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Evaluation of Benzobicyclon in Midsouth Rice (Oryza sativa) Production Systems

Jake Patterson
University of Arkansas, Fayetteville

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Evaluation of Benzobicyclon in Midsouth Rice (*Oryza sativa*) Production Systems

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by

Jake Patterson
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Jason K. Norsworthy, Ph.D
Thesis Director

Trenton L. Roberts, Ph.D
Committee Member

Edward E. Gbur, Ph.D
Committee Member

Thomas R. Butts, Ph.D
Committee Member

ABSTRACT

Controlling weedy rice postemergence is challenging for rice producers in the United States because of the lack of herbicide options. Weedy rice is genetically similar to cultivated rice, thus making it difficult to control with mid-season postemergence herbicide applications without also damaging the crop. Hence, there is a need for a new effective postemergence weedy rice control herbicide. Findings from this research indicate that the use of benzobicyclon in current standard quizalofop- and imidazolinone-resistant rice herbicide programs provides tremendous utility for Midsouth rice producers. In both of these production systems, the addition of benzobicyclon to the respective standard herbicide programs resulted in comparable or improved weedy rice control compared to the standard program alone. Additionally, minimal injury was observed from treatments containing the current standard herbicide program followed by the postflood application of benzobicyclon.

To validate that benzobicyclon is a viable weed control option for rice growers, research was conducted to evaluate varietal tolerances of commonly grown rice cultivars to the application of benzobicyclon. Plants are typically more sensitive to herbicides when they are small, and that sensitivity tends to decrease as the plant produces more vegetative growth. In the first year of this research, 4-leaf and tillering rice exhibited sufficient tolerance to benzobicyclon, whereas 2-leaf rice did not. However, in the second year, all treatments, or combinations of application timing/rice cultivar were not injurious to rice, which was partially attributed to loss of the herbicide from the field as a result of a rainfall event. Some rice cultivars, depending on genealogical lineage, are extremely susceptible to benzobicyclon and other 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibiting herbicides. More specifically, *japonica*-type rice cultivars show much better crop safety to benzobicyclon than *indica*-type or *japonica*- x

indica-type. In this research, the *indica*-type rice cultivar ‘Rondo’ was severely injured, regardless of benzobicyclon application timing.

Since benzobicyclon is a pro-herbicide, it does not directly inhibit HPPD enzymes in plants. Rather, benzobicyclon must undergo (in the presence of water) a non-enzymatic hydrolytic reaction to be converted to the potent and phytotoxic compound benzobicyclon hydrolysate. Therefore, since benzobicyclon requires the presence of water to be phyto-active, it must be applied postflood, and applications will likely occur in proximity to actively growing soybean. In this research, treatments containing benzobicyclon alone, regardless of reduced rate applied, injured soybean ≤8% at 14 days after treatment, indicating that benzobicyclon can be safely applied to rice near soybean with minimal risk for injury to the adjacent crop.

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My passion for weed science began while taking the Principles of Weed Science course at Auburn University instructed by Dr. J Scott McElroy. After excelling in his class, I expressed to him that I would like to explore options for completing an internship in the weed science research field. A few conversations and phone calls later, I was put in contact with Richard ‘Dickie’ Edmund, who at the time was the Field Development Representative for DuPont Crop Protection in Arkansas, North Louisiana, and Southeast Missouri. This led to me being awarded with an internship position in the Summer of 2017 in Arkansas, working for Dickie. That summer, I gained invaluable work experience and field research knowledge from Dickie, which led me to pursue a graduate degree in weed science. Thank you, Dr. McElroy and Dickie, for enabling me to realize that I had found my calling and future career.

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CHAPTER 1

REVIEW OF LITERATURE

Rice Overview. Rice **(***Oryza sativa***)** throughout many parts of the world serves as one of the main food sources for large quantities of people. Like many foreign countries, the adult population in the United States (U.S.) is responsible for consuming a significant portion of rice. Rice consumption in the U.S. has increased over the last several decades to levels upwards of 9.1 kilograms per capita per year (Batres-Marquez and Jensen 2005). Rice production in the U.S. is centered predominantly around the Arkansas Grand Prairie, the Mississippi Delta, Sacramento Valley, California, and the Gulf Coast. Prior to 1973, California, Louisiana, and Texas planted and harvested nearly equal amounts of rice as the state of Arkansas (Talbert and Burgos 2007). In present-day, Arkansas produces approximately half of the total U.S. rice and is the top rice-producing state. In 2018, U.S. rice farmers planted over 1.2 million hectares (2.95 million acres) of rice and of those total U.S. planted hectares, Arkansas was responsible for planting over 583,000 hectares (1.4 million acres) (NASS 2018). A large majority of Arkansas rice hectares are located on the eastern side of the state in the Mississippi River Delta.

