested in 2018 (USDA NASS 2019). Most rice produced in Arkansas is dry seeded into cultivated ground from late March until June (Gravois and Helms 1998). Once rice plants are approximately 5-leaf, they begin producing tillers and the field is typically flooded (Moldenhauer et al. 2018). This is known as a delayed flood system in which a majority of rice is flooded using a levee and bay system, with the flood maintained until maturity.

Three types of rice cultivars are grown in Arkansas: long-grain varieties; medium-grain varieties; and long-grain hybrids. Over 50% of rice hectares in Arkansas are planted to a long-grain hybrid, followed by long-grain varieties, which account for 39% of planted hectares (Hardke 2019). Hybrids are typically preferred because the yield potential is higher than for varieties (Yuan 1994). Medium-grain varieties are least commonly planted, accounting for only 13% of rice hectares. Long-grain cultivars are typically used for cooking while medium-grain cultivars are preferred for cereals, beer brewing, and soups (Hardke et al. 2018).

Within the three different types of rice cultivars grown in Arkansas, some cultivars may be herbicide resistant. Rice cultivars resistant to imidazolinone herbicides, or Clearfield® cultivars, were introduced in 2002 as a tool to manage red rice (Croughan 1996; Steele et al. 2002). Clearfield® rice cultivars accounted for 42% of all rice cultivars grown in Arkansas in 2018 (Hardke 2019). Additionally, cultivars tolerant to quizalofop (WSSA group 1) or Provisia™ herbicide were released in 2018 in order to better control troublesome grass weeds in rice;

however, these cultivars are not currently widespread throughout the state (Fogleman 2018; Hardke 2019).

Furrow-irrigated rice

Rice is most commonly grown in rotation with soybean (*Glycine max* L. Merr.), with this rotation accounting for 70% of all rice hectares (Hardke 2019). Most row crops in Arkansas are grown on raised bed and irrigated through furrow-irrigation, however in traditional levee and bay rice production, rice is irrigated through a system of levees. Thus, in a soybean-rice rotation, levees must be deconstructed following a rice crop and beds pulled for soybean or other upland crops such as corn. These beds must then, again, be torn down so rice can be planted, and levees pulled. This can be quite costly for growers due to associated labor, fuel, and equipment costs.

Unlike flood-irrigated rice, furrow-irrigated rice is typically drill seeded into beds, in a manner similar to that utilized in soybean production. Rather than being submerged in a continuous flood, rice is irrigated every few days to maintain soil moisture (Tracey et al. 1993). Often in furrow-irrigated rice, a tail levee is constructed on the lower end of the field to prevent water loss, thus creating a flooded environment (Hardke et al. 2017). Though yields from furrow-irrigated rice may not be as high as those from flooded rice production, cost savings associated with fewer tractor passes in the field and the associated labor and equipment costs are likely to result in an increase in furrow-irrigate rice acres (Tracey et al. 1993; Vories et al. 2002). In fact, furrow-irrigated rice acres in Arkansas have increased from nearly 16,000 hectares in 2017 to 40,000 in 2018, with this trend expected to continue (JT Hardke, personal communication; McGeeney 2018).

In traditional flooded rice production, flooding serves as a cultural weed management for terrestrial weeds (Gealy 1998; Norsworthy et al. 2011). In the absence of a flood, such as is found in furrow-irrigated rice, weed control can be challenging due to weed populations being more similar to those found in upland crops such as soybean (Norsworthy et al. 2008; Norsworthy et al. 2011). According to a survey of crop consultants, Palmer amaranth (*Amaranthus palmeri* S. Watts.) was the most problematic and important weed in soybean production (Schwartz-Lazaro et al. 2018). While Palmer amaranth is not typically troublesome in flooded rice production, the upland environment found in furrow-irrigated rice production creates a favorable environment for this weed to become problematic (Norsworthy et al. 2011). Palmer amaranth in Arkansas has evolved resistance to five herbicide modes of action: ALS inhibitors, EPSPS inhibitors, PPO inhibitors, microtubule inhibitors and long-chain fatty-acid inhibitors (Heap 2019). While there are herbicide-resistant rice cultivars, only imidazolinone tolerant cultivars could potentially be utilized in Palmer amaranth control. However, with occurrence of ALS and PPO resistant Palmer amaranth, weed control is further complicated (Burgos et al. 2001; Salas et al. 2016).

Rice levees

In traditional rice production, levees are constructed to help control and maintain a flood until the rice crop matures (Hardke 2019). During the growing season, levees are never fully submerged but remain moist, creating a favorable environment for weeds to emerge and grow (Norsworthy et al. 2010). As in furrow-irrigated rice production, problematic weed species tend to be more like those found in upland crop production. In recent years, broadleaf weeds, particularly Palmer amaranth, have become more problematic on rice levees, likely due to a soybean-rice rotation (Norsworthy et al. 2010; Norsworthy et al. 2013). Additionally, levees are typically only sprayed with a herbicide once per season, meaning weeds often grow larger than recommended for herbicide control (Norsworthy et al. 2010). Levees are often harvested so uncontrolled may result in devalued grain at the mill (Norsworthy et al. 2010). Additionally, weeds that produce seeds contribute to the soil seedbank, where they can be problematic in subsequent crops and can spread herbicide resistance (Norsworthy et al. 2012).

Current recommendations for Palmer amaranth control on rice levees include saflufenacil and 2,4-D (Barber et al. 2019). However, saflufenacil is a PPO-inhibiting herbicide and with the occurrence of PPO resistant Palmer amaranth in many fields, saflufenacil is no longer a viable herbicide option (Salas et al. 2016; JK Norsworthy, personal communication). 2,4-D is currently the standard for broadleaf weed control on levees, however its use in key rice producing counties is restricted due to the close proximity of cotton (*Gossypium hirsutum* L.). Cotton is extremely sensitive to 2,4-D so in many counties, a permit must be obtained before applying 2,4-D (ASPB 2002; Carns and Goodman 1956). Thus, options to control Palmer amaranth in non-flooded environments such as those found in furrow-irrigated rice production and on rice levees are limited, making weed control in these environments challenging.

Troublesome weeds

Weeds compete with rice throughout the growing season and cause economic losses from reduced yields and grain devaluation after harvest (Norsworthy et al. 2012). In a survey of rice consultants conducted by Norsworthy et al. (2013), results indicated that red rice, barnyardgrass (*Echinochloa crus-galli* L. Beauv.), and sprangletop species (*Leptochloa* spp.) were some of the most troublesome weeds in rice production. Of these weeds, barnyardgrass and red rice were the most difficult to control. Control of these weeds is imperative since barnyardgrass at 50 plants m^{-}

^{2} and red rice at 40 plants m^{-2} can reduce rice yields as much as 65% and 80%, respectively (Smith 1988).

Further complicating control of these weeds is the fact that both of these weeds, as well as several others problematic weeds are resistant to ALS-inhibiting herbicides (Heap 2019; Norsworthy et al. 2013). As mentioned previously, over 40% of rice in Arkansas is planted to an imidazolinone-resistant variety and thus will receive at least one application of an imidazolinone herbicide during the growing season (Hardke 2019). With the widespread adoption and use of any herbicide-resistant variety and the subsequent use of the herbicide, it is unsurprising that several weed species have evolved resistance to ALS-inhibiting herbicides. It is, however, concerning as ALS-inhibiting herbicide resistance appears to have increased in frequency and importance from a previous study conducted in 2007 (Norsworthy et al. 2007). Multiple herbicide resistance in conjunction with an increase in the occurrence of resistance highlights the necessity of additional effective herbicide sites of action and stewardship of the herbicides currently in use (Heap 2019; Riar et al. 2013).

Crop tolerance

Many factors can affect the herbicide tolerance of a crop, including cultivar, herbicide rate, crop growth stage, and environmental factors. Crop tolerance to a herbicide is due to the ability of a plant to metabolize and detoxify the herbicide into a non-toxic compound (Cole 1994). The most common detoxifying pathways are glutathione S-transferase enzymes and P450 monooxygenases. In fact, when certain P450-inhibiting insecticides are used in crops, it can cause a herbicide to be more injurious due to a reduced ability by the plant to metabolize the herbicide (Kaspar et al. 2011). One such example of this is applying the herbicide propanil, a photosystem II inhibitor within 14 days of malathion, a cytochrome P450-inhibiting insecticide that can cause significant injury to rice (Studebaker et al. 2019). A study conducted by Bowling and Hudgens (1966) found that when propanil was applied with malathion, rice was injured 50% and rough rice grain yield was reduced by 20% compared to the nontreated control.

Cultivars within a crop can exhibit differential tolerance to a herbicide, with one popular example being the tolerance of various soybean (*Glycine max* (L.) Merr.) varieties to metribuzin (Hardcastle 1979). There are several examples in the literature of differing responses of rice cultivars to herbicides. One such example is found in a study from Pantone and Baker (1992), where rice variety ‘Lemont’ was less tolerant to an application of triclopyr, a synthetic auxin herbicide (WSSA group 4) than the varieties ‘Tebonnet’ and ‘Mars’.

In this study, triclopyr was applied to these three rice varieties at two different rates at different growth stages. When a triclopyr application was made to 4- to 5-leaf rice at a rate of 800 g ae ha^{-1}, Lemont was injured 40%, while Mars and Tebonnet were injured less than 20% (Pantone and Baker 1992). However, when triclopyr was applied at 400 g ae ha^{-1}, injury to Lemont was less than 20% and injury to the other varieties was less than 10%. This study also demonstrates how crop injury can sometimes influence yield. Yield of Lemont was reduced over 30% when 800 g ae ha^{-1} triclopyr was applied to 2- to 3-leaf rice. However, yield was reduced only 5% when plants were treated at the lower rate. For all cultivars evaluated in this experiment, triclopyr applications made at 800 g ae ha^{-1} to small rice plants caused the most reductions in yield (Pantone and Baker 1992). This study demonstrates injury and crop yield can be affected by numerous factors, including herbicide rate, crop growth stage, and cultivar.

Another study from Bond and Walker (2011) evaluated the differential tolerance of imidazolinone-tolerant Clearfield® rice cultivars to applications of imazamox, am ALS-inhibiting herbicide in the imidazolinone family. In this study, two long-grain hybrids ‘CLXL745’ and

‘CLXL729’ were more injured by an application of imazamox than the long-grain variety ‘CL161’. This study also indicated the importance of crop growth stage at the time of herbicide application. Relative yield of the hybrid cultivar was reduced up to 21% when imazamox was applied in later reproductive stages (Bond and Walker 2011). This is significant when compared to no yield loss from imazamox applications made in the early reproductive stage of panicle initiation. Not only did this study demonstrate that different cultivars can exhibit varying tolerances to a herbicide, but also herbicide applications can reduce yields of sensitive cultivars. Additionally, growth stage at the time of application can influence injury and yield loss.

Other examples of crop tolerance include a study from Zhang and Webster (2002). In this study, the long-grain rice variety ‘Cocodrie’ was more tolerant to an application of bispyribac-sodium, an ALS-inhibiting herbicide, than the medium-grain variety ‘Bengal’. This study also exemplifies the importance of growth stage; fresh shoot weight was reduced nearly 50% when bispryribac-sodium was applied to 1- to 2-leaf rice, compared to only 23% when the herbicide was applied to 3- to 4-leaf rice. This indicates that for herbicide injury which occurs during vegetative growth, injury can be dependent on plant size, with larger plants having a greater ability to metabolize a herbicide.

In addition to injury being influenced by variety, rate, and growth stage, environmental conditions at and near the time of the herbicide application can affect injury. A growth chamber study conducted on corn found various thiocarbamate herbicides reduced corn growth for all plants subject to constant 30 C temperature compared to constant 20 C (Burt and Akinsorotan 1976). Conversely, a study from Wright and Rieck (1974) showed dry weights of several corn hybrids were reduced in a growth chamber maintained at 20 C compared to 33 C following an application of butylate. Both experiments demonstrate that environmental conditions, especially temperature, can influence crop tolerance to a herbicide.

Florpyrauxifen-benzyl

The introduction of new herbicides is rare, with no new herbicide modes of action released in over 20 years (Duke 2012). This not only highlights the need to preserve the current herbicide modes of action but also the need for research and discovery of new herbicide sites of action so the occurrence and evolution of herbicide resistant weeds can be minimized. In order to slow the evolution of herbicide resistance and allow farmers to have another herbicide tool to fight weeds in rice, Corteva™ Agriscience commercially released Loyant™ herbicide in 2018. Florpyrauxifen-benzyl is the active ingredient in this herbicide and is classified as a synthetic auxin (WSSA Group 4). It is a postemergence, broad-spectrum herbicide that has activity on several weed species. Much of the research conducted with florpyrauxifen-benzyl has explored chemical properties of the herbicide, including translocation and residual activity, and weed control. Miller and Norsworthy (2018a) found florpyrauxifen-benzyl controlled many problematic weeds in rice production, including hemp sesbania (*Sesbania herbacea* (Mill.) McVaugh) 98%, yellow nutsedge (*Cyperus esculentus* L.) 93%, and barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv.) 97% when applied at the recommended field rate of 30 g ae ha^{-1}. The same study also found Palmer amaranth (*Amaranthus palmeri*) was controlled 96% when florpyrauxifen-benzyl was applied at the recommended rate.

Barnyardgrass is one of the most troublesome weeds in rice production and has evolved resistance to seven herbicide modes of action, which correspond to many commonly used herbicides in rice production (Heap 2019). This includes imazethapyr (ALS inhibitor, WSSA group 2), propanil (PSII inhibitor, WSSA group 7), clomazone (DOXP inhibitor, WSSA group

13), and quinclorac (Synthetic auxin, WSSA group 4), to name a few. Florpyrauxifen-benzyl and quinclorac have differing sites of action, where florpyrauxifen-benzyl favors the AFB5 IAA co-receptor instead of the TIR1 co-receptor, allowing florpyrauxifen-benzyl to have activity on quinclorac-resistant barnyardgrass (Lee et al. 2014; Miller et al. 2018; Walsh et al. 2006).

Florpyrauxifen-benzyl is more effective with greater soil moisture; thus, it is expected to exhibit optimal control in a flooded system (Miller and Norsworthy 2018b). However, high levels of control have been observed for various grass and broadleaf weed species in the absence of a flood (Miller and Norsworthy 2018a). The versatility of florpyrauxifen-benzyl may lead to it being a good fit for weed control in non-flooded as well as flooded rice production systems.

Additional experiments from Miller and Norsworthy (2018c) indicate florpyrauxifen-benzyl has limited residual activity and should, therefore, be used in conjunction with a herbicide that does have residual weed control for an effective weed management program (Riar et al. 2013). Even with this limited residual activity, the reduced rates produced by the herbicide breaking down are still high enough to cause 10% injury to soybean planted 28 days after a 30 g ae ha^{-1} application of florpyrauxifen-benzyl to bare soil (Miller and Norsworthy 2018c). That same study also found that yield of soybean planted the same day as the 30 g ae ha^{-1} application of florpyrauxifen-benzyl was 85% less than the yield of the nontreated control, suggesting soybean are very sensitive to florpyrauxifen-benzyl.

As further evidence of soybean sensitivity to florpyrauxifen-benzyl, soybean treated with 0.3 g ae ha^{-1}, which is 1/100th of the field rate exhibited 44% and 21% injury 14 and 28 days after treatment (DAT), respectively. Additionally, at this rate, plant height and biomass of soybean were reduced 28% and 36% from the nontreated control 28 DAT (Miller and Norsworthy 2018d). Since soybean and rice are planted near each other, often with only a road separating a field, accidental drift of florpyrauxifen-benzyl to soybean is likely to be an issue that could cause substantial visible damage. However, Miller and Norsworthy (2018e) found that a low rate such as found in drift is unlikely to cause a reduction in yield.

While results from these studies conducted on florpyrauxifen-benzyl indicate it will be an effective and valuable herbicide weed management tool in rice, none of the studies conducted have explored the potential for herbicide injury to rice or cultivar differences in response to a herbicide application. Preliminary research has indicated florpyrauxifen-benzyl injury can be in the form of leaf malformations and reduced height and biomass (JK Norsworthy, personal communication). Additionally, the herbicide label also warns of potential risk for injury to long-grain hybrids and medium-grain varieties (Anonymous 2017). It is important to understand differences in cultivar tolerances when a new herbicide is introduced to reduce the risks of yield loss and to make better recommendations for farmers.

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Use of Florpyrauxifen-benzyl in Non-flooded Rice Production Systems

Abstract

The lack of a flood on rice levees and in furrow-irrigated rice creates a favorable environment for terrestrial weeds like Palmer amaranth to emerge and quickly overtake the crop for a longer portion of the year than in flooded rice culture. Florpyrauxifen-benzyl is a new auxin herbicide labeled for use in rice that has activity on both grasses and broadleaf weeds, as well as certain sedges. Field experiments were conducted to determine the efficacy of florpyrauxifen-benzyl in a non-flooded environment. Experiments were conducted in 2017 and 2018 at the Lon Mann Cotton Research Station in Marianna, AR, and at the Pine Tree Research Station near Colt, AR, in 2017 and 2018 to evaluate florpyrauxifen-benzyl within a herbicide-based weed control program in furrow-irrigated rice. Programs evaluated included two preemergence herbicide combinations, four mid-postemergence combinations, and a late-postemergence application versus none. Another experiment was conducted at the Pine Tree Research Station in 2017 and 2018 to compare florpyrauxifen-benzyl with 2,4-D in different herbicide mixtures for weed control on rice levees. Treatments consisted of several commonly used rice herbicides applied alone and in a mixture with florpyrauxifen-benzyl and with 2,4-D. In the furrow-irrigated rice experiment, programs containing florpyrauxifen-benzyl in the mid-postemergence application resulted in higher levels of late-season Palmer amaranth control (96 to 98%) compared to the standard mid-postemergence treatment (85%). Additionally, programs that included a late-postemergence herbicide application controlled Palmer amaranth 98% compared to programs where no late-postemergence herbicide was applied (91%). In the levee experiment, mixtures where florpyrauxifen-benzyl was used offered comparable control of Palmer amaranth to mixtures containing 2,4-D. Mixtures where 2,4-D or florpyrauxifen-benzyl were used controlled

Palmer amaranth better than the individual herbicide applied alone. Results from these experiments indicate florpyrauxifen-benzyl will sufficiently control Palmer amaranth in a non-flooded environment, providing a good alternative herbicide and viable weed control option in furrow-irrigated rice and on rice levees.

Nomenclature: 2,4-D; florpyrauxifen-benzyl; Palmer amaranth, *Amaranthus palmeri* S. Wats.; rice, *Oryza sativa* L.

Key Words: furrow-irrigated rice, levee weed control

Introduction

Rice in the midsouthern U.S. is mainly dry seeded into cultivated ground in early spring and irrigated by flooding using a levee and bay system. Once rice reaches the 4- to 5-leaf stage, a continuous flood is maintained until maturity, otherwise known as a delayed flood system (Moldenhauer et al. 2018). Rice is usually planted as a rotational crop with soybean [*Glycine max* (L.) Merr.], and this rotation accounts for 70% of rice hectares in Arkansas, with the remaining hectares being some other rotation or continuous rice (Hardke 2018).

Most row crops such as soybean and corn in Arkansas are grown on raised beds where they can be irrigated through furrow-irrigation. In the levee and bay system within a rice-soybean rotation, levees need to be built and torn down every year for rice and beds pulled for soybean, which can be expensive for growers due to the associated equipment, labor, and fuel costs. Unlike flood-irrigated rice, furrow-irrigated rice is drill-seeded into raised beds and irrigated every 3 to 4 days to maintain soil moisture (Tracey et al. 1993). Furrow-irrigated rice hectarage in Arkansas has dramatically increased from nearly 16,000 hectares in 2017 to 40,000 hectares in 2018, with this number expected to continue to increase due to cost savings through fewer tractor passes in the field for building and tearing down levees or beds every year in a soybean-rice rotation (McGeeney 2018; Tracey et al 1993).