Midsouth Rice Production. Rice in the Midsouth is typically planted starting in late March and continues into early June. Planting early is desirable for high-yield potential and optimal milling quality but planting extremely early can be detrimental to the crop. In some cases where cool environmental conditions persist, slow emergence, poor seedling vigor, depredation from birds, and reduced postemergence herbicide efficacy can result (Blanche et al. 2009). In Arkansas, many rice hectares (85%) are drill seeded. Other means of planting such as broadcast seeding, both dry seeded (10%) and water seeded (5%), are used as well but have not been widely adopted by farmers (Hardke 2018). Flood irrigation is the predominant type of irrigation used in

Arkansas rice production. With a flood irrigated system, the permanent flood is usually established when the rice plants reach the 4- to 5-leaf stage, but the rice plants should not be submerged (Blanche et al. 2009). One added benefit of Midsouth rice production predominantly utilizing continuous-flood irrigation practices is the increased suppression of germination and growth of many problematic weeds such as Palmer amaranth (*Amaranthus palmeri*). In addition to weed control, the presence of a continuous flood aids in facilitating optimum growth, reproductive growth, nutrient uptake, and high yields of rice (Beyrouty et al. 1994).

Benzobicyclon Overview. Benzobicyclon, [3-(2-chloro-4-mesylbenzoyl)-2-phenylthiobicyclo [3.2.1] oct-2-en-4-one] is a recently released rice herbicide for use as a postflood option to control Midsouth rice weeds. Currently, 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibiting herbicides do not have a label for use in U.S. rice production. HPPD herbicides, including benzobicyclon, disrupt plastoquinone biosynthesis within the plant causing bleached symptomology on the new growth, followed by chlorosis, and ultimately leading to plant death (Komatsubara et al. 2009). Benzobicyclon is not directly responsible for inhibiting HPPD enzymes in plants (Komatsubara et al. 2009). Rather, benzobicyclon is a pro-herbicide, therefore it must complete a non-enzymatic hydrolytic reaction to convert to the potent and phytotoxic compound benzobicyclon hydrolysate (Williams and Tjeerdema 2016). For this hydrolytic reaction to occur and for benzobicyclon hydrolysate to be formed, water must be present. Benzobicyclon hydrolysate is a triketone and therefore is responsible for the inhibition of HPPD enzymes (Komatsubara et al. 2009). Benzobicyclon was originally discovered by SDS Biotech K.K. in Japan in 2001. In California, benzobicyclon is labeled for use in water-seeded, paddy rice production. The benzobicyclon formulation used in California, produced by Gowan®, contains both benzobicyclon and halosulfuron and is known as Butte®. This benzobicyclon formulation is available as a slow release granular herbicide for use in water-seeded rice (Gowan 2017).

Because benzobicyclon requires the presence of water to convert to benzobicyclon hydrolysate, it is imperative that a continuous flood be present. Additionally, flood depth has an impact on the efficacy of benzobicyclon. Davis et al. (2013) documented that benzobicyclon performed optimally when at least a 10-cm flood depth is present. This is important because most of the rice grown in the Midsouth is paddy rice, albeit drill-seeded. Therefore, benzobicyclon applications will be made aerially.

Benzobicyclon controls a broad spectrum of aquatics, broadleaves, grasses, and sedges, including those currently resistant to the Group 2, acetolactate synthase (ALS)-inhibiting herbicides (Young 2017). Previous research conducted by Sekino et al. (2008) indicated that benzobicyclon provided effective weed control when applied early to small actively growing weeds.

Rice Weed Control. An effective weed control program is imperative in rice production systems. Weed pressure directly and negatively affects yield as well as crop quality. Effective management of weeds requires an understanding of how and when they compete with rice (Scott et al. 2018). Most growers in the Midsouth utilize dry-seeding practices when planting their rice. In many instances, weed competition in dry-seeded rice is so severe that failure to control weeds may result in complete crop failure (Mukhopadhyay 1981). Complete crop failure can most likely be attributed to problematic rice weeds emerging simultaneously with the crop, competing for nutrients, sunlight, and sometimes water, ultimately inhibiting crop growth to detrimental levels. Therefore, early season herbicide applications for weed control is important to achieve high rice yields (De Datta and Herdt 1981). If growers in the Midsouth can adequately control their weeds early in the season, the use of flood irrigation as a cultural weed control practice greatly reduces their risk for weed competition later in the season.