Flooding in the traditional delayed flood system is a cultural weed control practice used to manage terrestrial weeds (Gealy 1998; Norsworthy et al. 2011). However, furrow-irrigated rice production poses unique challenges to weed management due to the upland production environment where weed populations are more like that of crops such as soybean and corn (*Zea mays* L.) (Norsworthy et al. 2011; Norsworthy et al 2008). Palmer amaranth was listed as the most troublesome and important weed in soybean in a survey of consultants (Schwartz-Lazaro et al. 2018) and, although not an issue in flooded rice production, becomes problematic in furrow-irrigated rice (Norsworthy et al. 2011). Currently, Palmer amaranth in Arkansas is resistant to five herbicide modes of action: acetolactate synthase (ALS) inhibitors, protoporphyrinogen oxidase (PPO)-inhibitors, 5-enylpyruvyl-shikimate-3-phosphate (EPSP) synthase inhibitors, microtubule inhibitors, and long chain fatty acid inhibitors (Heap 2019). Imidazolinone-resistant rice cultivars are commonly planted (Hardke 2018); however, the occurrence of ALS resistance in Palmer amaranth complicates weed control in furrow-irrigated rice when these cultivars are used (Burgos et al. 2001).

Similarly, in traditional flood-irrigated rice production that utilizes a levee and bay system, levees are never fully submerged but remain moist throughout the season, which creates an environment favorable for weed emergence and growth (Norsworthy et al. 2010). Broadleaf weeds, especially Palmer amaranth, have become increasingly problematic on rice levees, and controlling weeds on levees can be difficult (Norsworthy et al. 2013). The soybean-rice crop rotation has likely led to the increased occurrence of Palmer amaranth on levees (Norsworthy et al. 2010; Norsworthy et al. 2013). Saflufenacil, a PPO-inhibiting herbicide, is recommended to control Palmer amaranth growing on levees (Barber et al. 2019). However, with the recent occurrence of PPO-resistant Palmer amaranth, saflufenacil is no longer a viable herbicide option in many fields, further complicating Palmer amaranth control on rice levees (Salas et al. 2016; JK Norsworthy, personal communication). Additionally, levees are typically sprayed with herbicides only once per growing season, allowing ample time for weeds to grow larger than the recommended height for control (Norsworthy et al. 2010).

2,4-D can be used to control broadleaf weeds in rice and is the current standard for weed control on levees (Norsworthy et al. 2010; Norsworthy et al. 2013). However, use of this herbicide in key rice producing counties in Arkansas is restricted due to the proximity of cotton (*Gossypium hirsutum* L.) to rice fields and cotton sensitivity to 2,4-D. In these counties, a permit must be obtained before applying 2,4-D and a buffer to sensitive crops must be followed (ASPB 2002). Options to control broadleaf weeds, particularly Palmer amaranth, are limited, making weed control in furrow-irrigated rice and on levees more challenging. The introduction of new herbicides and herbicide modes of action are rare. In fact, no new modes of action have been commercialized for more than 20 years in row crops (Duke 2012). This highlights the need for preserving our herbicides and slowing the evolution of resistance.

Florpyrauxifen-benzyl, the active ingredient in Loyant™ herbicide is a new postemergence (POST) synthetic auxin (WSSA group 4) herbicide from Corteva™ Agriscience. First available for commercial use in 2018, it has a broad spectrum of activity that is effective on multiple troublesome weed species, including Palmer amaranth (*Amaranthus palmeri* S. Wats), yellow nutsedge (*Cyperus esculentus* L.), and barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv.) (Miller and Norsworthy 2018a). A study from Miller et al. (2018) found that florpyrauxifen-benzyl has activity on multiple-resistant barnyardgrass, including quinclorac-resistant barnyardgrass. This means the site of action of florpyrauxifen-benzyl is different than that of quinclorac, another auxin, and will provide a much-needed control option for barnyardgrass control in rice. Additionally, florpyrauxifen-benzyl does not have residual activity and should be applied with a residual herbicide for control of troublesome weeds (Miller and Norsworthy 2018b).

Florpyrauxifen-benzyl is expected to exhibit optimal control under a flooded system; however, some control has been shown in dryland cropping systems as well (Miller and Norsworthy 2018c). The versatility of florpyrauxifen-benzyl may lead to it being a good fit for weed control in non-flooded systems. Thus, the objective of this experiment was to evaluate florpyrauxifen-benzyl for weed control in the absence of a flood.

It was hypothesized that herbicide-based weed control programs in furrow-irrigated rice containing florpyrauxifen-benzyl will have higher levels of late-season weed control than the program currently used in flooded rice due to Palmer amaranth control associated with florpyrauxifen-benzyl. Thus, the objective of this experiment was to evaluate florpyrauxifen-benzyl-containing weed control programs compared to programs without. Additionally, it was hypothesized that programs where florpyrauxifen-benzyl is applied with a residual herbicide will have higher levels of late-season Palmer amaranth control than programs that do not contain a residual herbicide mid-postemergence.

For the levee experiment, it was hypothesized that florpyrauxifen-benzyl-containing treatments would provide comparable weed control to 2,4-D-containing treatments, thereby providing an additional herbicide option in those areas where 2,4-D use is limited. Therefore, the objective of this experiment was to evaluate common rice herbicides for late-season weed control and compare these to treatments where florpyrauxifen-benzyl or 2,4-D are added. Lastly, it was hypothesized that treatments where at least two modes of action are used will control Palmer amaranth better than treatments with only one mode of action.

Materials and Methods

Field experiments were conducted in 2017 and 2018 to evaluate florpyrauxifen-benzyl-containing weed control programs in furrow-irrigated rice at the Lon Mann Cotton Research Station (LMCRS) near Marianna, AR, on a Convent silt loam soil (Coarse-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts) and at the Pine Tree Research Station (PTRS) near Colt, AR, on a Calhoun silt loam (fine-silty, mixed, active, thermic Typic

Glossaqualfs). The soil at LMCRS had sand, silt and clay contents of 9%, 80%, and 11%, respectively, a pH of 7.5, and an organic matter content of 1.8%. The soil at PTRS had sand, silt, and clay contents of 10%, 69%, and 21%, respectively, 1.3% organic matter, and a pH of 7.5.

long-grain rice varieties were used in both years of this experiment; 'CL172' in 2017 and 'CL153' in 2018 were drill seeded into raised beds at 72 seeds m^{-1} of row. Bedded row and drill row spacings at LMCRS were 97 cm and 19 cm, respectively, and 76 cm and 19 cm, respectively, at PTRS. Bedded row spacing is wider at LMCRS because bedding equipment is set wider for cotton (*Gossypium hirsutum* L.) production. Plots at both locations were four bedded rows wide by 6 m long. This experiment was designed as a randomized complete block with a three-factor factorial for a total of 16 herbicide programs and a nontreated with four replications. Factor A consisted of clomazone mixed with quinclorac or imazosulfuron applied preemergence (PRE) (Table 1). These herbicide combinations reflect commonly used PRE herbicide applications in Arkansas. Although imidazolinone-resistant varieties were used both years, imazethapyr was not selected as a herbicide treatment because nearly half of the rice in Arkansas is planted to conventional cultivars not tolerant to imidazolinone herbicides, and the goal of this experiment was to develop an effective herbicide program for all rice growers. An application of fenoxaprop at 122 g ai ha^{-1} was made to all plots, except the nontreated, as an early-postemergence (EPOST) herbicide application to control grasses. Factor B was four mid-postemergence (MPOST) herbicide combinations applied 2 weeks after EPOST. MPOST combinations were (1) florpyrauxifen-benzyl to determine the value of this herbicide in a non-flooded environment, (2) florpyrauxifen-benzyl plus pendimethalin to evaluate weed control with a residual herbicide, and (3) florpyrauxifen-benzyl plus pendimethalin plus cyhalofop to evaluate weed control with a residual along with a grass herbicide to see if there was an improvement in grass control over florpyrauxifen-benzyl alone. These three MPOST florpyrauxifen-benzyl-containing programs were compared to the standard program of propanil and pendimethalin at the same timing. Methylated seed oil (MSO) at 0.6 L ha^{-1} was added to all florpyrauxifen-benzyl-containing treatments. Factor C was a late postemergence (LPOST) application of penoxsulam plus triclopyr applied once when control ratings fell below 80% in two replications for any weed species. A complete list of treatments can be found in Table 2 and application dates are in Table 3. Experiments at PTRS were irrigated every three days and every two days at LMCRS until two weeks before rice was harvested. The differences in irrigation can be attributed to the presence of a clay pan at PTRS resulting in differences in water drainage between sites, thus PTRS did not require irrigation as frequently as LMCRS. Experimental sites were managed according to University of Arkansas System Division of Agriculture recommendations including preplant and postemergence fertilizer applications totaling 130 kg N ha^{-1} as urea and an early postemergence application of potassium chloride at 56 kg ha^{-1}.

To evaluate florpyrauxifen-benzyl- and 2,4-D-containing weed control programs on levees, field experiments were conducted in 2017 and 2018 at the PTRS near Colt, Arkansas. A levee plow was used to construct 0.6-meter-high levees with 6-meter-long plots. Levees were then over-seeded with CL151 rice on May 17, 2017, and CL153 rice on May 22, 2018, using a levee seeder at a rate of 72 seeds m^{-1} of row. These experiments were conducted as a randomized complete block design with four replications. Commonly used rice herbicides were applied at their labeled rates alone and in combination with florpyrauxifen-benzyl at 30 g ae ha^{-1} or 2,4-D choline at 1,600 g ae ha^{-1}. Herbicides used were saflufenacil at 25 g ai ha^{-1}, propanil at 6,720 g ai ha^{-1}, propanil plus thiobencarb at 4,450 plus 4,450 g ai ha^{-1}, triclopyr at 420 g ae ha^{-1}, quinclorac at g ae ha^{-1}, and penoxsulam at 49 g ai ha^{-1}. Additionally, florpyrauxifen-benzyl and 2,4-D were applied at the previous rates alone (Table 4). A complete list of herbicides used can be found in Table 5. Methylated seed oil (MSO) was added to all treatments containing florpyrauxifen-benzyl at 0.6 L ha^{-1}, as recommended by the herbicide label. Crop oil concentrate (COC) at 0.6 L ha^{-1} was added to a saflufenacil treatment to determine any differences in control by the addition of COC or MSO. Applications were made on June 14, 2017, and July 3, 2018. Weeds were 45 to 60 cm tall in 2017; however, in 2018 some weeds exceeded 120 cm. An application of fenoxaprop at 122 g ai ha^{-1} was used to control grass weeds in 2017 but due to low grass emergence was not necessary in 2018.

Assessments. In the furrow-irrigated rice study, crop injury, Palmer amaranth control, and barnyardgrass control ratings were recorded 3 and 5 weeks after LPOST. Additional Palmer amaranth control ratings were taken 1 week after MPOST and at the time of the LPOST application. Injury and control ratings were taken on a 0 to 100 scale with 0% being no injury or control and 100% being crop death or complete control (Frans and Talbert 1977). Rough rice grain yields were collected at crop maturity using a small-plot combine that harvested the middle 4 rows of each plot. Grain yields were then calculated, and moisture adjusted to 12%.

In the levee experiment, broadleaf weed control ratings were taken 2 and 4 weeks after application (WAA), where 0% equals no control and 100% equals complete control. Due to lack of uniform emergence and density, only Palmer amaranth control is reported for both years.

Statistical analyses. All data were analyzed using PROC GLIMMIX in SAS v 9.4 (SAS Institute Inc., Cary, N.C.), and means were separated using Fisher's protected least significant difference (P=0.05). In the furrow-irrigated rice experiment due to similarities in environment and control, site years at LMCRS in 2017 and 2018 and PTRS in 2018 were combined (Table 6). However, due to lower weed pressure and high levels of control at PTRS in 2017, the LPOST application was not necessary thus this location is analyzed separately. For the three combined site years, site year and replication nested within site year were treated as random effects and PRE, MPOST, and LPOST factors were fixed effects. For the PTRS 2017 location, replication was considered a random effect and PRE and MPOST factors were considered fixed effects. A beta distribution was assumed for injury and weed control (Gbur at al. 2012). Yield data for PTRS 2018, and LMCRS 2017 and 2018 were combined and run by treatment in order to make comparisons to the nontreated. Treatment was considered a fixed effect, while site year and replication within site year were considered random effects. Similarly, yield data for PTRS 2017 were analyzed by treatment, where treatment was considered a fixed effect and replication was considered a random effect. A gamma distribution was assumed for yield (Gbur et al. 2012).

In the levee experiment, both years were combined, again due to similarities in environment and control. Site year and replication nested within site year were considered random effects and herbicide treatment was considered a fixed effect. A beta distribution was assumed for Palmer amaranth control (Gbur et al. 2012).

Results and Discussion

Furrow-irrigated rice. There was a significant interaction between PRE and MPOST treatments on late-season visual injury to rice (Table 5). However, injury was <2% for all combinations, indicting all programs are safe to use on the cultivars CL151 and CL153 in furrow-irrigated rice (data not shown).

For Palmer amaranth control ratings taken at the time of the LPOST application, the main effect of MPOST treatments was significant (Table 5). MPOST applications were made 2 weeks prior to LPOST applications. Florpyrauxifen-benzyl-containing treatments had significantly higher levels of control (86 to 91%) than the standard treatment of propanil plus pendimethalin

(80%), averaged over PRE treatments (Table 6). For Palmer amaranth control 3 and 5 weeks after the LPOST application, there were significant main effects of PRE, MPOST, and LPOST treatments (Table 5).

At 3 weeks after LPOST, treatments where clomazone plus quinclorac was applied PRE controlled Palmer amaranth better than clomazone plus imazosulfuron, when averaged over MPOST and LPOST treatments. Although this difference was significant, it was numerically small (98 and 96%, respectively) (Table 6). MPOST treatments containing florpyrauxifen-benzyl had higher levels of Palmer amaranth control (97 to 99%) compared to the standard of propanil plus pendimethalin, which controlled Palmer amaranth only 90%, when averaged of PRE and LPOST treatments. Additionally, treatments that received a herbicide application LPOST, averaged over PRE and MPOST treatments, controlled Palmer amaranth 98% compared to 94% when no herbicide was used LPOST.

At 5 weeks after LPOST, treatments containing clomazone plus quinclorac applied PRE controlled Palmer amaranth 97%, while programs that received clomazone plus imazosulfuron PRE controlled Palmer amaranth 94% (Table 6). Again, treatments where florpyrauxifen-benzyl was used in the MPOST application controlled Palmer amaranth 96 to 98%, which was higher than the propanil plus pendimethalin treatment, which controlled Palmer amaranth 85%. Programs that received penoxsulam plus triclopyr LPOST controlled Palmer amaranth more at 98%, when averaged over PRE and MPOST treatments, compared to programs that did not receive a LPOST herbicide (91% control).

For barnyardgrass control 3 weeks after LPOST, there was a main effect of LPOST, when averaged over PRE and MPOST treatments (Table 5). However, this difference was numerically small, with treatments containing penoxsulam plus triclopyr controlling barnyardgrass 99% compared to 98% where no herbicide was used LPOST (data not shown).

For barnyardgrass control 5 weeks after LPOST, there was a three-way interaction between PRE, MPOST, and LPOST. Most programs provided 97 to 99% late-season control; however, clomazone plus imazosulfuron followed by propanil plus pendimethalin with no LPOST herbicide and clomazone plus quinclorac followed by florpyrauxifen-benzyl alone with no LPOST herbicide controlled barnyardgrass 93 and 95%, respectively (data not shown). High levels of late-season control indicate a program approach for herbicides in furrow-irrigated rice will provide sufficient levels of barnyardgrass control, contingent upon the barnyardgrass population not being resistant to the herbicides applied.

Rough rice yields differed among treatments (Table 5). Rice in the nontreated yielded the lowest among the evaluated treatments at 660 kg ha^{-1} (Table 7). Generally, the highest yielding rice was in programs that utilized a LPOST herbicide application, while the lowest yields were those that only contained a PRE and MPOST application. The program where clomazone plus imazosulfuron was applied PRE followed by propanil plus pendimethalin MPOST and no herbicide LPOST yielded 4,560 kg ha^{-1}. Though there were similar grain yields associated with other programs, the highest yielding program consisted of clomazone plus quinclorac PRE followed by florpyrauxifen-benzyl MPOST and penoxsulam plus triclopyr LPOST (10,140 kg ha^{-1}) (Table 7), which is 3,050 kg ha^{-1} higher than the treatment with the same PRE and MPOST but no LPOST. The improvement in grain yield can be attributed to Palmer amaranth control when an LPOST application was included in the program.

Results for PTRS 2017 location were similar to those found from the combined site years. Palmer amaranth control was greater than 90% for all MPOST treatments, averaged over

PRE combinations (Table 8 and 9). However, treatments that utilized florpyrauxifen-benzyl MPOST had higher levels of late season Palmer amaranth control at 98 to 99% compared to the standard treatment of propanil plus pendimethalin at 93% (Table 9). Barnyardgrass control was also rated 5 weeks after MPOST, however control was >99% for all treatments (data not shown).

Though Palmer amaranth densities were not recorded at PTRS in 2017, the yield the nontreated check at this location compared to the average of the other site years is evidence of the difference in weed pressure. Grain yield of the nontreated at PTRS in 2017 was 5,700 kg ha^{-1} (Table 10) while the average of the other site years was and 660 kg ha^{-1} (Table 7). There were differences in yield among treatments, however these differences were inconsistent with the other site years. The differences in yields from this site year compared to the combined site years can be attributed, in part, to weed competition. Though weed densities were not recorded at PTRS in 2017, weed competition is evidenced by the differences in yields of the nontreated controls.

Previous research has demonstrated clomazone provides poor control of Palmer amaranth (Scott et al. 2002; Troxler et al. 2002). This coupled with ALS-resistant Palmer amaranth likely led to earlier Palmer amaranth emergence in treatments where clomazone plus the ALS inhibitor imazosulfuron was applied PRE, impacting late-season weed control. Although there was no interaction between factors, high levels of late-season Palmer amaranth control in furrow-irrigated rice is the result of a program approach to weed management. Differences in control from MPOST treatments highlight the need for an effective mode of action and residual herbicide midseason.

Additionally, high levels of Palmer amaranth control in programs where a LPOST herbicide treatment is made indicate there is value in this later application. Norsworthy et al.

(2011) also demonstrated the value of a late-season herbicide application for Palmer amaranth control in furrow-irrigated rice on an as-needed basis. Since lower yields and higher herbicide costs are associated with furrow-irrigated rice due to the lack of a flood, fields should be scouted regularly for weeds and a LPOST herbicide application made when necessary.

Levees. There was a significant difference in Palmer amaranth control among treatments at 2 and 4 weeks after treatment (Table 11). At 2 weeks after treatment, Palmer amaranth control was improved by the addition of 2,4-D or florpyrauxifen-benzyl compared to herbicides applied alone. Additionally, mixtures containing florpyrauxifen-benzyl provided comparable control to 2,4-D-containing mixtures. At 4 weeks after application, treatments in which 2,4-D or florpyrauxifen-benzyl were used in conjunction with another herbicide controlled Palmer amaranth ≥90%. Again, florpyrauxifen-benzyl provided control of Palmer amaranth comparable to 2,4-D.

Practical Implications. Results from these experiments indicate florpyrauxifen-benzyl provides adequate weed control in the absence of a flood and adds value to a herbicide program in non-flooded systems. Programs containing florpyrauxifen-benzyl are superior in Palmer amaranth control compared to the standard program where propanil plus pendimethalin are used MPOST. Additionally, florpyrauxifen-benzyl is a viable alternative to 2,4-D for Palmer amaranth control on rice levees and in furrow-irrigated rice, where 2,4-D use is restricted. Although little injury was observed in these experiments, additional research is needed to determine the level of expected injury when florpyrauxifen-benzyl is used on hybrid rice in furrow-irrigated rice production.

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Tables

Table 1. List of herbicides tested in weed control programs in furrow-irrigated rice.[a]

Herbicide common name	Trade name	Manufacturer	Rate
			g ai ha^{-1}
Clomazone	Command® 3ME	FMC Corporation 2929 Walnut Street Philadelphia, PA 19104	336
Quinclorac	Facet® L	BASF Corporation 26 Davis Drive Research Triangle Park, NC 27709	420*
Imazosulfuron	League®	Valent U.S.A. Corporation P.O. Box 8025 Walnut Creek, CA 94596	336
Fenoxaprop	RiceStar® HT	Bayer Cropscience LP P.O. Box 12014 2 T.W. Alexander Drive Research Triangle Park, NC 27709	122
Propanil	SuperWHAM!®	RiceCo LLC 5100 Poplar Avenue, 24th Floor Memphis, TN 38137	4480
Pendimethalin	Prowl® H_2O	BASF Corporation 26 Davis Drive Research Triangle Park, NC 27709	70
Florpyrauxifen-benzyl	Loyant™	Dow AgroSciences LLC 9330 Zionsville Road Indianapolis, IN 46268	30*
Florpyrauxifen-benzyl + cyhalofop	No trade name established	Dow AgroSciences LLC 9330 Zionsville Road Indianapolis, IN 46268	30* + 328
Penoxsulam + triclopyr	Grasp® Xtra	Dow AgroSciences LLC 9330 Zionsville Road Indianapolis, IN 46268	44 + 360*

[a] * indicates g ae ha^{-1}

Table 2. List of herbicide treatments as a program for weed control in furrow-irrigated rice. [a,b]

Treatment	Timing	Herbicide	Rate
			g ai ha^{-1}
1	PRE	Clomazone + quinclorac	336 + 420*
	MPOST	Propanil + pendimethalin	4480 + 70
2	PRE	Clomazone + imazosulfuron	336 + 336
	MPOST	Propanil + pendimethalin	4480 + 70
3	PRE	Clomazone + quinclorac	336 + 420*
	MPOST	Propanil + pendimethalin	4480 + 70
	LPOST	Penoxsulam + triclopyr	44 + 360*
4	PRE	Clomazone + imazosulfuron	336 + 336
	MPOST	Propanil + pendimethalin	4480 + 70
	LPOST	Penoxsulam + triclopyr	44 + 360*
5	PRE	Clomazone + quinclorac	336 + 420*
	MPOST	Florpyrauxifen-benzyl + pendimethalin	30* + 70
6	PRE	Clomazone + imazosulfuron	336 + 336
	MPOST	Florpyrauxifen-benzyl + pendimethalin	30* + 70
7	PRE	Clomazone + quinclorac	336 + 420*
	MPOST	Florpyrauxifen-benzyl + pendimethalin	30 *+ 70
	LPOST	Penoxsulam + triclopyr	44 + 360*
8	PRE	Clomazone + imazosulfuron	336 + 336
	MPOST	Florpyrauxifen-benzyl + pendimethalin	30* + 70
	LPOST	Penoxsulam + triclopyr	44 + 360*
9	PRE	Clomazone + quinclorac	336 + 420*
	MPOST	Florpyrauxifen-benzyl + pendimethalin + cyhalofop	30* + 70 + 328
10	PRE	Clomazone + imazosulfuron	336 + 336
	MPOST	Florpyrauxifen-benzyl + pendimethalin + cyhalofop	30* + 70 + 328
11	PRE	Clomazone + quinclorac	336 + 420*
	MPOST	Florpyrauxifen-benzyl + pendimethalin + cyhalofop	30* + 70 + 328
	LPOST	Penoxsulam + triclopyr	44 + 360*
12	PRE	Clomazone + imazosulfuron	336 + 336
	MPOST	Florpyrauxifen-benzyl + pendimethalin + cyhalofop	30* + 70 + 328
	LPOST	Penoxsulam + triclopyr	44 + 360*
13	PRE	Clomazone + quinclorac	336 + 420*
	MPOST	Florpyrauxifen-benzyl	30*
14	PRE	Clomazone + imazosulfuron	336 + 336
	MPOST	Florpyrauxifen-benzyl	30*
15	PRE	Clomazone + quinclorac	336 + 420*
	MPOST	Florpyrauxifen-benzyl	30*
	LPOST	Penoxsulam + triclopyr	44 + 360*
16	PRE	Clomazone + imazosulfuron	336 + 336
	MPOST	Florpyrauxifen-benzyl	30*
	LPOST	Penoxsulam + triclopyr	44 + 360*

[a] * indicates g ae ha^{-1}

[b] Abbreviations: PRE, preemergence; MPOST, mid-postemergence; LPOST, late-postemergence

Table 3. Application dates for the furrow-irrigated rice trials at the Pine Tree Research Station (PTRS) near Colt, AR, and the Lon Mann Cotton Research Station (LMCRS) in Marianna, AR, for 2017 and 2018.[a]

Location	PRE	EPOST	MPOST	LPOST
PTRS 2017	May 15	June 7	June 20	-
PTRS 2018	May 14	June 5	June 13	June 28
LMCRS 2017	May 19	June 9	June 15	June 28
LMCRS 2018	May 16	May 30	June 12	June 25

[a] Abbreviations: PRE, preemergence; EPOST, early-postemergence; MPOST, mid-postemergence; LPOST, late-postemergence

Table 4. Weed densities and heights for Palmer amaranth and barnyardgrass at the time of the mid-postemergence application for the Pine Tree Research Station (PTRS) near Colt, AR, in 2018 and the Lon Mann Cotton Research Station (LMCRS) in Marianna, AR, in 2017. [a]

Species	PTRS 2018		LMCRS 2017		LMCRS 2018	
	density	Height	density	height	density	height
	plants m^{-2}	cm	plants m^{-2}	cm	plants m^{-2}	cm
Palmer amaranth	5	10-25	36	10-33	16	10-45
Barnyardgrass	NR		NR		54	2-15

[a] NR- not rated; no weeds present in plots

Table 5. P-values by factor for furrow-irrigated rice trials at the Lon Mann Cotton Research Station in Marianna, AR, in 2017 and 2018 and the Pine Tree Research Station near Colt, AR, in 2018 for rice injury, Palmer amaranth, and barnyardgrass visual estimates of control, and for grain yield, averaged over site year. [a]

	Injury		Palmer amaranth control				Barnyardgrass control		
Factor	3 WA LPOST	5 WA LPOST	1 WA MPOST	At LPOST	3 WA LPOST	5 WA LPOST	3 WA LPOST	5 WA LPOST	Grain yield
	-- p-value --								
PRE	0.4256	0.6907	0.0533	0.7443	0.0054*	0.0019*	0.7083	0.6509	
MPOST	0.6992	0.9718	0.1993	<0.0001*	<0.0001*	<0.0001*	0.2039	0.0006*	
LPOST	0.2504	0.0013*	-	-	<0.0001*	<0.0001*	0.0004*	<0.0001*	
PRE x MPOST	0.9563	0.0270*	0.6276	0.9505	0.8048	0.7021	0.1617	0.1301	
PRE x LPOST	0.7087	0.8162	-	-	0.3867	0.5298	0.3905	0.1944	
MPOST x LPOST	0.3016	0.5338	-	-	0.2484	0.5373	0.1506	0.0005*	
PRE x MPOST x LPOST	0.4121	0.1988	-	-	0.4540	0.1994	0.3153	0.0337*	
Treatment									<0.0001*

[a] Abbreviations: PRE, preemergence; MPOST, mid-postemergence; LPOST, late-postemergence; WA, weeks after

Table 6. Visible estimates of Palmer amaranth control at the time of and 3 and 5 weeks after the late-postemergence (LPOST) application for significant factors at the Lon Mann Cotton Research Station near Marianna, AR, in 2017 and 2018, and the Pine Tree Research Station near Colt, AR, in 2018, averaged over site year. [a,b]

Factor	Treatment	Palmer amaranth control At LPOST		3 WA LPOST		5 WA LPOST	
		----------%----------					
PRE	Clomazone + quinclorac			98	a	97	a
	Clomazone + imazosulfuron			96	b	94	b
MPOST	Florpyrauxifen-benzyl	91	a	99	a	98	a
	Florpyrauxifen-benzyl + pendimethalin	90	a	98	ab	98	ab
	Florpyrauxifen-benzyl + pendimethalin + cyhalofop	86	b	97	b	96	b
	Propanil + pendimethalin	80	c	90	c	85	c
LPOST	Penoxsulam + triclopyr			98	a	98	a
	None			94	b	91	b

[a] Only control for significant factors is reported. Means are separated using Fisher’s protected LSD (α=0.05). Means with the same letter within the same column and factor are not significantly different.

[b] Abbreviations: PRE, preemergence; MPOST, mid-postemergence; LPOST, late-postemergence; WA, weeks after

Table 7. Grain yields of rice in all herbicide programs evaluated in furrow-irrigated rice trials at the Lon Mann Cotton Research Station near Marianna, AR, in 2017 and 2018, and the Pine Tree Research Station near Colt, AR, in 2018, averaged over site year. [a,b]

Treatment	Timing	Herbicide	Grain yield	
			kg ha^{-1}	
	-	Nontreated	660	g
1	PRE MPOST	Clomazone + quinclorac Propanil + pendimethalin	6,420	ef
2	PRE MPOST	Clomazone + imazosulfuron Propanil + pendimethalin	4,560	f
3	PRE MPOST LPOST	Clomazone + quinclorac Propanil + pendimethalin Penoxsulam + triclopyr	8,310	abcde
4	PRE MPOST LPOST	Clomazone + imazosulfuron Propanil + pendimethalin Penoxsulam + triclopyr	7,450	cde
5	PRE MPOST	Clomazone + quinclorac Florpyrauxifen-benzyl + pendimethalin	7,660	bcde
6	PRE MPOST	Clomazone + imazosulfuron Florpyrauxifen-benzyl + pendimethalin	7,020	e
7	PRE MPOST LPOST	Clomazone + quinclorac Florpyrauxifen-benzyl + pendimethalin Penoxsulam + triclopyr	9,590	ab
8	PRE MPOST LPOST	Clomazone + imazosulfuron Florpyrauxifen-benzyl + pendimethalin Penoxsulam + triclopyr	9,180	abc
9	PRE MPOST	Clomazone + quinclorac Florpyrauxifen-benzyl + pendimethalin + cyhalofop	6,780	e
10	PRE MPOST	Clomazone + imazosulfuron Florpyrauxifen-benzyl + pendimethalin + cyhalofop	6,540	ef
11	PRE MPOST LPOST	Clomazone + quinclorac Florpyrauxifen-benzyl + pendimethalin + cyhalofop Penoxsulam + triclopyr	9,550	ab
12	PRE MPOST LPOST	Clomazone + imazosulfuron Florpyrauxifen-benzyl + pendimethalin + cyhalofop Penoxsulam + triclopyr	9,470	abc
13	PRE MPOST	Clomazone + quinclorac Florpyrauxifen-benzyl	7,090	de
14	PRE MPOST	Clomazone + imazosulfuron Florpyrauxifen-benzyl	8,100	abcde

Table 7. Grain yields of rice in all herbicide programs evaluated in furrow-irrigated rice trials at the Lon Mann Cotton Research Station near Marianna, AR, in 2017 and 2018, and the Pine Tree Research Station near Colt, AR, in 2018, averaged over site year. [a,b]

15	PRE	Clomazone + quinclorac	10,140	a
	MPOST	Florpyrauxifen-benzyl		
	LPOST	Penoxsulam + triclopyr		
16	PRE	Clomazone + imazosulfuron	9,120	abcd
	MPOST	Florpyrauxifen-benzyl		
	LPOST	Penoxsulam + triclopyr		

[a] Abbreviations: PRE, preemergence; MPOST, mid-postemergence; LPOST, late-postemergence

[b] Means are separated using Fisher's protected LSD (α=0.05). Means with the same letter within a column are not significantly different

Table 8. P-values by factor for furrow-irrigated rice trials at the Pine Tree Research Station near Colt, AR, in 2017 for injury, Palmer amaranth, and barnyardgrass visual estimates of control, and for grain yield. [a]

Factor	Injury		Palmer amaranth control		Barnyardgrass control	Grain yield
	3 WA MPOST	5 WA MPOST	3 WA MPOST	5 WA MPOST	5 WA MPOST	
PRE	0.7297	0.9996	0.6213	0.8516	0.4619	
MPOST	0.0038*	0.1263	0.0341*	<0.0001*	0.2199	
PRE x MPOST	0.1493	0.6247	0.4528	0.7420	0.4510	
Treatment						<0.0001*

[a] Abbreviations: PRE-preemergence; MPOST-mid-postemergence; WA- weeks after

Table 9. Visible estimates of Palmer amaranth control at 3 and 5 weeks after application for significant factors at the Pine Tree Research Station in 2017. [a,b]

		Palmer amaranth control			
Factor	Treatment	3 WA MPOST		5 WA MPOST	
		----------%----------			
MPOST	Florpyrauxifen-benzyl	97	a	99	a
	Florpyrauxifen-benzyl + pendimethalin	93	bc	98	a
	Florpyrauxifen-benzyl + pendimethalin + cyhalofop	96	ab	98	a
	Propanil + pendimethalin	92	c	93	b

[a] Control for significant factors only is reported. Means are separated using Fisher's protected LSD (α=0.05). Means with the same letter within the same column are not significantly different.

[b] Abbreviations: WA- weeks after; MPOST-mid-postemergence

Table 10. Grain yields of rice in all herbicide programs evaluated in the furrow-irrigated rice trial at the Pine Tree Research Station near Colt, AR, in 2017. [a,b]

Timing	Herbicide	Grain yield	
		kg ha^{-1}	
-	Nontreated	5,700	f
PRE MPOST	Clomazone + quinclorac Propanil + pendimethalin	10,000	a
PRE MPOST	Clomazone + imazosulfuron Propanil + pendimethalin	8,460	bcd
PRE MPOST	Clomazone + quinclorac Florpyrauxifen-benzyl + pendimethalin	7,820	de
PRE MPOST	Clomazone + imazosulfuron Florpyrauxifen-benzyl + pendimethalin	8,270	cde
PRE MPOST	Clomazone + quinclorac Florpyrauxifen-benzyl + pendimethalin + cyhalofop	8,980	abc
PRE MPOST	Clomazone + imazosulfuron Florpyrauxifen-benzyl + pendimethalin + cyhalofop	8,660	bcd
PRE MPOST	Clomazone + quinclorac Florpyrauxifen-benzyl	7,310	e
PRE MPOST	Clomazone + imazosulfuron Florpyrauxifen-benzyl	9,440	ab

[a] Abbreviations: PRE, preemergence; MPOST, mid-postemergence

[b] Means are separated using Fisher's protected LSD ($\alpha=0.05$). Means with the same letter are not significantly different.

Table 11. Visible estimates of Palmer amaranth control 2 and 4 weeks after treatment (WAT) for herbicide treatments made on levees.[a,b]

		Palmer amaranth control			
Herbicide treatment	Rate	2 WAT		4 WAT	
	g ai ha^{-1}	------------% -----------			
Penoxsulam	49	42	f	38	d
Triclopyr	420*	57	e	76	c
Propanil	6720	90	c	90	ab
Propanil + thiobencarb	4450 + 4450	71	d	71	c
Saflufenacil + COC	25	67	de	66	c
Saflufenacil + MSO	25	58	e	63	c
Quinclorac	630*	33	f	39	d
2,4-D	1600*	90	c	95	ab
Florpyrauxifen-benzyl	30*	90	c	95	ab
Penoxsulam + 2,4-D	49 + 1600*	93	abc	89	b
Triclopyr + 2,4-D	420* + 1600*	91	bc	96	ab
Propanil + 2,4-D	6720 + 1600*	98	a	95	ab
Propanil + thiobencarb + 2,4-D	4450 + 4450 + 1600*	96	ab	94	ab
Saflufenacil + 2,4-D + COC	25 + 1600*	92	bc	96	ab
Saflufenacil + 2,4-D + MSO	25 + 1600*	95	abc	97	a
Quinclorac + 2,4-D	630* + 1600*	92	bc	96	ab
Penoxsulam + florpyrauxifen-benzyl	49 + 30*	94	abc	97	ab
Triclopyr + florpyrauxifen-benzyl	420* + 30*	92	bc	95	ab
Propanil + florpyrauxifen-benzyl	6720 + 30*	94	abc	95	ab
Propanil + thiobencarb + florpyrauxifen-benzyl	4450 + 4450 + 30*	92	bc	93	ab
Saflufenacil + florpyrauxifen-benzyl + COC	25 + 30*	95	abc	95	ab
Saflufenacil + florpyrauxifen-benzyl + MSO	25 + 30*	95	abc	97	ab
Quinclorac + florpyrauxifen-benzyl	630* + 30*	90	c	92	ab
p-value		<0.0001		0.0003	

[a] * indicates g ae ha^{-1}

[b] Means are separated using Fisher's protected LSD (α=0.05). Means with the same letter within a column are not different.

Table 12. List of herbicides tested for weed control programs on rice levees. [a]

Herbicide common name	Trade name	Manufacturer	Rate
			g ai ha^{-1}
Fenoxaprop	RiceStar® HT	Bayer Cropscience LP P.O. Box 12014 2 T.W. Alexander Drive Research Triangle Park, NC 27709	122
Penoxsulam	Grasp® SC	Dow AgroSciences LLC 9330 Zionsville Road Indianapolis, IN 46268	49
Triclopyr	Grandstand® R	Dow AgroSciences LLC 9330 Zionsville Road Indianapolis, IN 46268	420*
Propanil	SuperWHAM!®	RiceCo LLC 5100 Poplar Avenue, 24th Floor Memphis, TN 38137	6720
Propanil + thiobencarb	Ricebeaux®	RiceCo LLC 5100 Poplar Avenue, 24th Floor Memphis, TN 38137	4450 + 4450
Saflufenacil	Sharpen®	BASF Corporation 26 Davis Drive Research Triangle Park, NC 27709	25
Quinclorac	Facet® L	BASF Corporation 26 Davis Drive Research Triangle Park, NC 27709	630*
2,4-D	Enlist™	Dow AgroSciences LLC 9330 Zionsville Road Indianapolis, IN 46268	1600*
Florpyrauxifen-benzyl	Loyant™	Dow AgroSciences LLC 9330 Zionsville Road Indianapolis, IN 46268	30*

[a] * indicates g ae ha^{-1}

Rice Cultivar Response to Florpyrauxifen-benzyl when Applied with Imazethapyr and a Cytochrome P450 Inhibitor

Abstract

Understanding cultivar responses to a new herbicide is crucial to determining appropriate herbicide use and management practices. Florpyrauxifen-benzyl is a new rice herbicide developed to control troublesome weeds in rice production. Little research has been conducted to characterize rice cultivar responses to florpyrauxifen-benzyl, thus a field experiment was conducted at the Pine Tree Research Station (PTRS) in 2017 and 2018 and at the Rice Research and Extension Center (RREC) in 2018 to determine rice cultivar tolerance to florpyrauxifen-benzyl as influenced by rate applied with imazethapyr and growth stage at application. Another experiment was conducted in 2018 at PTRS and RREC to assess crop response when florpyrauxifen-benzyl at different rates is applied with and without malathion, a known cytochrome P450 inhibitor. Three cultivars were evaluated in both experiments; long-grain variety ‘CL111’, an inbred medium grain variety ‘CL272’, and a hybrid, long grain variety ‘CLXL745’. Injury in the first experiment was higher when florpyrauxifen-benzyl was applied at 60 g ae ha^{-1} than at the labeled rate of 30 g ha^{-1}, with the most injury being 10% when averaged over growth stage at the time of application. Generally, applications made at the 3-leaf growth stage resulted in the most injury, however this injury was at most 14%. Additionally, there was no reduction in grain yield for any cultivar, indicating florpyrauxifen-benzyl can be used safely in conjunction with imazethapyr in imidazolinone-resistant rice. In the second experiment, there was no more than 10% injury and no reduction in grain yield, with the addition of malathion not causing an increase in rice injury. Results from these experiments indicate florpyrauxifen-benzyl can be mixed with imazethapyr and the addition of malathion will not lead to increased risk for injury to rice.

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

Key words: Crop injury, tank-mixtures, growth stage, cytochrome P450 inhibitor, acetolactate synthase inhibitor, imidazolinone-resistant rice.

Introduction

Crop tolerance to a herbicide, in most instances, is due to the ability of the plant to metabolize and detoxify the toxin to a non-phytotoxic compound, with the most common detoxifying pathways being P450 monooxygenase and glutathione S-transferase (GST) enzymes (Cole 1994). In certain instances, P450-inhibiting insecticides such as malathion can cause a herbicide to be more injurious to the crop, due to a reduced ability to metabolize the herbicide (Kaspar et al. 2011). Understanding the ability of a crop to metabolize a new herbicide is crucial in determining if the herbicide will be a good fit for use in production.