Herbicide resistance is a major issue in many commodity crops, including rice. Weed resistance to the first highly effective rice herbicide, propanil, was first reported in 1989 (Talbert and Burgos 2007). Then, in 1999, resistance to quinclorac was reported in Arkansas (Malik et al. 2010). Currently, herbicide resistance in problematic rice weeds has been documented to many commonly used rice herbicides including quinclorac, bensulfuron, imazethapyr, imazamox, penoxsulam, bispyribac, clomazone, halosulfuron, cyhalofop, florpyrauxifen-benzyl, and propanil (Scott et al. 2018; Barber et al. 2022). Six of these are Group 2 herbicides or ALS-inhibitors. The sole reliance and repeated use of these herbicides over many years has heavily influenced selection for resistance.

Propanil, introduced in 1959, was the first highly effective herbicide used for rice weed control (Talbert and Burgos 2007). Propanil was also the first photosystem II (PSII) herbicide commercially available for use in rice (Smith 1961). Before resistance issues arose in barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.] in 1989, propanil was used to effectively control barnyardgrass, sedges, broadleaf aquatics, and various grasses. Propanil is still used today, but to a much lesser extent.

Shortly after propanil resistance was reported in barnyardgrass, quinclorac was released for use in Midsouth rice production in 1992 (Talbert and Burgos 2007). Quinclorac is a synthetic auxin herbicide that effectively controls susceptible barnyardgrass, large crabgrass [*Digitaria sanguinalis* (L.) Scop.], and other problematic rice weeds. Seven years after its release into Midsouth rice fields, quinclorac-resistant barnyardgrass was reported in 1999 (Malik et al. 2010).

Cyhalofop, fenoxaprop, and quizalofop are all acetyl CoA carboxylase (ACCase)-inhibiting herbicides used in Midsouth rice production. These herbicides are recommended for use in rice to control barnyardgrass, Amazon sprangletop [*Leptochloa panicoides* (J. Presl) McNeill], and other grass weeds. In 2018, quizalofop, or Provisia® herbicide, was released for use in the Midsouth in conjunction with the Provisia® Rice System. Quizalofop can be tank-mixed with other herbicides, but antagonism can be common, therefore it is recommended that broadleaf herbicides be tank-mixed with quizalofop only in the first of two sequential applications (Scott et al. 2018). Quizalofop has utility in Midsouth rice production due to its ability to effectively control ALS-resistant barnyardgrass and weedy rice (*Oryza sativa* L.) (Singh et al. 2017).

Bispyribac, penoxsulam, imazethapyr, bensulfuron, halosulfuron, and imazamox are a few of the ALS-inhibiting herbicides that are currently registered for use in Midsouth rice production. Since the discovery of barnyardgrass with resistance to both propanil and quinclorac, ALS-inhibiting herbicides have been used heavily. This over-dependence on one mode of action has given rise to ALS-inhibitor-resistance in many weed species including barnyardgrass, weedy rice, yellow nutsedge (*Cyperus esculentus* L.), and rice flatsedge (*Cyperus iria* L.), among others (Norsworthy et al. 2013).

Problematic Weeds in Midsouth Rice Production. Among the many problematic weeds in rice production systems, barnyardgrass is one of the most common and detrimental. Barnyardgrass and other *Echinochloa* species have a high degree of genetic diversity and are capable of evolving resistance to a wide range of herbicides and multiple sites of action (Heap 2013). In a survey of Arkansas crop consultants conducted by Norsworthy et al. (2013), 54% of consultants ranked barnyardgrass as the most problematic weed in Arkansas rice production. Barnyardgrass grows extremely well in drill- or water-seeded rice cultures and is very competitive (Talbert and Burgos 2007). Multiple factors are associated with barnyardgrass and its interference in rice. These factors include: density of the weeds, duration of interference, nitrogen fertility levels, the density of the rice crop, and the growth habit of the rice (Talbert and Burgos 2007). Barnyardgrass populations in the Midsouth have evolved resistance to propanil, quinclorac, clomazone, florpyrauxifen-benzyl, and numerous ALS- and ACCase-inhibiting herbicides, (Heap 2013; Barber et al. 2022) leaving growers with limited options for barnyardgrass control.