Malathion is an organophosphate insecticide used in many crops and is recommended in rice for control of rice stink bug (*Oebalus pugnax*) (Bowling 1962). It is a cytochrome P450 inhibitor, and when applied as a mixture with other pesticides, or in close succession of a herbicide application, could cause the herbicide to injure the crop (Studebaker et al. 2019). For example, malathion should not be applied within 14 days of propanil, a photosystem II-inhibiting herbicide. A study from Bowling and Hudgins (1966) found that propanil applied with malathion resulted in 50% injury to rice and a significant reduction in rough rice yield.

There are several examples of rice cultivars exhibiting differential tolerances to herbicides. One example is greater tolerance of rice varieties ‘Mars’ and ‘Tebonnet’ to a triclopyr application, a synthetic auxin herbicide (WSSA Group 4), than ‘Lemont’. This was especially evident when triclopyr was applied at a higher rate to 2- to 3-leaf rice (Pantone and Baker 1992). Another study showed differential tolerance of Clearfield® rice cultivars, which are imidazolinone-resistant. A long grain, inbred rice variety ‘CL161’ experienced less injury following an application of imazamox, another acetolactate synthase-inhibiting herbicide in the imidazolinone family (WSSA Group 2), than two hybrids, ‘CLXL745’ and ‘CLXL729’. In this study by Bond and Walker (2011), the inbred variety had no reduction in yield compared to the hybrids, which saw a 9 to 21% reduction in yield. From that same study, it is evident that growth stage or timing of the herbicide application can affect the level of injury. Relative yield was not affected by an application of imazamox when the herbicide was applied at panicle initiation, however relative yield was reduced when the herbicide was applied 14 days after panicle initiation and boot (Bond and Walker 2011).

In another study, Bond et al. (2006) also found that a 12.5% drift rate of acetolactate synthase (ALS)-inhibiting herbicides on non-imidazolinone-resistant rice resulted in as much as 35% injury 7 days after application when applied early-postemergence (EPOST) on 2- to 3-leaf rice compared to 0% when application was made at panicle differentiation as a late-postemergence (LPOST) application. However, relative yield was more affected by applications made at LPOST than EPOST. From these studies, it is apparent that rice injury following a herbicide application can be influenced by cultivar, growth stage, and herbicide rate. Also, injury may or may not ultimately effect yield.

Imidazolinone-resistant rice cultivars were introduced to allow imazethapyr and imazamox to be used for red rice (*Oryza sativa* L.) control beginning in 2002 (Croughan 1996; Steele et al. 2002). Imidazolinone herbicides are used to control numerous weeds in rice but are most valuable for red rice control (Steele et al. 2002). A survey of rice consultants in Arkansas and Mississippi indicated that barnyardgrass (*Echinochloa crus-galli* L. Beauv.), sprangletop species (*Leptochloa* spp.), and red rice were among the most troublesome weeds in rice production in this region (Norsworthy et al. 2013). Of these, red rice and barnyardgrass are the most difficult to control, and when not controlled can cause as much as 82% and 65% yield loss at 40 and 50 plants m^{-2}, respectively (Smith 1988). Further complicating this issue, 45% of

Arkansas rice is planted to an imidazolinone-resistant cultivar and will receive an application of an imidazolinone herbicide at least once during the growing season (Hardke 2018). As expected with the widespread use of any herbicide, several weed species have evolved resistance to ALS-inhibiting herbicides. Norsworthy et al. (2013) indicated that four out of the top five most problematic weeds in rice production had at least some resistance to ALS-inhibiting herbicides, which is concerning as resistance to this site of action appears to have increased from a previous survey and is now a more pressing issue in rice production (Norsworthy et al. 2007; Heap 2019). Increased occurrence of resistance coupled with weeds having multiple resistance highlights the need for herbicide stewardship and additional effective sites of action (Heap 2019; Riar et al. 2013).

To combat the evolution of herbicide resistance, florpyrauxifen-benzyl was commercialized in U.S. rice in 2018 by Corteva™ Agriscience as the active ingredient in Loyant™ herbicide. Florpyrauxifen-benzyl is a synthetic auxin herbicide (WSSA Group 4) with a broad spectrum of activity. Florpyrauxifen-benzyl has a unique site of action compared to other auxin herbicides in that it prefers the AFB5 IAA co-receptor rather than the TIR1 co-receptor (Walsh et al. 2006; Lee et al. 2014). This difference in binding site affinity allows florpyrauxifen-benzyl to control quinclorac-resistant barnyardgrass, indicating resistance to quinclorac does not confer resistance to florpyrauxifen-benzyl (Miller et al. 2018). Florpyrauxifen-benzyl also provides high levels of control of other troublesome weeds in rice production including sedges and various broadleaf weeds, such as Palmer amaranth (*Amaranthus palmeri* S. Wats.) and hemp sesbania (*Sesbania herbacea* (Mill.) McVaugh) (Miller and Norsworthy 2018). The use rate of the florpyrauxifen-benzyl is 30 g ae ha^{-1}, with a season maximum of 60 g ae ha^{-1} and a minimum of 14 days between sequential applications

(Anonymous 2017). Florpyrauxifen-benzyl has limited residual activity, and therefore should be applied in conjunction with a residual herbicide to mitigate the evolution of resistance (Miller and Norsworthy 2018; Riar et al. 2013).

While florpyrauxifen-benzyl can be an effective herbicide option in rice, the label indicates there could be increased risk for injury to medium-grain varieties and long-grain hybrids in the form of height reductions and malformed leaves (Anonymous 2017). However, due to the novelty of florpyrauxifen-benzyl limited data exists on differential cultivar tolerances thus, further experimentation is needed to determine cultivar responses to this herbicide.

The objectives of these experiments were to further quantify cultivar tolerance to florpyrauxifen-benzyl when applied with a cytochrome P450-inhibiting insecticide and when mixed with imazethapyr.

Materials and Methods

Florpyrauxifen-benzyl plus imazethapyr. Field experiments were initiated in 2017 and 2018 at the Pine Tree Research Station (PTRS) near Colt, AR on a Calloway silt loam (fine-silty, mixed, active, thermic Aquic Fraglossudalf) with 1.3% organic matter, 10.6% sand, 68.6% silt, 20.8% clay and a pH of 7.5 and in 2018 at the Rice Research and Extension Center (RREC) in Stuttgart, AR on a DeWitt silt loam (fine, smectic, thermic typic Albaqualf) with 1.8% organic matter, 8.4% sand, 71.4% silt, 20.2% clay, and a pH of 6.0.

The experiment was a randomized complete block, two-factor factorial with four replications. The first factor was rate of florpyrauxifen-benzyl and the second factor was crop stage at second application. Three rice cultivars were planted in separate trials on May 17, 2017 at PTRS and April 19, 2018 at both locations using a 10-row drill with 18-cm row spacing. A long-grain variety ‘CL111’ and medium-grain variety ‘CL272’ were planted at 72 seeds m^{-1} row and a long-grain hybrid ‘CLXL745’ was planted at 26 seeds m^{-1} row. Though there are several varieties of medium-grain and long-grain rice and several long-grain hybrid cultivars, only one of each was selected for trail size management. Long-grain variety CL111, medium-grain variety CL272, and long-grain hybrid CLXL745 were selected for these studies due to their acreage in 2016. Plots were 5.2 m long. A nontreated control was included for each cultivar. Imazethapyr at 106.5 g ai ha^{-1} and imazosulfuron at 341 g ae ha^{-1} were applied immediately following planting. A second application of imazethapyr at 106.5 g ha^{-1} was applied alone and with florpyrauxifen-benzyl at 30 or 60 g ha^{-1} when rice reached the 1-leaf, 3-leaf, or 5-leaf growth stage. Methylated seed oil was added to florpyrauxifen-benzyl treatments at 0.6 L ha^{-1}. Nonionic surfactant was added to imazethapyr only treatment at 0.25% v/v. The 1-leaf applications were made May 11 and 14, 3-leaf applications were made May 16 and 17, and 5-leaf applications were made May 28 and 30 at RREC and PTRS in 2018, respectively. Applications were made on May 30, June 6, and June 14 in 2017. Herbicide applications were made using a CO_2-pressurized backpack and handheld boom sprayer at 140 L ha^{-1} with 110015 AIXR nozzles (TeeJet Technologies, Springfield, IL 62703). The test sites at RREC were flooded on May 31, 2018 and at PTRS the flood was established on June 21, 2017 and June 2, 2018. These trials were maintained weed-free using labeled herbicides and hand-weeding as necessary and were managed according to University of Arkansas System Division of Agriculture recommendations by preplant and preflood applications of nitrogen in the form of urea totaling 130 kg N ha^{-1}. Additionally, an early-postemergence application of potassium chloride was made at PTRS, and preplant potassium chloride and phosphorous were applied at RREC.

Florpyrauxifen-benzyl plus malathion. Additional field experiments were conducted in 2018 at RREC and PTRS using the same cultivars to determine the impact of malathion on rice tolerance when applied in close proximity to florpyrauxifen-benzyl. The same three previously mentioned cultivars were seeded on April 19, 2018 at both locations.

This experiment was established as a randomized complete block with a two-factor factorial arrangement of treatments and four replications. The first factor consisted of florpyrauxifen-benzyl applied at 0, 30, or 60 g ha^{-1}. Methylated seed oil was added to florpyrauxifen-benzyl treatments at 0.6 L ha^{-1}. The second factor was the addition of malathion at 0 or 700 g ai ha^{-1}. Treatments were applied pre-flood when rice was at the 5-leaf growth stage which was May 28 and 30 at RREC and PTRS, respectively. Rice at RREC was flooded on May 31, 2018 and at PTRS on June 2, 2018. These trials were kept weed free and managed according to University of Arkansas System Division of Agriculture recommendations. Florpyrauxifen-benzyl plus malathion is not a labeled mixture (Anonymous 2017).

Assessments. In the imazethapyr experiment, visible injury was recorded 2 and 4 weeks after each POST application. Heights and number of tillers for three plants were recorded in each plot 2 weeks after the last herbicide application and reported relative to the non-treated control. In the malathion experiment, visible injury was recorded 2 and 4 weeks after application. Injury for both experiments was determined as reduced tillering, reduced canopy formation, and onion-like leaf appearance and estimated on a 0 to 100 scale, where 0 is no injury and 100 is plant death. The nontreated for each cultivar was used for comparison and did not have any injury. In both experiments, days to 50% heading were recorded and reported relative to the nontreated for each cultivar. Additionally, rice grain was harvested from the center of each plot using a small-plot combine, and rough rice yields then calculated and adjusted to 12% moisture.

Statistical analyses. Locations were analyzed separately due to differences in environment and soil characteristics (Figure 1a, b; Figure 2). Additionally, the purpose of this experiment was to report responses inbred, long-grain varieties, inbred, medium-grain varieties, and long-grain hybrids rather than make comparisons among cultivars, thus cultivars were analyzed separately. In the imazethapyr experiment, florpyrauxifen-benzyl rate and growth stage at the time of application were considered fixed effects. Site years for the PTRS location were combined due to similarities in soil texture and crop response. Replication was considered a random effect for RREC and replication nested within site year was considered a random effect for PTRS, since there were two years of data for that location. In the malathion experiment, florpyrauxifen-benzyl rate and malathion rate were considered fixed effects and replication was considered a random effect. All data were analyzed using PROC GLIMMIX in SAS v 9.4. A beta distribution was assumed for injury data and a gamma distribution was assumed for yield, number of tillers, and plant heights (Gbur et al. 2012). An analysis of variance was conducted, and means were separated using Fisher's protected least significant difference ($P = 0.05$). Due to the large number of zeros, formal analysis was not performed on heading data for both experiments and on injury 4 weeks after application for the malathion experiment, thus means and standard error are reported.

Results and Discussion

Response to florpyrauxifen-benzyl and imazethapyr. For the inbred long-grain variety CL111, there was an interaction between florpyrauxifen-benzyl rate and growth stage at PTRS, but at RREC there was only a main effect of florpyrauxifen-benzyl rate on injury 2 weeks after the second application (WAA) (Table 1). No more than 3% injury was observed at any location 2 WAA. At 4 WAA, only growth stage was significant at both locations. Applications made at the

3-leaf growth stage averaged over rate caused 3 and 4% injury at PTRS and RREC, respectively (Table 1). Additionally, there was no significant reduction in height or tillers for any treatment (Table 2). A 0.6 to 2.1-day delay in heading was found for CL111 relative to the nontreated at PTRS and 0 to 3.8-day delay in heading was found at RREC (Table 3). Grain yields ranged from 6,890 to 7,730 kg ha^{-1} at PTRS and 7,410 to 8,550 kg ha^{-1} at RREC. There were no differences among treatments, likely due to variability across replication within the trial area.

For the inbred, medium-grain variety CL272, there was no interaction between florpyrauxifen-benzyl rate and growth stage at the time of POST application at 2 WAA; however, the main effects were significant at both locations (Table 4). Generally, florpyrauxifen-benzyl at 60 g ae ha^{-1} caused more injury, when averaged over growth stage, and applications made at the 5-leaf growth stage resulted in more injury, when averaged over florpyrauxifen-benzyl rate. However, the highest injury observed 2 WAA was only 9%. Again, at 4 WAA there was no significant interaction, only the main effects of growth stage at PTRS and florpyrauxifen-benzyl rate and growth stage at RREC. There were no reductions in number of tillers or plant heights (Table 2). A 0.1 to 2.1-day delay in heading was found at PTRS and a 0 to 1-day delay in heading was found for RREC. Grain yields ranged from 7,210 to 8,470 kg ha^{-1} at PTRS and 6,120 to 8,080 kg ha^{-1} at RREC, and there were no significant differences in yields among treatments at either location (Table 5).

For long-grain hybrid CLXL745 at 2 WAA, florpyrauxifen-benzyl applied at the higher rate with imazethapyr resulted in 8 and 10% injury at PTRS and RREC, respectively, when averaged over growth stage at the time of application (Table 6). At 4 WAA, the higher rate of florpyrauxifen-benzyl still exhibited more injury than the lower rate or imazethapyr only treatments with 8 and 5% injury. There was no reduction in number of tillers or heights for any treatment relative the corresponding nontreated (Table 2). Days delayed in heading ranged from 0.6 to 2.4 at PTRS and 0 to 0.8 at RREC. Yields ranged from 8,540 to 9,510 kg ha^{-1} at PTRS and 8610 to 11000 kg ha^{-1}, with no significant differences, again likely due to variability within the field (Table 7).

Based on the findings from this experiment, crop injury increases when florpyrauxifen-benzyl is applied in conjunction with imazethapyr. However, the increase in injury could be intensified by stressing rice plants early in development by using two ALS-inhibiting herbicides preemergence, leading to a reduction in rate of florpyrauxifen-benzyl metabolism in rice. Further research is needed to determine crop injury response when plants are not stressed by herbicides early in the season.

Injury was slightly higher at RREC than PTRS and is likely a function of site differences. Florpyrauxifen-benzyl applied at a higher rate resulted in more injury, which is consistent with previous research that found triclopyr, another auxin herbicide, caused more injury to rice when applied at a higher rate (Pantone and Baker 1992). However, the maximum application rate for florpyrauxifen-benzyl is the lower rate of 30 g ae ha^{-1}, so injury from a higher rate is likely to be an issue only where there is an overlap during application. Generally, applications made at the 5-leaf growth stage exhibited higher levels of injury 2 WAA and could be due to proximity to flooding and anaerobic environment, however, by 4 WAA most of this injury was non-existent. These results appear to be contradictory to the results in Chapter 4, where 1-leaf rice was more injured than 5-leaf rice. However, that experiment was conducted in a controlled environment, whereas the injury observed in this experiment was the result of a field experiments conducted in an uncontrolled environment. Additionally, in Chapter 4 results indicate warmer temperatures can increase visual injury. In this experiment, daily high temperatures at the time of and following the 5-leaf application were above or near 30 C, which could explain the injury observed. Low levels of injury combined with no reduction in yield suggests that injury had no lasting impact on rice development, which is likely a function of applications being made during the vegetative growth stage. Further research should be conducted to determine the impacts of florpyrauxifen-benzyl applied in early reproductive stages. Under the conditions of this study, results from this experiment indicate that florpyrauxifen-benzyl applied with imazethapyr does not cause a reduction in grain yield, indicating it is a good fit for use in imidazolinone-resistant rice production.

Response to florpyrauxifen-benzyl and malathion. Injury for the long-grain variety CL111 at 2 and 4 WAA at PTRS was very low (2%) (Table 8). Additionally, only florpyrauxifen-benzyl at 60 g ae ha^{-1} applied with malathion at 700 g ai ha^{-1} respectively resulted in a 1.7-day delay in heading while all other treatments caused no delay in heading. There was no significant difference in yield for any treatment, and yields ranged from 8,350 to 9,430 kg ha^{-1}. At RREC, the most injury seen was 3% at 2 WAA, and no injury was present at 4 WAA. There was a 0.3-day delay in heading for all treatments, and yields ranged from 7,880 to 9,020 kg ha^{-1} with no differences among treatments.

For the medium grain variety CL272, florpyrauxifen-benzyl at 60 g ae ha^{-1} plus malathion at 700 g ai ha^{-1} resulted in 11 and 15% injury at PTRS and RREC, respectively 2 WAA, which was higher than florpyrauxifen-benzyl alone (8 and 7%) (Table 9). However, this injury was transient and rice plants were mostly recovered by 4 WAA. While the addition of malathion to the higher rate of florpyrauxifen-benzyl caused more injury than florpyrauxifen-benzyl alone, this difference was numerically small. There was a 0.3 to 1.3-day delay in heading at PTRS but no delay in heading at RREC. Additionally, grain yields ranged from 7,880 to 9,590 kg ha^{-1} at PTRS and 6,360 to 7,890 kg ha^{-1} at RREC, and there were no differences among treatments.

For the long-grain hybrid CLXL745, more injury was observed at PTRS than RREC 2 WAA, with the most injury being 12 and 3%, respectively (Table 10). However, by 4 WAA, there was at most 3% injury at PTRS and no injury at RREC. Injury data show florpyrauxifen-benzyl applied at the higher rate caused more injury and do not suggest the addition of malathion caused an increase in injury. Additionally, there was a 0 to 0.5-day delay in heading at both PTRS and RREC. Grain yields at both locations ranged from 10,140 to 11,600 kg ha^{-1} and 10,240 to 12,050 kg ha^{-1} at PTRS and RREC, respectively, with no significant differences.

There was injury associated with an application of florpyrauxifen-benzyl, with generally more injury caused by the higher rate. However, this injury was transient and was nearly undetectable by 4 WAA. Additionally, no treatment for any cultivar resulted in more than a 2-day delay in heading or reduction in grain yield. One explanation for the absence of injury or reduction in grain yield could be due to florpyrauxifen-benzyl metabolism in rice not being through the P450 pathway or the P450 enzymes inhibited by malathion are not responsible for metabolism in rice. The lack of high injury and yield loss could also be because florpyrauxifen-benzyl was not applied at a high enough rate to cause substantial injury. From other experiments, it is known that growth stage can influence crop response to a herbicide, especially on yield when herbicide applications are made during reproductive stages (Bond et al. 2006; Pantone and Baker 1992; Richard et al. 1981). Additionally, these herbicide applications were made 1 and 4 days before flooding at RREC and PTRS, respectively, when rice was at the tillering vegetative growth stage and thus had ample time to recover with no effects on yield. Based on the findings reported here, florpyrauxifen-benzyl can be safely applied with malathion; however, this is not currently a labeled application. Further research is needed to determine what extent environment impacts risk for injury when florpyrauxifen-benzyl is applied with malathion.

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Tables and Figures

Table 1. Rice injury for CL111 as influenced by florpyrauxifen-benzyl rate applied with imazethapyr at various rice growth stages [a,b,c].

		Injury 2 WAA		Injury 4 WAA	
Factor		PTRS	RREC	PTRS	RREC
		---% of nontreated---			
Rate	0	1	<1 b	1	<1
	30	1	2 a	1	<1
	60	2	3 a	1	1
Stage	1-leaf	2	2	<1 b	<1 b
	3-leaf	2	1	3 a	4 a
	5-leaf	1	1	<1 b	<1 b
Rate x stage	0 x 1-leaf	1 bc	<1	<1	<1
	30 x 1-leaf	3 ab	2	2	<1
	60 x 1-leaf	2 abc	4	<1	2
	0 x 3-leaf	1 bc	<1	3	3
	30 x 3-leaf	2 abc	1	2	6
	60 x 3-leaf	3 a	3	3	3
	0 x 5-leaf	2 abc	<1	1	<1
	30 x 5-leaf	<1 c	2	<1	<1
	60 x 5-leaf	2 abc	2	1	<1
		--- p-value ---			
Rate		0.1064	0.0224*	0.7921	0.4447
Stage		0.7724	0.7290	0.0003*	<0.0001*
Rate x stage		0.0252*	0.9455	0.3990	0.0631

[a] Factors: Florpyrauxifen-benzyl rate and growth stage at the time of the second application. All rates of florpyrauxifen-benzyl are reported in g ae ha^{-1} were applied with imazethapyr at 106.5 g a ha^{-1}. Florpyrauxifen-benzyl rates of 0 g ae ha^{-1} were imazethapyr only treatments.

[b] Abbreviations: WAA- weeks after application; PTRS- Pine Tree Research Station near Colt, AR; RREC- Rice Research and Extension Center near Stuttgart, AR

[c] Means are separated using Fisher’s protected LSD (P=0.05). Means followed by the same letter within a column and factor are not different.

Table 2. Number of tillers and plant height for CL111, CL272, and CLXL745 to various rates of florpyrauxifen-benzyl and imazethapyr at different growth stages [a,b,c].

		CL111				CL272				CLXL745			
		PTRS		RREC		PTRS		RREC		PTRS		RREC	
Rate	Stage	tillers	height	tiller	height	tiller	height	tiller	height	tiller	height	tiller	height
g ae ha^{-1}		#	cm	#	cm	#	cm	#	cm	#	cm	#	cm
Nontreated		4.1	35.5	4.3	47.5	4.6	37.0	5.0	46.0	5.9	32.5	8.3	47.0
0	1-leaf	4.1	35.0	3.9	48.0	4.7	38.0	4.4	53.5	3.9	31.5	6.8	47.0
30	1-leaf	4.6	33.5	4.1	48.0	3.5	36.0	3.4	48.0	4.6	33.5	6.5	48.0
60	1-leaf	3.9	30.0	4.8	48.0	4.1	35.0	3.2	48.0	4.7	32.5	7.4	45.5
0	3-leaf	4.3	35.0	4.6	51.5	4.4	36.0	4.2	51.0	4.3	34.5	6.9	45.5
30	3-leaf	3.9	33.5	3.6	46.0	3.3	33.0	4.2	52.0	5.4	32.0	6.7	47.5
60	3-leaf	3.3	34.0	3.4	50.0	4.2	35.0	4.2	46.0	3.7	33.0	6.6	44.0
0	5-leaf	3.8	34.0	3.6	51.5	4.1	36.5	5.2	49.5	5.6	31.5	7.6	50.5
30	5-leaf	3.3	34.0	3.7	49.0	4.3	34.5	5.1	47.0	4.3	31.5	7.9	46.5
60	5-leaf	3.3	33.0	4.6	50.5	4.8	34.5	4.3	51.0	5.3	28.5	6.8	48.0
		p-value											
		0.7729	0.4884	0.3463	0.1394	0.6228	0.1311	0.4872	0.4651	0.1259	0.1629	0.6822	0.4068

[a] All rates of florpyrauxifen-benzyl were mixed with imazethapyr at 106.5 g ai ha^{-1}. Florpyrauxifen-benzyl rates of 0 g ae ha^{-1} were imazethapyr only treatments.

[b] Crop growth stage at second application following the first application made preemergence.

[c] Abbreviations: PTRS, Pine Tree Research Station near Colt, AR; RREC, Rice Research and Extension Center near Stuttgart, AR.

Table 3. Heading and grain yield response of CL111 at the Pine Tree Research Station (PTRS) and Rice Research and Extension Center (RREC) [a,b,c].

Florpyrauxifen-benzyl rate	Stage	PTRS				RREC			
		Delay in heading		Grain yield		Delay in heading		Grain yield	
g ae ha^{-1}		----days----		kg ha^{-1}		----days----		kg ha^{-1}	
Nontreated		-	-	6,890	(767)	-	-	7,410	(338)
0	1-leaf	0.6	(0.4)	7,730	(861)	1.8	(1.2)	8,430	(384)
30	1-leaf	1.5	(1.0)	7,560	(841)	1.3	(0.3)	8,110	(370)
60	1-leaf	1.3	(0.7)	7,550	(840)	2.3	(1.3)	8,540	(389)
0	3-leaf	0.8	(0.5)	7,130	(794)	1.0	(0.4)	8,260	(377)
30	3-leaf	1.3	(0.7)	7,600	(846)	3.8	(0.8)	7,860	(358)
60	3-leaf	0.9	(0.4)	7,540	(839)	1.5	(0.9)	8,500	(388)
0	5-leaf	1.3	(0.5)	7,490	(834)	0	(0)	8,550	(390)
30	5-leaf	0.9	(0.5)	7,490	(834)	0.3	(0.3)	8,050	(367)
60	5-leaf	2.1	(0.9)	7,190	(800)	0.3	(0.3)	8,180	(434)
p-value				0.6382				0.3997	

[a] All rates of florpyrauxifen-benzyl were applied with imazethapyr at 106.5 g ai ha^{-1}. Florpyrauxifen-benzyl rates of 0 g ae ha^{-1} were imazethapyr only treatments.

[b] Crop growth stage at second application.

[c] Mean followed by standard error in parenthesis.

Table 4. Rice injury for CL272 as influenced by florpyrauxifen-benzyl rate applied with imazethapyr at various rice growth stages [a,b,c].

		Injury 2 WAA		Injury 4 WAA	
Factor		PTRS	RREC	PTRS	RREC
		---------------------% of nontreated-------------------------			
Rate	0	1 b	2 b	1	1 b
	30	2 b	3 b	2	3 b
	60	6 a	6 a	3	6 a
Stage	1-leaf	2 b	1 b	3 a	1 b
	3-leaf	2 b	2 b	3 a	14 a
	5-leaf	4 a	9 a	<1 b	1 b
Rate x stage	0 x 1-leaf	<1	<1	1	<1
	30 x 1-leaf	2	1	4	1
	60 x 1-leaf	6	5	5	2
	0 x 3-leaf	<1	1	2	10
	30 x 3-leaf	2	4	2	13
	60 x 3-leaf	5	4	7	21
	0 x 5-leaf	4	8	<1	<1
	30 x 5-leaf	3	7	1	1
	60 x 5-leaf	7	13	<1	5
		------------------------- p-value ----------------------------			
Rate		<0.0001*	0.0080*	0.0998	0.0143*
Stage		0.0086*	0.0001*	0.0078*	<0.0001*
Rate x stage		0.2274	0.2002	0.2232	0.6779

[a] Factors: Florpyrauxifen-benzyl rate and growth stage at the time of the second application. All rates of florpyrauxifen-benzyl are reported in g ae ha^{-1} were applied with imazethapyr at 106.5 g a ha^{-1}. Florpyrauxifen-benzyl rates of 0 g ae ha^{-1} were imazethapyr only treatments.

[b] Abbreviations: WAA- weeks after application; PTRS- Pine Tree Research Station near Colt, AR; RREC- Rice Research and Extension Center near Stuttgart, AR

[c] Means are separated using Fisher’s protected LSD (P=0.05). Means followed by the same letter within a column and factor are not different.

Table 5. Heading and grain yield response of CL272 at the Pine Tree Research Station (PTRS) and Rice Research and Extension Center (RREC) [a,b,c].

Florpyrauxifen-benzyl rate	Stage	PTRS				RREC			
		Delay in heading		Grain yield		Delay in heading		Grain yield	
g ae ha^{-1}		----days----		kg ha^{-1}		----days----		kg ha^{-1}	
Nontreated		-	-	7,210	(403)	-	-	6,870	(515)
0	1-leaf	0.1	(0.1)	8,020	(420)	0	(0)	6,900	(520)
30	1-leaf	0.5	(0.5)	8,120	(426)	0.3	(0.3)	8,030	(605)
60	1-leaf	0.8	(0.4)	8,060	(422)	1.0	(1.0)	6,120	(461)
0	3-leaf	0.9	(0.4)	7,350	(385)	0.8	(0.8)	7,830	(590)
30	3-leaf	0.4	(0.3)	8,470	(444)	0.3	(0.3)	7,740	(583)
60	3-leaf	1.3	(0.6)	7,220	(378)	0.3	(0.3)	7,790	(587)
0	5-leaf	1.3	(0.5)	7,700	(404)	0.5	(0.5)	6,850	(596)
30	5-leaf	1.8	(0.8)	7,790	(408)	0	(0)	8,080	(609)
60	5-leaf	2.1	(0.8)	7,860	(412)	0.3	(0.3)	7,050	(530)
p-value				0.3490				0.2623	

[a] All rates of florpyrauxifen-benzyl were applied with imazethapyr at 106.5 g ai ha^{-1}. Florpyrauxifen-benzyl rates of 0 g ae ha^{-1} were imazethapyr only treatments.

[b] Crop growth stage at second application.

[c] Mean followed by standard error in parenthesis.

Table 6. Rice injury for CLXL745 as influenced by florpyrauxifen-benzyl rate applied with imazethapyr at various rice growth stages [a,b,c].

		Injury 2 WAA		Injury 4 WAA	
Factor		PTRS	RREC	PTRS	RREC
		---------------------% of nontreated-------------------------			
Rate	0	1 b	2 b	1	1 b
	30	2 b	3 b	2	3 b
	60	6 a	6 a	3	6 a
Stage	1-leaf	2 b	1 b	3 a	1 b
	3-leaf	2 b	2 b	3 a	14 a
	5-leaf	4 a	9 a	<1 b	1 b
Rate x stage	0 x 1-leaf	<1	<1	1	<1
	30 x 1-leaf	2	1	4	1
	60 x 1-leaf	6	5	5	2
	0 x 3-leaf	<1	1	2	10
	30 x 3-leaf	2	4	2	13
	60 x 3-leaf	5	4	7	21
	0 x 5-leaf	4	8	<1	<1
	30 x 5-leaf	3	7	1	1
	60 x 5-leaf	7	13	<1	5
		------------------------ p-value ---------------------------			
Rate		<0.0001*	0.0080*	0.0998	0.0143*
Stage		0.0086*	0.0001*	0.0078*	<0.0001*
Rate x stage		0.2274	0.2002	0.2232	0.6779

a Factors: Florpyrauxifen-benzyl rate and growth stage at the time of the second application. All rates of florpyrauxifen-benzyl are reported in g ae ha-1 were applied with imazethapyr at 106.5 g a ha^{-1}. Florpyrauxifen-benzyl rates of 0 g ae ha^{-1} were imazethapyr only treatments.

Table 7. Heading and grain yield response of CLXL745 at the Pine Tree Research Station (PTRS) and Rice Research and Extension Center (RREC) [a,b,c].

Florpyrauxifen-benzyl rate	Stage	PTRS				RREC			
		Delay in heading		Grain yield		Delay in heading		Grain yield	
g ae ha^{-1}		----days----		kg ha^{-1}		----days----		kg ha^{-1}	
Nontreated		-	-	8,540	(1,049)	-	-	9,910	(638)
0	1-leaf	0.6	(0.3)	9,440	(1,159)	0.3	(0.3)	9,600	(618)
30	1-leaf	1.3	(0.9)	8,970	(1,101)	0.5	(0.3)	10,680	(794)
60	1-leaf	2.3	(0.9)	9,440	(1,159)	0.3	(0.3)	10,760	(692)
0	3-leaf	1.6	(0.7)	8,700	(1,068)	0	(0)	11,000	(708)
30	3-leaf	1.7	(0.8)	9,510	(1,167)	0.8	(0.5)	10,400	(671)
60	3-leaf	2.4	(0.9)	8,770	(1,077)	0.5	(0.5)	8,610	(554)
0	5-leaf	2.4	(0.8)	9,400	(1,154)	0	(0)	10,100	(650)
30	5-leaf	1.4	(0.5)	9,270	(1,137)	0.3	(0.3)	10,250	(659)
60	5-leaf	1.6	(0.5)	8,800	(1,080)	0.5	(0.5)	9,640	(621)
p-value				0.2338				0.3201	

[a] All rates of florpyrauxifen-benzyl were applied with imazethapyr at 106.5 g ai ha^{-1}. Florpyrauxifen-benzyl rates of 0 g ae ha^{-1} were imazethapyr only treatments.

[b] Crop growth stage at second application.

[c] Mean followed by standard error in parenthesis.

Table 8. Injury 2 and 4 weeks after application (WAA), heading delay, and grain yield response of CL111 to different rates of florpyrauxifen-benzyl and malathion applied preflood.[a,b]

Rate	PTRS						RREC					
	Injury			Delay in heading		Grain yield	Injury			Delay in heading		Grain yield
	2 WAA	4 WAA					2 WAA	4 WAA				
g ai ha^{-1}	----%----			----days----		kg ha^{-1}	----%----			----days----		kg ha^{-1}
Nontreated	-			-		9,430	-			-		8,600
30 + 0	<1	0	(0)	0.0	(0.0)	9,010	<1	0	(0)	0.3	(0.3)	9,020
60 + 0	2	0	(0)	0.0	(0.0)	9,250	2	0	(0)	0.3	(0.3)	8,760
30 + 700	<1	0	(0)	0.0	(0.0)	9,290	1	0	(0)	0.3	(0.3)	8,170
60 + 700	2	2	(1.7)	1.7	(1.2)	8,350	3	0	(0)	0.3	(0.3)	7,880
p-value	0.2925					0.6245	0.0645					0.2078

[a] Rate of florpyrauxifen-benzyl + malathion. Florpyrauxifen-benzyl rate is reported in g ae ha^{-1}.

[b] Mean followed by standard error in parenthesis.

Table 9. Injury 2 and 4 weeks after application (WAA), heading delay, and grain yield response of CL272 to different rates of florpyrauxifen-benzyl and malathion applied preflood. [a,b,c]

Rate	PTRS							RREC						
	Injury				Delay in heading		Grain yield	Injury				Delay in heading		Grain yield
	2 WAA		4 WAA					2 WAA		4 WAA				
g ai ha^{-1}	----%----				----days----		kg ha^{-1}	----%----				----days----		kg ha^{-1}
Nontreated	-				-		9,590	-				-		7,610
30 + 0	2	c	0	(0)	0.3	(0.3)	8,710	4	c	<1	(0.3)	0.0	(0.0)	7,320
60 + 0	8	ab	0	(0)	1.0	(0.4)	7,880	7	bc	0	(0)	0.0	(0.0)	6,730
30 + 700	5	b	0	(0)	1.0	(0.6)	8,380	9	b	<1	(0.8)	0.0	(0.0)	6,360
60 + 700	11	a	<1	(0.8)	1.3	0.5	8,810	15	a	2	(1.2)	0.0	(0.0)	7,890
p-value	0.0084						0.4231	0.0042						0.1947

[a] Rate of florpyrauxifen-benzyl + malathion. Florpyrauxifen-benzyl rate is reported in g ae ha^{-1}.

[b] Mean followed by standard error in parenthesis.

[c] Means are separated using Fisher's protected LSD (P=0.05). Means in a column containing the same letter are not significantly different.

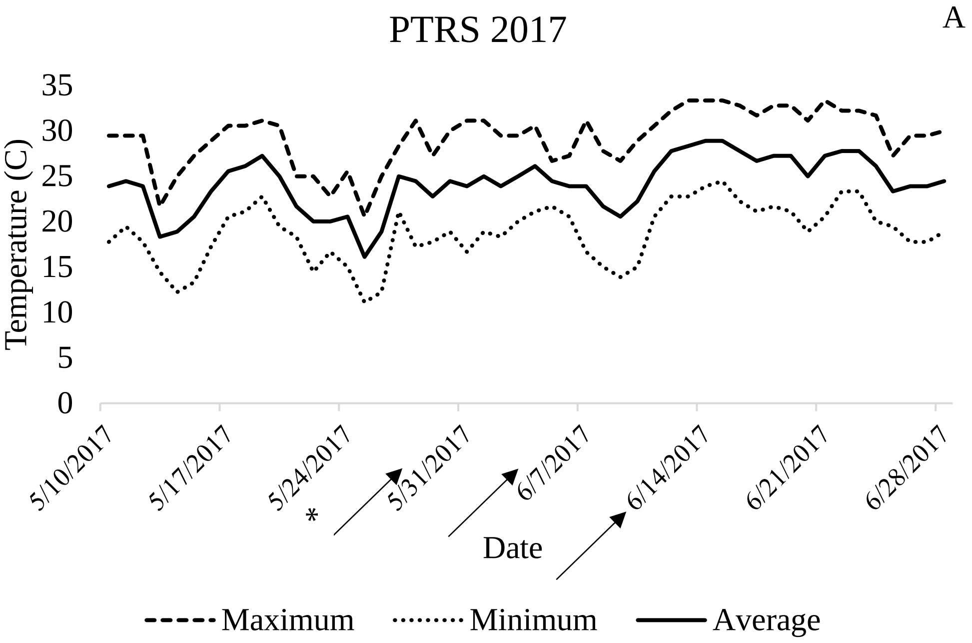
Table 10. Injury 2 and 4 weeks after application (WAA), heading delay, and grain yield response of CLXL745 to different rates of florpyrauxifen-benzyl and malathion applied preflood. [a,b,c]

	PTRS							RREC					
Rate	Injury				Delay in heading		Grain yield	Injury			Delay in heading		Grain yield
	2 WAA		4 WAA					2 WAA	4 WAA				
g ai ha^{-1}	----%----				----days----		kg ha^{-1}	----%----			----days----		kg ha^{-1}
Nontreated	-				-		11,600	-			-		11,600
30 + 0	4	b	2	(1.2)	0.3	(0.3)	10,140	2	0	(0)	0.3	(0.3)	11,230
60 + 0	9	a	3	(1.0)	0.5	(0.3)	10,790	2	0	(0)	0.5	(0.3)	10,240
30 + 700	4	b	2	(0.9)	0	(0)	10,900	2	0	(0)	0	(0)	11,940
60 + 700	12	a	1	(1.0)	0.5	(0.3)	10,950	3	0	(0)	0.3	(0.3)	12,050
p-value	0.0015						0.3634	0.7870					0.4468

[a] Rate of florpyrauxifen-benzyl + malathion. Florpyrauxifen-benzyl rate is reported in g ae ha^{-1}.

[b] Mean followed by standard error in parenthesis.

[c] Means are separated using Fisher's protected LSD (P=0.05). Means in a column containing the same letter are not significantly different.



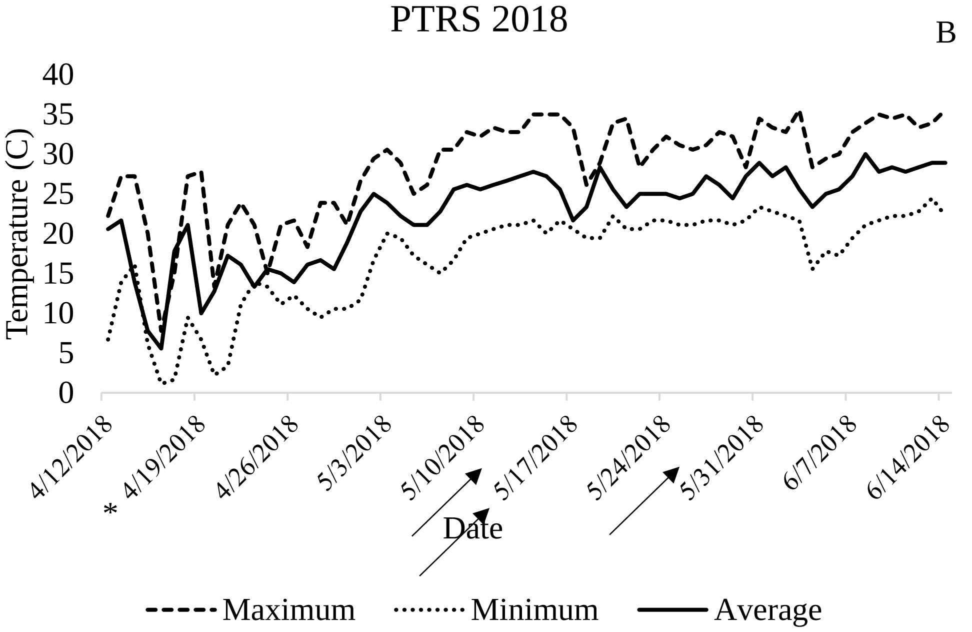


Figure 1a,b. Daily minimum, maximum, and average temperatures at the Pine Tree Research Station near Colt, AR in 2017 and 2018 (A, B) for dates ranging from 7 days before planting to 14 days after the last application for the florpyrauxifen-benzyl and imazethapyr experiment. Rice cultivars CL111, CL272, and CLXL745 were planted on April 19, 2018 and on May 27, 2017. The 1-leaf (lf) applications were made May 30 and 14, 3-lf applications were made June 6 and May 17, and 5-lf applications were made June 14 and May 30 in 2017 and 2018, respectively. Planting date is indicated by (*) and application dates are indicted by an arrow.