Weedy rice is the third-most problematic weed in Midsouth rice production behind barnyardgrass and sprangletop (*Leptochloa* spp.) (Norsworthy et al. 2013). Weedy rice has long been one of the most damaging weeds in direct-seeded rice cropping systems throughout the Midsouth (Burgos et al. 2014), causing up to 80% yield loss and reduction of grain quality (Shivrain et al. 2010). Reduced grain quality is common when weedy rice plants are permitted to emerge and actively grow until harvest. Although the degree to which weedy rice competes with cultivated rice for nitrogen (N) is unknown, even if just 50% of applied N fertilizer is removed, yields and economic returns from fertilizer inputs will be greatly diminished (Burgos et al. 2006). Weedy rice is the same species as cultivated rice, making it difficult to control without also damaging the crop (Burgos et al. 2014). Since weedy rice and cultivated rice are so closely related, the risk for herbicide resistance from transgene flow from herbicide-resistant (HR) rice cultivars to weedy rice populations is prevalent (Gressel and Valverde 2009).

Rice Technologies. With the evolution of herbicide resistance to multiple herbicides in problematic Midsouth rice weeds, the need for new technologies to effectively control these weeds became imperative. Midsouth rice producers needed new options to control these weeds mid-season without potentially negatively impacting yields.

In 2002, Louisiana State University commercialized the first two Clearfield rice cultivars, CL121 and CL141, for use in Midsouth rice production (Tan et al. 2005; Sudianto et al. 2013). These cultivars were developed to have tolerance to imidazolinone (IMI) herbicides such as imazethapyr and imazamox. A few years later, more Clearfield cultivars were released with increased IMI herbicide tolerance. Clearfield technology enables growers to make IMI herbicide applications mid-season without the risk for crop injury in most instances. Imazethapyr (Newpath®) has activity on rice weeds when applied either preemergence or postemergence, and when mixed with other herbicides can provide season-long control (Sudianto et al. 2013).

Weedy rice with resistance to ALS-inhibiting herbicides, such as imazethapyr and imazamox, are common today in rice fields across Arkansas. Resistance to this chemistry is mainly attributed to the wide-spread adoption of Clearfield cultivars (nearly 61% of all rice hectares in Arkansas) resulting in significant use of the IMI herbicides (Wilson et al. 2013). Additionally, as a result of the overuse of ALS-inhibiting herbicides in Clearfield rice, Norsworthy et al. (2014) reported that ALS-inhibitor-resistant barnyardgrass had been detected in Arkansas rice fields.

Rising concerns centered around IMI-resistant weedy rice as well as multiple-resistant barnyardgrass prompted BASF to develop a new rice cultivar with resistance to quizalofop, a WSSA Group 1 ACCase-inhibiting herbicide. Unlike many other herbicide-resistant crops, Provisia rice is nontransgenic (Scott et al. 2018). Launched in 2018, the introduction of this new technology provided Midsouth rice growers with another herbicide option for postemergence control of grass species, including weedy rice. Previously, quizalofop was only recommended for postemergence grass control in soybean and cotton (Barber et al. 2022). Quizalofop has no activity on broadleaf weeds or sedges; therefore, to achieve weed-free fields it must be mixed with other herbicides. It is recommended that broadleaf herbicides only be mixed with quizalofop on the first of two sequential applications to alleviate the risk for antagonism and ultimately decreased efficacy with the later application near flood establishment (Scott et al. 2018).

Benzobicyclon & Rice Cultivar Lineage. For benzobicyclon to be a viable weed control option for Midsouth rice growers, research must be conducted to evaluate varietal tolerances of many commonly grown rice cultivars to the application of benzobicyclon. In a study conducted by Kwon et al. (2012), various applications of benzobicyclon at different timings and different rates were made to multiple transplanted rice cultivars. Key symptomology of HPPD herbicides (bleaching and necrosis) were seen on many of the *indica*-type rice cultivars. As reported by Kwon et al. (2012), *japonica*-type rice cultivars show much better crop safety to benzobicyclon than *indica*-type or *japonica*- x *indica*-type. Increased tolerance to benzobicyclon in japonica rice cultivars is important because a vast majority of rice cultivars planted in the U.S. are of japonica origin as opposed to *indica* origin (Burgos et al. 2014). Similar to results observed by Kwon et al. (2012), Young (2017) reported that out of 19 planted japonica-type cultivars, at two different locations in the Midsouth, no injury was observed at one week after the application of benzobicyclon and halosulfuron when applied at the rates of 494 g ha^{-1} and 72 g ha^{-1}, respectively. Conversely, the *indica* cultivars Rondo and Purple Maker were severely injured and high levels of chlorosis were observed when assessed two weeks after treatment (Young 2017). Given the findings by Kwon et al. (2012) and Young (2017), conclusions can be drawn that *indica*-type rice cultivars, or rice cultivars that have a predominant *indica*-type background, will not provide adequate crop safety.