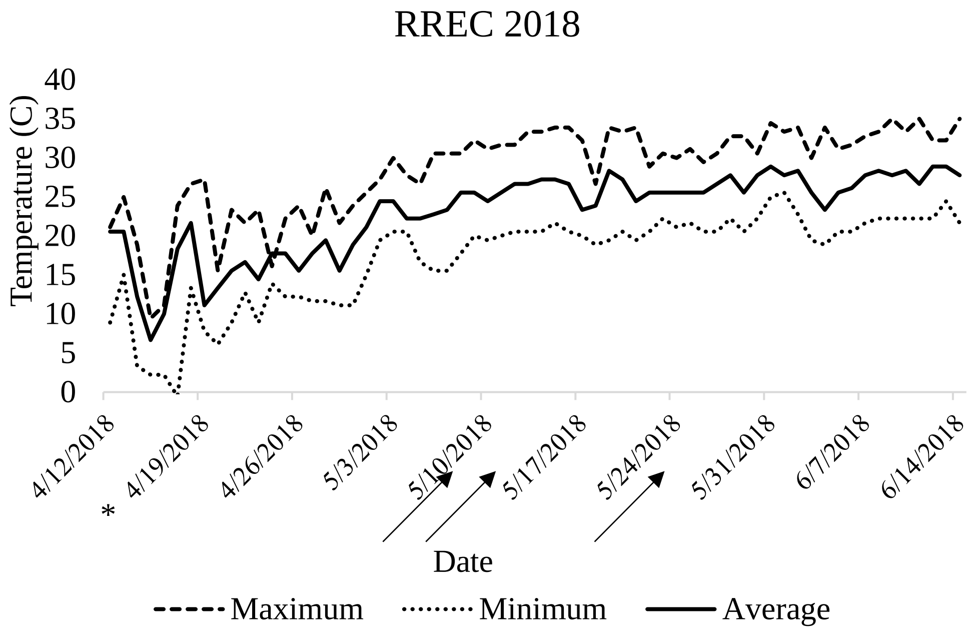


Figure 2. Daily minimum, maximum, and average temperatures at the Rice Research and Extension Center (RREC) in Stuttgart, AR in 2018 for dates ranging from 7 days before planting to 14 days after the last application for the florpyrauxifen-benzyl and imazethapyr experiment. Rice cultivars CL111, CL272, and CLXL745 were planted on April 19, 2018. The 1-leaf (lf) application was made May 11, the 3-lf application was made May 16, and the 5-lf application was made May 28. Planting date is indicated by (*) and application dates are indicted by an arrow.

Characterization of Rice Cultivar Response to Florpyrauxifen-benzyl

Abstract

Many factors can influence cultivar response to herbicides, including environmental factors, herbicide rate, crop growth stage at application, and days between sequential applications. Florpyrauxifen-benzyl is a new broad-spectrum, postemergence herbicide commercialized in U.S. rice in 2018. A field experiment was conducted in 2018 at the Pine Tree Research Station (PTRS) near Colt, AR, and the Rice Research and Extension Center (RREC), near Stuttgart, AR, to evaluate crop injury and yield response of three rice cultivars to sequential applications of florpyrauxifen-benzyl made several days apart. Additionally, greenhouse and growth chamber experiments were conducted at the Altheimer Laboratory in Fayetteville, AR, to evaluate cultivar responses when florpyrauxifen-benzyl is applied at 30 or 60 g ae ha^{-1} to rice treated with a different temperature regime or at various growth stages. Three rice cultivars were used in all experiments; a long-grain, inbred variety ‘CL111’, a medium-grain, inbred variety ‘CL272’, and a long-grain hybrid ‘CLXL745’. Data from these experiments indicate CL111 exhibits sufficient tolerance to florpyrauxifen-benzyl with only 10% visible injury and no impact on yield. CL272 showed 15% injury 3 weeks after the second application in the field experiment when sequential applications were made 14 days apart. Additionally, 12% injury was observed in the greenhouse when florpyrauxifen-benzyl was applied at 30 g ae ha^{-1}, averaged over growth stage at application. There was no reduction in yield in the field experiment, indicating CL272 can recover from florpyrauxifen-benzyl injury. As much as 64% injury was observed for CLXL745 at 3 weeks after application (WAA) when sequential herbicide applications were made 4 days apart, regardless of rate. High levels of injury occurred in the growth chamber and greenhouse studies for this cultivar as well. Additionally, there was a significant reduction in the yields of nearly all treatments from sequential applications of florpyrauxifen-benzyl to CLXL745. Data from these experiments suggest CL272 and CLXL745 are sensitive to sequential applications of florpyrauxifen-benzyl. CLXL745, is especially sensitive, and caution should be used when applying florpyrauxifen-benzyl to this rice cultivar.

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

Key words: crop tolerance, herbicide injury.

Introduction

Florpyrauxifen-benzyl is a new synthetic auxin (WSSA Group 4) herbicide released for commercial use in rice in 2018 by Corteva™ Agriscience. Previous research has explored both the weed control spectrum and the chemical properties of the herbicide, including residual activity and translocation. A study from Miller and Norsworthy (2018a) indicated florpyrauxifen-benzyl controlled many troublesome weeds in rice production when used at the labeled rate of 30 g ae ha^{-1}, including yellow nutsedge (*Cyperus esculentus* L.), hemp sesbania [*Sesbania herbacea* (Mill.) McVaugh], and barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.]. Florpyrauxifen-benzyl has a site of action different than quinclorac (WSSA Group 4), favoring the AFB5 IAA co-receptor instead of the TIR1 co-receptor, which allows florpyrauxifen-benzyl to have activity on quinclorac-resistant barnyardgrass (Lee et al. 2014; Miller et al. 2018; Walsh et al. 2006). Additional experiments from Miller and Norsworthy (2018b) indicate florpyrauxifen-benzyl has minimal residual activity and should, therefore, be used in conjunction with a herbicide that does have residual activity to better control weeds with prolonged emergence. Florpyrauxifen-benzyl can be applied at 30 g ae ha^{-1} in a single application, with a maximum of two applications per growing season (Anonymous 2017).

Much of the research conducted with florpyrauxifen-benzyl to date has focused on weed control and characterization of chemical properties of the herbicide; however, little research has been conducted to determine differences in cultivar responses to an application of the herbicide. Prior research has shown injury to rice from florpyrauxifen-benzyl can be in the form of leaf malformations, reduced height, and reduced biomass (JK Norsworthy, personal communication). The herbicide label also warns of potential risk for rice injury to long-grain hybrid and medium-grain varieties (Anonymous 2017).

Arkansas is the top producer of rice in the US, producing roughly half of all rice hectares harvested in the country in 2018 (USDA 2019). Of the rice grown in Arkansas, 49% is planted to long-grain hybrids, 39% is planted to long-grain, inbred varieties, and 13% is planted to medium-grain, inbred varieties (Hardke 2018). Understanding cultivar tolerances is crucial when new herbicides are introduced to reduce the risk of yield loss and to make better recommendations for farmers.

Tolerance to herbicides in crops is due, in part, to the ability of a crop to metabolize and detoxify a herbicide (Cole 1994). Different cultivars of the same crop can exhibit varying tolerance to a herbicide. A popular example of this is the differential tolerance of soybean [*Glycine max* (L.) Merr.] varieties to metribuzin (Hardcastle 1979). Additionally, there are several examples of rice cultivars exhibiting differing responses to herbicides. One such example is a study from Bond and Walker (2011) in which different imidazolinone-resistant rice cultivars exhibited varying sensitivity to imazamox, a herbicide in the imidazolinone family. In that study, two rice hybrids exhibited more injury than a long-grain variety to an application of imazamox.

Many factors can affect crop tolerance to a herbicide, including herbicide rate, crop growth stage at application, and environmental factors near the time of application. Not only did the study from Bond and Walker (2011) demonstrate cultivar differences in response to a herbicide, but also the effect of growth stage on injury and yield. Grain yield of hybrids was reduced 9 to 21% when imazamox was applied 14 days after panicle initiation and at boot, but there was no reduction in yield when the herbicide was applied at panicle initiation.

Another example of differences in cultivar tolerance to an application of a herbicide at various growth stages is from Zhang and Webster (2002). In that study, Zhang and Webster found the medium-grain variety ‘Bengal’ was less tolerant to bispyribac-sodium than the long-grain variety ‘Cocodrie’. When bispyribac-sodium was applied to 1- to 2-leaf rice, fresh shoot weight was reduced nearly 50% 3 weeks after treatment (WAT) compared to applications made to 3- to 4-leaf rice, which was reduced only 23%. This difference indicates rice tolerance to a herbicide can be growth stage dependent and as rice plants grow, they have a greater ability to metabolize a herbicide.

In a study from Pantone and Baker (1992), rice injury to triclopyr was influenced by variety, herbicide rate, and growth stage at the time of application. Triclopyr was applied to three different rice cultivars at different growth stages and at two different rates, and ‘Lemont’ was more injured by triclopyr than ‘Mars’ and ‘Tebonnet’. In that experiment, when triclopyr was applied at panicle initiation, little injury was observed; however, when triclopyr was applied during vegetative growth, at least 10% injury was observed regardless of rate. Applications made at the 2- to 3-leaf stage resulted in more injury than applications made at the 4- to 5-leaf stage, regardless of rate and variety. As expected with herbicide injury, the higher rate of triclopyr, 800 g ae ha^{-1}, resulted in more injury than at the lower rate of 400 g ae ha^{-1}.

Environmental conditions surrounding the time of application can influence injury following a herbicide application. In a growth chamber experiment, corn (*Zea mays* L.) plant growth was reduced following treatment of thiocarbamate herbicides for all plants in the higher temperature regime (Burt and Akinsorotan 1976). Plant growth was slowed following herbicide treatment, regardless of herbicide rate or soil moisture, when the growth chamber was maintained at 30 C compared to 20 C. Conversely, in a different study from Wright and Rieck (1974), dry weights from various corn hybrids were reduced following an application of butylate when temperature was 20 C compared to 33 C. Both experiments demonstrate that temperature or environmental conditions can influence crop response to a herbicide. Because of the limited knowledge of the impact of florpyrauxifen-benzyl on rice cultivar responses, the objective of these experiments was to further evaluate rice response to florpyrauxifen-benzyl rate while considering days between sequential applications, temperature, and growth stage.

Materials and Methods

Sequential applications of florpyrauxifen-benzyl. Field experiments were conducted in 2018 at the Pine Tree Research Station (PTRS) near Colt, AR, and the Rice Research and Extension Center (RREC) in Stuttgart, AR, to evaluate the effect of florpyrauxifen-benzyl rate over sequential applications and number of days between applications on rice injury and grain yield of three rice cultivars. The soil at PTRS was a Calloway silt loam (fine-silty, mixed, active, thermic Aquic Fraglossudalf) with 1.3% organic matter, 10.6% sand, 68.6% silt, 20.8% clay, and a pH of 7.5 The soil at RREC was a DeWitt silt loam (fine, smectic, thermic typic Albaqualf) with 1.8% organic matter, 8.4% sand, 71.4% silt, 20.2% clay, and a pH of 6.0.

This experiment was set up as a randomized complete block, two-factor factorial with four replications. The first factor was florpyrauxifen-benzyl rate for sequential applications and the second factor was the number of days between sequential applications. Three rice cultivars were evaluated in separate experiments: long-grain variety ‘CL111’; a medium-grain variety ‘CL272’; and a long-grain hybrid ‘CLXL745’. Only three cultivars were selected to manage the size of the trial. Long-grain variety CL111, medium-grain variety CL272, and long-grain hybrid CLXL745 were selected for these studies due to their acreage in 2016. Rice was drill seeded on April 19, 2018, at both locations using a 10-row cone drill with an 18-cm row spacing, and plots were 5.2 m long. Inbred varieties were seeded at a rate of 72 seeds m^{-1} row and the hybrid was seeded at a rate of 26 seeds m^{-1} row. A nontreated control was included for each cultivar. These trials were maintained weed-free using labeled herbicides and hand-weeding as necessary and were managed according to University of Arkansas System Division of Agriculture recommendations by preplant and preflood applications of nitrogen in the form of urea totaling 130 kg N ha^{-1}. Additionally, an early-postemergence application of potassium chloride was made at PTRS, and preplant potassium chloride and phosphorous were applied at RREC.

Florpyrauxifen-benzyl (Loyant™ Herbicide, Dow AgroSciences LLC, 9330 Zionsville Road Indianapolis, IN 46268) was applied at 30 or 60 g ae ha^{-1} early-postemergence on 2- to 3-leaf rice. A second application of florpyrauxifen-benzyl was targeted for 7, 10, 14, and 21 days after the first application, but were actually made 5, 13, 18, and 21 days after the initial application at PTRS and 4, 11, 14, and 20 days after the initial application at RREC. Application dates at PTRS are May 17 for the first application, and May 22, May 30, June 4, and June 7 for the sequential applications. At RREC, the first application was made on May 17 and sequential applications were made May 21, May 28, May 31, and June 6. The same florpyrauxifen-benzyl rates were used in the sequential application such that plots that received 30 g ae ha^{-1} EPOST also received 30 g ae ha^{-1} in the sequential application and plots that received 60 g ae ha^{-1} EPOST also received 60 g ae ha^{-1} in the sequential application. Methylated seed oil was included with all florpyrauxifen-benzyl treatments at a rate of 0.6 L ha^{-1}. Herbicide treatments were made using a CO_2-pressurized backpack sprayer at 140 L ha^{-1} with 110015 AIXR nozzles (TeeJet Technologies, Springfield, IL 62703). The flood was established at PTRS on June 2, 2018, and at RREC on May 31, 2018. Visible injury was assessed 2 and 3 weeks after the second application on a scale of 0% to 100%, where 0 equals no injury and 100 equals crop death (Frans and Talbert 1977). Visible injury observed included leaf malformations, reduced height, and decreased biomass. Additionally, groundcover and yield can be correlated (Donald 1998); thus, groundcover was assessed using drone images taken with a DJI Phantom 4 Pro drone equipped with a multispectral camera (Sentera 6636 Cedar Avenue S., Minneapolis, MN 55423). Images were taken one and three weeks after the last application at each location from a height of approximately 60 m. Those images consisted of approximately 6.7 million pixels and were analyzed using Field Analyzer (Turf Analyzer, Fayetteville, AR 72702) where percent groundcover was calculated. Rough rice grain yield was collected at crop maturity from the center of each plot using a small-plot combine. Grain yields were calculated and adjusted to 12% moisture. Groundcover is reported as a percentage of the nontreated control.

Florpyrauxifen-benzyl rate and temperature. A growth chamber experiment was conducted at the University of Arkansas Altheimer Laboratory in Fayetteville, AR, in fall of 2018 and repeated twice in spring of 2019 to determine the effect of different day/night temperatures on injury for rice cultivars following an application of florpyrauxifen-benzyl. Rice was seeded into 10-cm-diameter pots filled with a 50:50 (v/v) mixture of field soil and potting mix (Metro-Mix®, Sun Gro® Horticulture, 770 Silver Street, Agawam, MA 01001), thinned to 1 plant per pot, and grown in the greenhouse until plants reached the 2-leaf growth stage. Field soil was a Captina silt loam (Fine-silty, siliceous, active, mesic Typic Fragiudults) with 1.7% organic matter and a pH of 6.1. The same cultivars in the field experiments were used in this experiment, and a nontreated control was included for each cultivar. This experiment was set up as a split-plot design with temperature as the whole plot factor and florpyrauxifen-benzyl rate as the split plot factor. There were three runs in time and five replications per run. Plants were placed in their respective growth chambers 3 days before herbicide application to allow acclimation and minimize compounding injury from shock and herbicide application. Temperature regime in the chambers consisted of 27/18 C day/night temperature and 32/24 C day/night temperature with a 16-hour photoperiod. Light quantity at plant height in both growth chambers was approximately 500 μmol m^{-2} s^{-1}. When plants reached the 2- to 3-leaf growth stage, florpyrauxifen-benzyl was applied at a rate of 0 (nontreated control), 30, and 60 g ae ha^{-1} using a two-nozzle boom equipped with 800067 flat fan nozzles in a spray chamber calibrated to deliver 187 L ha^{-1}. Methylated seed oil was added to all florpyrauxifen-benzyl treatments at 0.6 L ha^{-1}. Plants were returned to their respective growth chamber following application. Injury was assessed 14 and 28 days after application (DAA) on a scale of 0% to 100%, where 0 is no injury and 100 is crop death. Plant heights were recorded 14 and 28 DAA. Tillers were counted and aboveground biomass collected at 28 DAA, then oven dried at 66 C for 4 days and weighed. Heights, tillers, and dried biomass are reported relative to the nontreated.

Florpyrauxifen-benzyl rate and growth stage. A greenhouse experiment was conducted in the fall of 2018 and spring of 2019 at the University of Arkansas Altheimer Laboratory in Fayetteville, AR, to evaluate the effect florpyrauxifen-benzyl rate and growth stage at the time of application. The three cultivars used in field and growth chamber experiments were seeded into 10-cm-diameter pots with a 50:50 mixture of field soil and potting mix (Metro-Mix®, Sun Gro® Horticulture, 770 Silver Street, Agawam, MA 01001) and thinned to 1 plant per pot. Field soil was a Captina silt loam (Fine-silty, siliceous, active, mesic Typic Fragiudults) with 1.7% organic matter and a pH of 6.1. Plants were grown in the greenhouse at a 32 C daytime and 22 C nighttime (±3 C) temperature regime with a 16-hour photoperiod. This experiment was established as a completely randomized design, two-factor factorial, with florpyrauxifen-benzyl rate being one factor and growth stage being the second factor. There were three runs in time with five replications per run and a nontreated control was included for each variety at each growth stage. Florpyrauxifen-benzyl was applied at 30 or 60 g ae ha^{-1} once rice reached the 1-, 3-, or 5-leaf stage and immediately returned to the greenhouse. Applications were made using the same setup as noted for the growth chamber experiment. Visible injury was assessed 14 and 28 DAA on a 0% to 100% scale. Heights were also taken 14 and 28 DAA. Tillers were counted and aboveground biomass was collected at 28 DAA. Heights, tillers, and biomass are reported relative to the nontreated.

Statistical analyses. All data from each experiment was analyzed in SAS 9.4 (SAS Institute, Cary, NC 27513) using the GLIMMIX procedure. Each cultivar in the field experiment was analyzed separately by location because of differences in environmental conditions during and after application as well as differences in number of days between sequential applications for both locations. A beta distribution was assumed for injury data (Gbur et al. 2012). Due to a significant Shapiro-Wilke test, a gamma distribution was assumed for yield and percent groundcover (Gbur et al. 2012). Because of the large number of zero days delayed in 50% heading, formal analysis was not performed on heading data. Thus, delay in 50% heading data are reported with mean and standard error. Cultivars were analyzed separately in the greenhouse and growth chamber experiments as well. Again, a beta distribution was assumed for injury and a gamma distribution was assumed for height, tiller number, and biomass. Replication and runs were considered random effects with replication nested within run. All data were subject to analysis of variance using Fisher’s protected least significant difference (α=0.05) to separate means when appropriate. P-values from the field experiment are provided in Table 1 and p-values from the growth chamber and greenhouse experiments are provided in Table 2.

Results and Discussion

Long-grain variety. The field experiment conducted on CL111 showed florpyrauxifen-benzyl had little effect on this variety. In the field experiment, CL111 was injured less than 10% at 3 weeks after sequential applications (WAA) of florpyrauxifen-benzyl, regardless of herbicide rate

(Table 3). Additionally, no treatment had a significant reduction in groundcover from the nontreated at 1 or 3 WAA at either location. Additionally, there was no more than a 1.5-day delay in 50% heading, and there was no reduction in yield (Table 4).

Visible injury recorded in the temperature experiment in the growth chamber was consistent with the field experiment, with no more than 9% injury 14 DAA (Table 5). However, plant heights recorded 28 DAA showed those treated with florpyrauxifen-benzyl at 60 g ae ha^{-1} were 84% of the nontreated control, while plants treated with 30 g ae ha^{-1} were 87% of the nontreated control, averaged over temperature (Table 5). Regardless of the differences in height, there was no reduction in number of tillers or biomass collected 28 DAA (Table 5). This suggests applications of florpyrauxifen-benzyl to CL111 will not have lasting negative effects.

While initial applications in the field and the growth chamber experiments were made to 2- to 3-leaf rice, the experiment in the greenhouse explored the influence of growth stage on injury. In the growth stage experiment, 17% injury was observed 14 DAA when florpyrauxifen-benzyl was applied to 1-leaf rice, averaged over rate (Table 5). While this was the highest injury observed in the growth stage experiment, it is important to note the label restricts florpyrauxifen-benzyl applications to 2-leaf or larger rice (Anonymous 2017). The levels of injury associated with applications made to 3- and 5-leaf rice are consistent with both the sequential application field experiment and the growth stage experiment, suggesting that florpyrauxifen-benzyl causes low risk for high levels of visible injury to CL111.

There was a slight reduction from the nontreated control in height, tiller production, and biomass associated with florpyrauxifen-benzyl treatments in the growth stage experiment (Table 5). Height 14 DAA was reduced from the nontreated control when florpyrauxifen-benzyl was applied at the 1-leaf growth stage (Table 5). There was over 20% reduction in tillers associated with applications made to 1-leaf plants, regardless of florpyrauxifen-benzyl rate (Table 5). Additionally, biomass was reduced by florpyrauxifen-benzyl at 60 g ae ha^{-1} at all growth stages tested, indicating injury may not always be detected visually (Table 5). Florpyrauxifen-benzyl applied at 30 g ae ha^{-1} to 1-leaf rice plants also reduced biomass. However, the herbicide product label indicates plants must be at least 2-leaf before applying florpyrauxifen-benzyl, thus the reductions in height, tillers, and biomass observed when the herbicide is applied at the 1-leaf stage are unlikely to be problematic in production scenarios.

It is possible that differences in the level of injury observed in the temperature and growth stage experiments versus the field experiment are the result of lower light quantity. Sunlight on a clear day in the summer months often exceeds 2,000 µmols m^{-2} s^{-1}; however, this level of light intensity drastically decreases on a cloudy day, which in turn decreases photosynthesis and herbicide metabolism (Bazzaz and Carlson 1982). Light quantity in the temperature experiment conducted in the growth chambers was near 500 µmols m^{-2} s^{-1}. Though light in the greenhouse was supplemented with a light-emitting diode system on a 16-hour photoperiod, low light was likely in the greenhouse because the experiment was conducted in winter months. Bond and Walker (2012) attributed the decrease in the translocation and metabolism of quinclorac in rice to lower solar radiation, or light intensity. Further, Pritchard and Warren (1980) documented a reduction in tomato (*Solanum lycopersicum* L.), velvetleaf (*Abutilon theophrasti* Medik.), and jimsonweed (*Datura stramonium* L.) tolerance to metribuzin when plant were shaded prior to herbicide application. In that study, light intensity was reduced 76% by using a shade cloth. This reduction in light intensity is equivalent to a moderately cloudy day (Pritchard and Warren 1980). The study from Prichard and Warren (1980) also attributed reduced herbicide metabolism to a reduction in the formation of metabolic carbohydrates as a result in a decrease in photosynthesis. Thus, the low light intensity conditions observed in the greenhouse and growth chamber studies conducted in this research likely affected florpyrauxifen-benzyl metabolism, leading to a decrease in height and biomass.

Based on these three experiments, it is concluded that the long-grain variety CL111 exhibits sufficient tolerance to florpyrauxifen-benzyl. Low levels of visible injury, little impact on groundcover, no more than a 1.5-day delay in heading, and no yield loss lead to the conclusion that sequential applications of florpyrauxifen-benzyl do not cause serious, lasting impacts on CL111 when applied at the 2-leaf growth stage with a minimum of 14 days between applications.

Medium-grain variety. Numerically, ‘CL272’ was injured more at RREC than at PTRS. Injury was no more than 11% at PTRS at 3 WAA whereas up to 50% injury was observed at RREC (Table 6). However, at RREC, applications made 14 days apart, the minimum length of time required by the label, resulted in only 15% injury (Table 6). Florpyrauxifen-benzyl applied more than 20 days apart injured rice less than 5%. Yield of CL272 was not reduced at either site, which is not surprising considering there was no more than a 3-day delay in 50% heading (Table 7).

Injury of CL272 rice in the temperature experiment was consistent with injury at PTRS in the field experiment (Table 8). Although little injury was observed, height and biomass were reduced by florpyrauxifen-benzyl. Generally, height and biomass were reduced at least 20% and 13%, respectively, compared to the control, regardless of rate and temperature (Table 8).

In the growth stage experiment conducted in the greenhouse, injury to CL272 at 14 DAA was highest when applied to 1-leaf plants (46%) when averaged over florpyrauxifen-benzyl rate, with injury generally decreasing as applications were delayed (Table 8). Although injury in this experiment was generally higher than the field and growth chamber experiments, it is expected since applications in those experiments were made to 2- to 3-leaf rather than 1-leaf rice. In a weed control experiment from Teló et al. (2018), fall panicum control (*Panicum dichotomiflorum* Michx.) was higher when florpyrauxifen-benzyl was applied at 30 g ae ha^{-1} to 3- to 4-leaf rice as opposed to larger, 1- to 2-tiller rice. This may be applied to rice as well, though rice is more tolerant to florpyrauxifen-benzyl than fall panicum. When rice plants are small, they will be more affected by an application of florpyrauxifen-benzyl than when plants are larger, likely due to an increase in plant growth and metabolism.

Additionally, there was no reduction in rice height 14 DAA from any treatment, except those applied to 1-leaf rice (Table 8). As in the temperature experiment, biomass of plants treated with florpyrauxifen-benzyl was significantly reduced from the nontreated; biomass of plants treated with 30 g ae ha^{-1} was 74% of the nontreated, and biomass from plants treated with 60 g ae ha^{-1} was 62% of the nontreated, averaged over growth stage (Table 8).

These results indicate that CL272 can potentially recover from early-season injury. However, considering the high level of injury at RREC, growers should abide by the 14-day interval between applications to minimize negative effects on the crop. Based on these data, injury appears to be exacerbated by warmer temperatures; however, plants recover more quickly under relatively warmer compared to cooler temperatures. This was observed in the field experiment at RREC, a period of warm temperatures between May 29 and June 4 (average high temperature 33 C) caused greater than expected injury from applications made May 28 and 31 (Table 6; Figure 1a, b).

Long-grain hybrid. At PTRS, CLXL745 injury 3 weeks after florpyrauxifen-benzyl was applied 5 days apart was 34%, averaged over herbicide rate. However, applications made 4 days apart at RREC resulted in 64% injury when averaged over herbicide rate (Table 9). Injury decreases as there is more time between sequential applications; however, at RREC 17% injury was still observed 3 WAA when applications were made 14 days apart, averaged over rate (Table 9).

There was a significant reduction inCLXL745 rice groundcover relative to the nontreated control 1 WAA at both locations ($P=0.0008$ at PTRS, $P<0.0001$ at RREC). At PTRS, sequential applications of florpyrauxifen-benzyl at 60 g ae ha^{-1} made 5 and 13 days apart resulted in 47% and 76% groundcover relative to the nontreated, respectively, while sequential applications of 60 g ae ha^{-1} made 4 days apart resulted in 29% groundcover (Table 10).

In this experiment, yields for most treatments were significantly reduced from the nontreated, even treatments where label directions were followed (Table 10). At PTRS, CLXL745 grain yields following treatments where florpyrauxifen-benzyl was applied sequentially at 30 g ae ha^{-1} 18 days apart or 60 g ae ha^{-1} 21 days apart were not significantly less than the nontreated. Additionally, at RREC, applications made 4 days apart at both rates were not significantly less than the nontreated. This could be due to rice plants having additional time to recover from injury before harvest compared to the other treatments, however because this is inconsistent with results from PTRS, further research is needed to confirm. Yield reduction from herbicide applications has been observed in other studies as well. Mid-season herbicide injury from quinclorac has been shown to reduce yield up to 19% for another hybrid ‘XL723’ (Bond and Walker 2012). Yield reductions coupled with injury data lead to the conclusion that CLXL745 is particularly sensitive to sequential applications of florpyrauxifen-benzyl.

In the temperature experiment, injury was 25% at 14 DAA for florpyrauxifen-benzyl at 60 g ae ha^{-1} applied to plants maintained at 32/24 C (Table 11). Injury for all other treatments was less than 10%. By 28 DAA, no more than 10% injury was observed, indicating plants had begun to recover. Recovery is also reflected in heights of CLXL745 at 28 DAA, where heights of plants treated with florpyrauxifen-benzyl in the 32/24 C growth chamber were not different than those of nontreated plants (Table 11). Heights of treated plants, regardless of rate, were reduced from the nontreated plants in the 27/18 C growth chamber, however this difference was numerically small (Table 11). This suggests plants may recover more quickly under warmer growing conditions Since differences were slight, temperature appears to have a minimal effect on hybrid recovery from florpyrauxifen-benzyl injury. Additionally, biomass was reduced for plants treated with florpyrauxifen-benzyl for both rates when averaged over temperature, further suggesting that CLXL745 is sensitive to florpyrauxifen-benzyl.

Injury in the growth stage experiment was highest 14 DAA when florpyrauxifen-benzyl was applied at 60 g ae ha^{-1} to 1- and 3-leaf rice plants, (43% and 30% injury, respectively) (Table 11). By 28 DAA, injury was highest for plants treated at 1-leaf and 3-leaf averaged over rate, with 27% and 18%, respectively, while injury for plants treated at the 5-leaf stage was only 5% (Table 11). There was a height reduction 28 DAA in plants treated at the 5-leaf growth stage, which can be attributed to a shift in resources due to tillering (Table 11). There was also a reduction in height for plants treated with the 60 g ae ha^{-1} rate at the 1- and 3-leaf stage. Additionally, biomass was reduced only from rice treated with florpyrauxifen-benzyl applied at 60 g ae ha^{-1} averaged over growth stage ($P = 0.0003$; Table 11). These data suggest that as rice plants are larger, they can metabolize and detoxify florpyrauxifen-benzyl better than when plants are smaller, however, florpyrauxifen-benzyl is still injurious to CLXL745, resulting in height and biomass reduction.

These experiments lead to the conclusion that a single application of florpyrauxifen-benzyl, especially made at the standard field rate of 30 g ae ha^{-1}, does not cause high levels of injury to rice and can be utilized on CLXL745 when plants are larger than 1 leaf. However, florpyrauxifen-benzyl applied sequentially to CLXL745 can reduce grain yields, indicating only a single application of the herbicide should be used per season on this cultivar.

Discussion. It is important to note that most biomass collected from plants treated with florpyrauxifen-benzyl was reduced from the nontreated, which is seemingly in contrast to data from the field experiment. However, in the field experiment, plants had several months to recover from florpyrauxifen-benzyl injury, while plants in the growth chamber had only one month before biomass was collected. Additionally, the herbicide may have been metabolized more slowly in these experiments because of the low light quantity. Research conducted using 2,4-D, another auxinic herbicide, showed that by increasing the light intensity, translocation of the herbicide was increased (Schultz and Burnside 1980). Future research is needed to evaluate the impact of light quantity on the propensity for florpyrauxifen-benzyl to injure rice. This could be significant if there are many cloudy days in a growing season, which could prolong the effects of herbicide injury and reduce plant vigor, resulting in lower yields and greater weed pressure due to reduced groundcover (Norsworthy 2004).

Because a symptom of florpyrauxifen-benzyl injury is leaf malformation evidenced by rolled leaves, this may be a contributing factor to the reduction in biomass seen. Additionally, stems are an important factor in rice lodging resistance (Kashiwagi et al. 2008; Zuber et al. 2001), and damaged stems could cause rice to lodge. Further research is necessary to ensure there is not an increased risk of lodging when florpyrauxifen-benzyl is applied to CLXL745, since this cultivar was most injured by the herbicide.

These experiments explored various factors that could affect injury and rice yield; however, the herbicide label dictates florpyrauxifen-benzyl may be applied at 30 g ae ha^{-1} per application, with two applications allowed per season to 2- leaf or larger rice, and a minimum of 14 days between applications (Anonymous 2017). The label also warns that medium-grain varieties and long-grain hybrids are more sensitive to florpyrauxifen-benzyl, and the findings in these experiments for medium-grain variety CL272 and long-grain hybrid CLXL745 support the label recommendations. Montgomery et al. (2014) reported that hybrid CLXL745 and medium-grain varieties ‘Caffey’ and ‘CL261’ were more sensitive to saflufenacil and carfentrazone than two long-grain cultivars. This was also observed by Pantone and Baker (1992) with injury from triclopyr at 800 g ae ha^{-1} applied to different cultivars.

Rice growers should expect some level of injury when sequential applications of florpyrauxifen-benzyl are applied to CL272 and CLXL745. Because injury coupled with reductions in yield for CLXL745, sequential applications of florpyrauxifen-benzyl are not recommended. Since CLXL745 is particularly sensitive to florpyrauxifen-benzyl, further research should be conducted to determine if other hybrids exhibit injuries similar to those observed in these experiments. Additionally, further research should be conducted to determine if there is yield loss associated with labeled sequential applications of florpyrauxifen-benzyl to other hybrids.

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Tables and Figures

Table 1. P-values for the long-grain variety CL111, the medium-grain variety CL272, and the long-grain hybrid CLXL745 at the Pine Tree Research Station (PTRS) near Colt, AR, and the Rice Research and Extension Center (RREC) near Stuttgart, AR, in 2018 for florpyrauxifen-benzyl rate and number of days between sequential applications. [a,b]

		PTRS					RREC				
		Injury		Yield	Relative groundcover		Injury		Yield	Relative groundcover	
Variety	Factor	2 WAA	3 WAA		1 WAA	3 WAA	2 WAA	3 WAA		1 WAA	3 WAA
		--- p-value ---									
CL111	Rate	0.1769	0.1616				0.0477*	0.0142*			
	Days	0.1881	0.1651				0.8193	0.0018*			
	Rate x days	0.3915	0.4472	0.5021	0.1158	0.1647	0.5097	0.3957	0.6533	0.6577	0.9043
CL272	Rate	<0.0001*	0.2138				0.1051	0.0423*			
	Days	<0.0001*	0.0026*				0.0363*	<0.0001*			
	Rate x days	0.1047	0.4488	0.2397	0.2451	0.6408	0.4368	0.2153	0.2385	0.1691	0.2702
CLXL 745	Rate	0.0024*	0.0012*				0.0029*	0.0522			
	Days	0.1103	<0.0001*				0.0002*	<0.0001*			
	Rate x days	0.3853	0.2459	0.0366*	0.0008*	0.1593	0.1325	0.9458	0.0254*	<0.0001*	0.5508

[a] Abbreviation: WAA, weeks after application

[b] * indicates significance at P=0.05

Table 2. P-values for the long-grain variety CL111, medium-grain variety CL272, and long-grain hybrid CLXL745 for injury, height, tiller number, and biomass for the growth chamber and greenhouse experiments. [a,b]

Variety	Experiment	Factor	Injury		Height		Tillers	Biomass
			14 DAA	28 DAA	14 DAA	28 DAA		
				----------------------------- p-value -----------------------------				
CL111	Growth chamber	Temperature	0.3680	0.4191	0.3416	0.0658	0.4074	0.2259
		Rate	0.0016*	0.0367*	0.0004*	<0.0001*	0.0329*	0.6354
		Temperature x rate	0.4808	0.0401*	0.8486	0.0750	0.6126	0.6509
	Greenhouse	Stage	<0.0001*	0.0021*	0.0006*	0.0112*	<0.0001*	0.1156
		Rate	<0.0001*	0.0347*	0.0021*	0.2763	0.3897	0.0007*
		Stage x rate	0.3901	0.0015*	0.0186*	0.0635	0.0138*	0.0198*
CL272	Growth chamber	Temperature	0.0669	0.1915	0.0061*	<0.0001*	0.1496	0.0004*
		Rate	0.0406*	0.0695	0.5096	<0.0001*	0.3754	0.0008*
		Temperature x rate	0.0008*	0.0279*	0.4517	<0.0001*	0.5201	0.0217*
	Greenhouse	Stage	<0.0001*	0.4594	<0.0001*	0.0390*	0.5314	0.2121
		Rate	0.0359*	<0.0001*	<0.0001*	0.0003*	0.1382	<0.0001*
		Stage x rate	0.7766	0.5063	<0.0001*	0.1889	0.9559	0.7015
CLXL745	Growth chamber	Temperature	0.1223	0.9371	0.0115*	<0.0001*	0.1197	0.5640
		Rate	0.0027*	0.1610	0.4894	0.4192	0.3496	0.0056*
		Temperature x rate	0.0038*	0.0458*	0.2956	0.0080*	0.6941	0.2013
	Greenhouse	Stage	<0.0001*	0.0004*	0.0086*	<0.0001*	0.2520	0.9701
		Rate	0.0002*	0.0117*	<0.0001*	0.0090*	0.1526	0.0003*
		Stage x rate	0.0025*	0.2828	0.1552	0.0094*	0.0549	0.0935

[a] Abbreviation: DAA, days after application

[b] * indicates significance at P=0.05

Table 3. Injury for CL111 at the Rice Research and Extension Center (RREC) near Stuttgart, AR in 2018 as influenced by florpyrauxifen-benzyl rate and number of days between sequential applications. [a,b,c]

		Injury RREC			
Factor		2 WAA		3 WAA	
		----------------- % -----------------			
Rate	30 fb 30	5	b	1	b
	60 fb 60	11	a	4	a
Days	4			7	a
	11			3	b
	14			3	b
	20			<1	c

[a] Abbreviations: WAA, weeks after second application; fb, followed by

[b] Florpyrauxifen-benzyl rate is reported in g ae ha^{-1}

[c] Means are separated using Fisher's protected least significant difference (α=0.05). Means with the same letter within a factor and column are not significantly different.