Soybean Sensitivity to Rice Herbicides. Since the evolution of resistance to multiple widely applied herbicides in the Midsouth, options for growers have been somewhat limited. Thus, growers are tasked with constantly changing their herbicide programs to control herbicide-resistant weeds. With the addition of new herbicide options for postemergence control of problematic weeds in rice, an understanding of how these herbicides affect adjacent crops is imperative.

ALS-inhibiting herbicides have been heavily relied upon since the discovery of herbicide resistance to propanil and quinclorac in the Midsouth. The cultivation of Clearfield rice has enabled Midsouth growers to effectively control problematic rice weeds with ALS-inhibiting herbicides. While the use of ALS-inhibiting herbicides in rice has been beneficial to growers for controlling weeds that are resistant to previously extensively used herbicides, there are potential risks associated. Due to many ALS-inhibiting herbicides having activity on soybean, the risk for damage associated with off-target movement is high. Developed by DuPont, sulfonylurea-tolerant-soybean (STS) were released into the market to allow growers to use ALS-inhibiting chemistries mid-season in their soybean crops without causing damage to the crop (Albrecht et al. 2017). STS soybean cultivars may provide additional options for weed control, but other modes of action are commonly used due to many problematic weeds in soybean being resistant to ALS-inhibiting herbicides. Therefore, a majority of Midsouth soybean hectares are susceptible to the ALS-inhibiting herbicides that are being applied to rice fields. With this knowledge, care should be taken to mitigate all off-target movement of herbicides.

Synthetic auxin herbicides have been the foundation that many rice herbicide programs have been built upon for the past several decades. These herbicides have provided growers in the Midsouth with very effective options for control of the most problematic weeds. Auxins such as indole-3-acetic acid (IAA) are an important group of phytohormones responsible for regulating cell division, tropic responses, and cell elongation (Grossmann 2009). Synthetic auxin herbicides, except for quinclorac and florpyrauxifen-benzyl, are only selective to dicot weeds and are translocated systemically throughout the plant (Grossmann 2009). When applied at low doses, in some plants, synthetic auxin herbicides have stimulated plant growth, but at high concentrations, plant growth is disturbed, and lethal damage can be caused (Grossmann 2009). Synthetic auxin herbicides have been used in rice for many years and will continue to be used since the release of florpyrauxifen-benzyl (Loyant), for use in Midsouth rice production. These herbicides pose risks to adjacent soybean due to their capacity to injure the crop at low doses. As with any herbicide application, extra care must be taken to alleviate the risk for off-target movement.

HPPD-inhibiting herbicides have activity on problematic weeds by blocking an enzyme within the plant that is responsible for forming carotenoids, which protect chlorophyll from powerful UV light (Dunne 2012). Although HPPD-inhibiting herbicides tend to be most phyto-active on broadleaves or dicots, they also have activity on some grasses. The triketone herbicide family inhibits HPPD. Triketone herbicides will readily persist in the soil and can potentially cause damage to subsequent crops (Riddle et al. 2013). The subsequent damage caused by these herbicides is important to keep in mind because benzobicyclon is a triketone HPPD-inhibiting herbicide. Previous research conducted by Young (2017) showed that when applied into a continuous flood, benzobicyclon did not injure subsequent soybean nor did it decrease crop height or grain yield, rendering it safe for rotational use. Additionally, benzobicyclon requires a continuous flood to be phyto-active; therefore, it is unlikely to injure actively growing adjacent soybean if off-target movement were to occur.

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CHAPTER 2

BENZOBICYCLON FOR WEEDY RICE CONTROL IN QUIZALOFOP- AND IMIDAZOLINONE-RESISTANT RICE SYSTEMS

ABSTRACT

Weedy rice is difficult to control in Midsouth rice cropping systems due to its highly competitive and resilient nature, genetic similarity to cultivated rice, and resistance to herbicides. Hence, there is a need for new modes of action in rice production. Gowan Company recently registered benzobicyclon, a WSSA Group 27 herbicide, as a postflood option in rice. It is the first 4-hydroxyphenylpyruvate dioxygenase-inhibiting herbicide commercially available in Midsouth rice production. In 2018 and 2019, field experiments were conducted at the Pine Tree Research Station near Colt, AR, and the Rice Research and Extension Center near Stuttgart, AR, to determine if the addition of benzobicyclon to quizalofop- or imidazolinone-resistant rice herbicide programs would improve weedy rice control versus a standard program in these systems. Across site years, one application of quizalofop, either at the 1- or 3-leaf rice stage, followed by benzobicyclon applied postflood, provided comparable weedy rice control to two sequential applications of quizalofop, which is a standard herbicide program in quizalofop-resistant rice. Additionally, treatments containing quizalofop or quizalofop followed by benzobicyclon injured the rice ≤5% at 28 days after the postflood application. Across site years, at 28 days after the postflood application of benzobicyclon, all treatments containing a full-season herbicide program followed by benzobicyclon postflood provided comparable or improved weedy rice control when compared to two sequential early postemergence applications of imazethapyr, which is a standard imidazolinone-resistant rice postemergence herbicide program. In both experiments, rice treated with benzobicyclon yielded comparably or better than treatments containing the standard herbicide program for each system. Findings from this research suggest that the use of benzobicyclon in quizalofop- and imidazolinone-resistant rice systems could be an additional and viable weedy rice control option for Midsouth rice producers.

Nomenclature: benzobicyclon; weedy rice, *Oryza sativa* L.; rice, *Oryza sativa* L.

Keywords: weedy rice, control, quizalofop-resistant rice, imidazolinone-resistant rice

INTRODUCTION

Weedy rice is challenging to control in Midsouth rice cropping systems due to its highly competitive and resilient nature, similarity to cultivated rice, and its capacity for readily evolving resistance to commonly applied herbicides, such as the acetolactate synthase-inhibiting herbicides. Weedy rice is one of the most detrimental weeds in direct-seeded rice cropping systems (Burgos et al. 2014) and can cause up to 80% yield loss and a reduction in grain quality (Shivrain et al. 2010b). Weedy rice is genetically similar to commercially cultivated rice, making it particularly difficult to control with postemergence herbicide applications without also damaging the crop (Burgos et al. 2014). Due to the genetic similarity of weedy rice and cultivated rice, the risk for evolution of herbicide resistance from transgene flow from herbicide-resistant (HR) rice cultivars to weedy rice populations is prevalent (Gressel and Valverde 2009). In 2012, a survey of Midsouth crop consultants was conducted in an effort to identify the most problematic weeds of rice (Norsworthy et al. 2013). Results from this study concluded that weedy rice and barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.] were the third and first most problematic weeds of rice in the Midsouth, respectively.

Cultivated rice is comprised of two species, *Oryza sativa* L., which is grown throughout the world, and *Oryza glaberrima* Steud., which is grown in West Africa (Shivrain et al. 2010a). In the *Oryza* genus, which includes cultivated rice, there are 21 wild species, and most of these species can hybridize with each other and produce viable seeds (Shivrain et al. 2010a). Cultivated rice hybridized with its wild ancestor *Oryza rufipogon* Griff., which ultimately led to the production of weedy red rice (Ellstrand 2003; Londo and Schaal 2007; Shivrain et al. 2010a). Presence or absence of awns, hull color, and pericarp color are some of the phenotypic traits shared by *Oryza* species, but these characteristics can vary by ecotype (Burgos et al. 2014;

Kovach et al. 2007). The term "weedy rice" is comprised of many genetically similar types of rice, all in the *Oryza* genus, and "red rice" specifically, is the product of hybridization that results in a red-colored pericarp on the rice seed. Today, any *Oryza* plant found in a rice field that was not intentionally planted can be considered "weedy rice."