Table 4. Heading and grain yield of the long-grain variety CL111 at the Pine Tree Research Station (PTRS) near Colt, AR and the Rice Research and Extension Center (RREC) near Stuttgart, AR. [a,b,c,d]

Location	Florpyrauxifen-benzyl rate	Days between sequential applications	Delay in 50% heading		Grain yield
	g ae ha^{-1}		---days---		kg ha^{-1}
PTRS	Nontreated		-	-	7,490
	30 fb 30	5	1.0	(1.2)	8,500
		13	0	(0)	8,410
		18	1.5	(1.9)	7,110
		21	1.3	(1.9)	7,660
	60 fb 60	5	1.0	(0.8)	7,940
		13	0.5	(0.6)	7,370
		18	1.5	(0.6)	6,990
		21	1.3	(1.9)	7,480
					NS
RREC	Nontreated		-	-	8,510
	30 fb 30	4	1.0	(1.4)	7,690
		11	0.8	(1.0)	7,470
		14	1.0	(0.8)	7,760
		20	1.0	(1.4)	8,030
	60 fb 60	4	1.0	(1.2)	8,260
		11	1.0	(0.8)	8,640
		14	1.5	(1.0)	8,440
		20	1.3	(0.5)	7,040
					NS

[a] Mean followed by standard error in parenthesis

[b] NS indicates no significant difference

[c] - represents nontreated delay in heading as 0

[d] Abbreviation: fb, followed by

Table 5. Injury, height, tiller number, and biomass for the long-grain variety CL111 as influenced by day/night temperature regime and florpyrauxifen-benzyl rate for the growth chamber experiment and growth stage at application and florpyrauxifen-benzyl rate for the greenhouse experiment. [a,b,c,d,e]

	Factor		Injury		Height		Tiller	Biomass
			14 DAA	28 DAA	14 DAA	28 DAA		
			% of nontreated					
Growth chamber	Temperature	27/18						
		32/24						
	Rate	nontreated	-		100 b	100 a	100 b	
		30	3 b	2 b	114 a	87 b	104 ab	
		60	9 a	4 a	112 a	84 c	114 a	
	Temperature x rate	27/18 nontreated	-					
		27/18 x 30		1 b				
		27/18 x 60		6 a				
		32/24 nontreated	-					
		32/24 x 30		3 b				
		32/24 x 60		3 b				
Greenhouse	Stage	1-leaf	17 a		81 b	97 ab	85 c	
		3-leaf	12 b		99 a	102 a	110 a	
		5-leaf	6 c		93 a	91 b	95 b	
	Rate	nontreated	-		100 a			100 a
		30	8 b		84 b			81 b
		60	15 a		89 b			71 b
	Stage x rate	1-leaf nontreated	-		100 a		100 abc	100 ab
		1-leaf x 30		15 a	66 c		76 e	55 d
		1-leaf x 60		9 ab	81 b		79 ed	74 bcd
		3-leaf nontreated	-		100 a		100 abc	100 ab

Table 5. Injury, height, tiller number, and biomass for the long-grain variety CL111 as influenced by day/night temperature regime and florpyrauxifen-benzyl rate for the growth chamber experiment and growth stage at application and florpyrauxifen-benzyl rate for the greenhouse experiment. [a,b,c,d,e]

3-leaf x 30	5	cd	99	a	118	a	107	a
3-leaf x 60	11	ab	98	a	113	ab	67	dc
5-leaf nontreated	-		100	a	100	abc	100	ab
5-leaf x 30	4	d	91	ab	90	cde	89	abc
5-leaf x 60	8	bc	89	ab	94	bcd	71	dc

[a] Abbreviation: DAA, days after application;

[b] Florpyrauxifen-benzyl rate is reported in g ae ha^{-1}

[c] Means are separated using Fisher's protected least significant difference (α=0.05). Means with the same letter within a factor and column are not significantly different. Data not shown for some treatments and variables indicate data is not significant.

[d] - represents nontreated data as 0% injury

[e] Height 14 DAA for the nontreated in the 27/18 C growth chamber was 30 cm and 36 cm for the nontreated in the 32/24 C growth chamber Average number of tillers for the nontreated control in both growth chambers was 4. Height at 14 DAA was 38, 41, and 59 cm and at 28 DAA was 45, 47, and 75 cm for 1-, 3-, and 5-leaf growth stages, respectively. Additionally, average number of tillers for the nontreated control of all growth stages was 2. Biomass of the nontreated treatments for 1-, 3-, and 5-leaf growth stages at 28 DAA was 0.35 g, 0.60 g, and 1.80 g, respectively.

Table 6. Injury for the medium-grain variety CL272 at the Pine Tree Research Station near Colt, AR and the Rice Research and Extension Center near Stuttgart, AR in 2018 as influenced by florpyrauxifen-benzyl rate and number of days between sequential applications. [a,b,c]

			Injury	
Location	Factor		2 WAA	3 WAA
			------------ % ------------	
PTRS	Rate	30 fb 30	6 b	
		60 fb 60	15 a	
	Days	5	5 b	11 a
		13	14 a	6 b
		18	17 a	6 b
		21	6 b	3 c
RREC	Rate	30 fb 30		10 b
		60 fb 60		21 a
	Days	4	30 a	50 a
		11	31 a	23 b
		14	25 a	15 b
		20	2 b	2 c

[a] Abbreviations: WAA, weeks after second application; fb, followed by

[b] Florpyrauxifen-benzyl rate is reported in g ae ha^{-1}

[c] Means are separated using Fisher's protected least significant difference (α=0.05). Means with the same letter within a factor and column are not significantly different.

Table 7. Heading and grain yield of the medium-grain variety CL272 at the Pine Tree Research Station (PTRS) near Colt, AR and the Rice Research and Extension Center (RREC) near Stuttgart, AR. [a,b,c,d]

Location	Florpyrauxifen-benzyl rate	Days between sequential applications	Delay in 50% heading		Grain yield
	g ae ha^{-1}		---days---		kg ha^{-1}
PTRS	Nontreated		-	-	8,040
	30 fb 30	5	0.8	(0.5)	7,840
		13	1.3	(1.9)	6,750
		18	0.8	(1.0)	8,170
		21	1.0	(2.0)	8,190
	60 fb 60	5	3.0	(0.8)	8,020
		13	2.8	(1.5)	8,450
		18	2.3	(1.7)	7,380
		21	2.5	(2.1)	7,550
					NS
RREC	Nontreated		-	-	6,400
	30 fb 30	4	1.5	(1.0)	6,290
		11	1.0	(0.8)	6,560
		14	1.3	(1.3)	6,270
		20	2.3	(2.8)	5,990
	60 fb 60	4	2.3	(1.5)	6,660
		11	2.5	(1.9)	7,190
		14	2.0	(2.7)	5,840
		20	1.5	(2.4)	5,880
					NS

[a] Mean followed by standard error in parenthesis

[b] NS indicates to significant difference

[c] - represents nontreated delay in heading as 0

[d] Abbreviation: fb, followed by

Table 8. Injury and height for the medium-grain variety CL272 in the grow chamber experiment as influenced by day/night temperature regime and florpyrauxifen-benzyl rate and by growth stage and florpyrauxifen-benzyl rate in the greenhouse experiment. [a,b,c,d,e]

	Factor		Injury		Height		Biomass
			14 DAA	28 DAA	14 DAA	28 DAA	
			% of nontreated				
Growth chamber	Temperature	27/18			104 a	79 b	82 b
		32/24			98 b	85 a	95 a
	Rate	nontreated	-			100 a	100 a
		30	9 b			74 b	81 b
		60	13 a			72 c	86 b
	Temperature x rate	nontreated	-			100 a	100 a
		27/18 x 30	11 b	4 b		73 d	76 b
		27/18 x 60	8 b	5 b		64 e	72 b
		nontreated	-			100 a	100 a
		32/24 x 30	8 b	2 b		76 c	86 ab
		32/24 x 60	18 a	15 a		80 b	100 a
Greenhouse	Stage	1-leaf	46 a		67 b	96 ab	
		3-leaf	24 b		96 a	98 a	
		5-leaf	14 c		92 a	89 b	
	Rate	nontreated	-		100 a	100 a	100 a
		30	22 b	12 b	77 b	96 a	74 b
		60	30 a	26 a	77 b	87 b	62 b
	Stage x rate	1-leaf nontreated			100 a		
		1-leaf x 30			52 b		
		1-leaf x 60			58 b		

Table 8. Injury and height for the medium-grain variety CL272 in the grow chamber experiment as influenced by day/night temperature regime and florpyrauxifen-benzyl rate and by growth stage and florpyrauxifen-benzyl rate in the greenhouse experiment. [a,b,c,d,e]

3-leaf nontreated	100	a
3-leaf x 30	98	a
3-leaf x 60	90	a
5-leaf nontreated	100	a
5-leaf x 30	91	a
5-leaf x 60	87	a

[a] Abbreviation: DAA, days after application

[b] Florpyrauxifen-benzyl rate is reported in g ae ha^{-1}

[c] Means are separated using Fisher's protected least significant difference (α=0.05). Means with the same letter within a factor and column are not significantly different. Data not shown for some treatments and variables indicate data is not significant.

[d] - represents nontreated data as 0% injury

[e] Height and biomass collected at 28 DAA for the nontreated of the 27/18 C growth chamber was 35 cm, 4, and 1.80 g, respectively, and for the nontreated of the 32/24 C growth chamber 44 cm, 3, and 1.60 g, respectively. Height 14 DAA was 51, 55, and 67 cm and 28 DAA was 60, 61, and 82 cm for the nontreated control of 1-, 3-, and 5-leaf growth stages. Biomass for the nontreated control at the 1-, 3-, and 5-leaf growth stages was 0.40 g, 0.95 g, and 1.60 g at 28 DAA, respectively in the greenhouse experiment.

Table 9. Injury for the long-grain rice hybrid CLXL745 at the Pine Tree Research Station near Colt, AR at the Rice Research and Extension Center near Stuttgart, AR in 2018 as influenced by florpyrauxifen-benzyl rate and number of days between sequential applications. [a,b,c,d]

Location	Factor		Injury			
			2 WAA		3 WAA	
			---------------- % ----------------			
	Rate	30 fb 30	5	b	9	b
		60 fb 60	24	a	22	a
PTRS	Days	5			34	a
		13			17	b
		18			10	bc
		21			6	c
	Rate	30 fb 30	24	b		
		60 fb 60	46	a		
RREC	Days	4	66	a	64	a
		11	24	b	13	b
		14	30	b	17	b
		20	22	b	1	c

[a] Abbreviations: WAA, weeks after second application; fb, followed by

[b] Florpyrauxifen-benzyl rate is reported in g ae ha^{-1}

[c] Means are separated using Fisher's protected least significant difference (α=0.05). Means with the same letter within a factor and column are not significantly different.

Table 10. Heading and grain yield of the long-grain rice hybrid CLXL745 at the Pine Tree Research Station (PTRS) near Colt, AR and the Rice Research and Extension Center (RREC) near Stuttgart, AR.[a,b,c,d,e,f]

Location	Florpyrauxifen-benzyl rate	Days between sequential applications	Delay in 50% heading	Grain yield	Relative groundcover 1 WAA
	g ae ha^{-1}		---days---	kg ha^{-1}	%
PTRS	Nontreated		- -	11,180 a	100 a
	30 fb 30	5	1.0 (1.4)	9,910 bc	90 ab
		13	0.8 (1.0)	9,910 bc	101 a
		18	0 (0)	10,530 ab	107 a
		21	0.3 (0.5)	9,080 c	89 ab
	60 fb 60	5	7.0 (1.4)	9,180 c	47 c
		13	4.0 (2.3)	9,930 bc	76 b
		18	2.3 (3.2)	9,460 bc	88 ab
		21	3.0 (2.2)	10,270 abc	85 ab
				P = 0.0366	P = 0.0008
RREC	Nontreated		- -	12180 a	100 a
	30 fb 30	4	4.0 (2.9)	10730 ab	76 a
		11	1.0 (1.4)	8500 c	107 a
		14	0.8 (0.5)	9130 bc	111 a
		20	1.8 (2.2)	9590 bc	110 a
	60 fb 60	4	6.5 (3.4)	10370 ab	29 b
		11	3.3 (4.6)	9780 bc	106 a
		14	3.0 (2.0)	9600 bc	96 a
		20	3.3 (4.6)	9980 bc	106 a
				P = 0.0254	P < 0.0001

[a] Means followed by standard error in parenthesis

[b] Percent groundcover for the nontreated was 82% and 88%, respectively at PTRS and RREC.

[c] NS indicates no significant difference

[d] - represents nontreated delay in heading as 0

[e] Abbreviation: fb, followed by

[f] Means are separated using Fisher's protected least significant difference (α=0.05). Means with the same letter within a factor and column are not significantly different.

Table 11. Injury and height for the long-grain rice hybrid CLXL745 in the growth chamber experiment as influenced by day/night temperature regime and florpyrauxifen-benzyl rate and florpyrauxifen-benzyl rate and by growth stage and florpyrauxifen-benzyl rate in the greenhouse experiment. [a,b,c,d,e]

			Injury		Height		
	Factor		14 DAA	28 DAA	14 DAA	28 DAA	Biomass
			----- % of nontreated -----				
Growth chamber	Temperature	27/18			96 b	96 b	
		32/24			101 a	102 a	
	Rate	nontreated	-				100 a
		30	6 b				87 b
		60	17 a				81 b
	Temperature x rate	27/18 nontreated	-			100 ab	
		27/18 x 30	9 b	8 ab		93 c	
		27/18 x 60	9 b	8 ab		96 bc	
		32/24 nontreated	-			100 ab	
		32/24 x 30	4 b	6 b		102 a	
		32/24 x 60	25 a	10 a		104 a	
Greenhouse	Stage	1-leaf		27 a	85 ab	100 a	
		3-leaf		18 a	78 b	100 a	
		5-leaf		5 b	93 a	79 b	
	Rate	nontreated	-		100 a	100 a	100 a
		30		10 b	82 b	92 ab	92 a
		60		20 a	75 b	85 b	76 b
	Stage x rate	1-leaf nontreated	-			100 a	
		1-leaf x 30	13 cd			108 a	
		1-leaf x 60	43 a			92 a	
		3-leaf nontreated	-			100 a	

Table 11. Injury and height for the long-grain rice hybrid CLXL745 in the growth chamber experiment as influenced by day/night temperature regime and florpyrauxifen-benzyl rate and florpyrauxifen-benzyl rate and by growth stage and florpyrauxifen-benzyl rate in the greenhouse experiment. [a,b,c,d,e]

3-leaf x 30	18	c		102	a
3-leaf x 60	30	a		97	a
5-leaf nontreated			-	100	a
5-leaf x 30	11	cd		71	b
5-leaf x 60	10	d		70	b

[a] Abbreviation: DAA, days after application

[b] Florpyrauxifen-benzyl rate is reported in g ae ha^{-1}

[c] Means are separated using Fisher's protected least significant difference (α=0.05). Means with the same letter within a factor and column are not significantly different. Data not shown for some treatments and variables indicate data is not significant.

[d] - represents nontreated data as 0% injury

[e] Height 28 DAA for the nontreated of the 27/18 C growth chamber was 49 cm and 42 cm for the nontreated of the 32/24 C growth chamber. Height 14 DAA was 45, 54, and 64 cm and 28 DAA was 56, 61, and 78 cm for the nontreated s of 1-, 3-, and 5-leaf growth stages. Biomass for the nontreated s at the 1-, 3-, and 5-leaf growth stages was 0.70 g, 1.50 g, and 2.10 g at 28 DAA, respectively in the greenhouse experiment

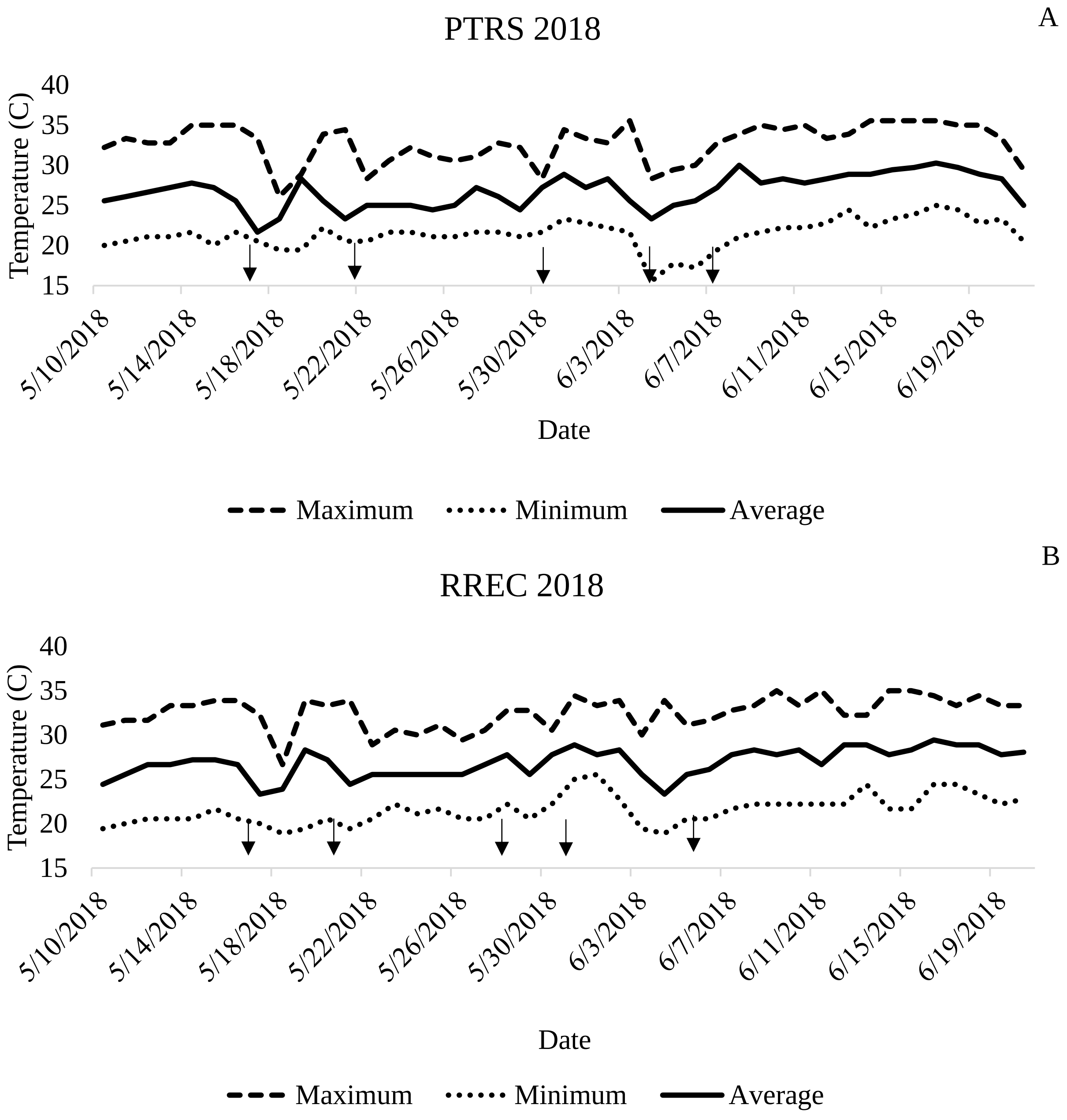

Figure 1a, b. Daily minimum, maximum, and average temperatures (A) at the Pine Tree Research Station near Colt, AR, in 2018 and (B) the Rice Research and Extension Center (RREC) near Stuttgart, AR, in 2018 for dates ranging from 7 days before first florpyrauxifen-benzyl application to 14 days after the second florpyrauxifen-benzyl. Rice cultivars CL111, CL272, and CLXL745 were planted on April 19, 2018 at PTRS and RREC. The first florpyrauxifen-benzyl application was made to 2- to 3-leaf rice on May 17, 2018 at both locations. Sequential applications were made May 22, May 30, June 4, and June 7 at PTRS and May 21, May 28, May 31, and June 6 at RREC. Application dates are indicated by an arrow.

General Conclusions

Florpyrauxifen-benzyl will provide a much-needed herbicide rotation option for Palmer amaranth control in furrow-irrigated rice and on rice levees. When used in conjunction with residual herbicides in a full season program, the addition of florpyrauxifen-benzyl improves late season Palmer amaranth control over the current standard program. On rice levees, florpyrauxifen-benzyl provides comparable weed control to the current standard 2,4-D, providing an effective option for broadleaf weed control on Arkansas rice levees in areas where 2,4-D is restricted. Generally, the long-grain variety CL111 exhibited the most tolerance to florpyrauxifen-benzyl, while the long-grain hybrid CLXL745 was most sensitive to the herbicide. The addition of an acetolactate synthase-inhibiting herbicide to a florpyrauxifen-benzyl application did not result in higher levels of injury, indicating florpyrauxifen-benzyl can be incorporated into Clearfield® rice production systems, thus providing another herbicide option for growers. Further, applying florpyrauxifen-benzyl with a cytochrome P450-inhibiting insecticide did not cause additional injury to rice, suggesting there is not an increased risk for injury when these are applied together. Sequential applications of florpyrauxifen-benzyl resulted in higher levels of injury for all cultivars when applications were made temporally close together, however there were no negative effects on yield for the long-grain variety CL111 or the medium-grain variety CL272. Yields were only reduced for the long-grain hybrid CLXL745, indicating sequential florpyrauxifen-benzyl applications are not safe for this cultivar. Additionally, there appears to be an increased risk for injury when temperatures are warmer, however plants can recover from this injury. Generally, applications made to 1-leaf rice plants resulted in higher levels of injury compared to applications made to 3- or 5-leaf plants. The florpyrauxifen-benzyl rate of 30 g ae ha^{-1} did not cause substantial levels of injury to the long-grain variety CL111 or the medium-grain variety CL272. Only sequential applications at this rate resulted in reduced yield for the long-grain hybrid CLXL745, indicating that only one application per growing season is safe for this cultivar.