In an effort to control weedy rice in cultivated rice fields, imidazolinone (IMI)-resistant rice was commercialized by Louisiana State University and became commercially available for use in rice production in 2002 (Tan et al. 2005; Sudianto et al. 2013). IMI-resistant rice, known as Clearfield® rice technology or FullPage® rice cropping solution, enables producers to make mid-season postemergence applications of IMI herbicides such as imazethapyr or imazamox for the control of problematic rice weeds (Chin et al. 2007). When Clearfield technology was first introduced, IMI herbicides were very effective in controlling weedy rice as well as propanil- and quinclorac-resistant barnyardgrass. The ability to effectively control these problematic weeds postemergence without also injuring the crop was appealing to producers, and the technology was widely adopted. By 2012, upwards of 61% of all rice hectares in Arkansas were planted with Clearfield cultivars (Wilson et al. 2013). This widespread adoption ultimately led to the evolution of IMI-resistant weedy rice and barnyardgrass (Burgos et al. 2008, 2014; Heap 2020). Consequently, IMI-herbicides are no longer an effective option for controlling weedy rice and barnyardgrass in the Midsouth (Norsworthy et al. 2012); thus, Clearfield rice hectares are steadily declining (Hardke 2018).

The occurrence of widespread IMI-resistant weedy rice as well as multiple-resistant barnyardgrass prompted BASF to develop a new rice cultivar which would provide rice producers with a new option for controlling these problematic weeds. In 2018, Provisia® rice was commercialized for use in the Midsouth (Hines 2018). Provisia rice from BASF possesses resistance to quizalofop, a WSSA Group 1 acetyl CoA carboxylase (ACCase)-inhibiting herbicide. The introduction of this new technology provided Midsouth rice growers with an additional, very effective, herbicide option for postemergence control of grass species, including weedy rice. Unlike many other herbicide-resistant crops, quizalofop-resistant rice is non-transgenic (Scott et al. 2018). Quizalofop has no herbicidal activity on broadleaf weeds or sedges. Therefore, prior to the release of Provisia rice, quizalofop was only recommended for postemergence grass control in soybean [*Glycine max* (L.) Merr.] and cotton (*Gossypium hirsutum* L.) (Barber et al. 2020). Due to the risk of antagonism and decreased herbicide efficacy with applications made near flood establishment, it is recommended that broadleaf herbicides only be mixed with quizalofop on the first of two sequential applications (Scott et al. 2018). Quizalofop is an effective postemergence option for controlling weedy rice, but repeated use of this chemistry will ultimately lead to the evolution of resistance.

Widespread resistance of common rice weeds to many commonly applied herbicides poses challenges for Midsouth rice producers. As a result, strategies have been implemented to mitigate further evolution of herbicide resistance. One of the most effective tactics for combatting target-site herbicide resistance evolution is the use of multiple effective sites of action (SOA) for season-long weed control (Norsworthy et al. 2012). Using a program approach while implementing multiple effective herbicide SOA will greatly reduce the risk for target-site resistance, thus providing producers with a sustainable and effective weed control program.

Benzobicyclon, [3-(2-chloro-4-mesylbenzoyl)-2-phenylthiobicyclo [3.2.1] oct-2-en-4-one] is a 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibiting herbicide that was registered by Gowan Company® in fall of 2021 as a postflood weed control option in Midsouth rice. Benzobicyclon was originally discovered by SDS Biotech K.K. in Japan in 2001 (Komatsubara et al. 2009) and has been used in California as a weed control option in water-seeded, paddy rice production since 2017 (Gowan 2017). The benzobicyclon formulation used in California, also produced by Gowan Company, contains both benzobicyclon and halosulfuron and is sold under the trade name Butte®. The benzobicyclon formulation used in California is available as a slow release granular herbicide for use in water-seeded rice (Gowan 2017). Although HPPD-inhibiting herbicides such as mesotrione (Callisto) and tembotrione (Laudis) are currently registered for use in Midsouth corn (*Zea mays* L.) (Barber et al. 2020); there were no labeled HPPD-inhibiting herbicides registered for use in Midsouth rice prior to benzobicyclon.

Benzobicyclon, as well as other HPPD-inhibiting herbicides, disrupt plastoquinone biosynthesis within the plant, causing bleached symptomology on the new growth, followed by chlorosis, and ultimately leading to plant death (Komatsubara et al. 2009). Benzobicyclon is a pro-herbicide; therefore, it does not directly inhibit HPPD enzymes in plants (Komatsubara et al. 2009). Rather, benzobicyclon must undergo a non-enzymatic hydrolysis reaction in the presence of water to be converted to the potent and phytotoxic compound benzobicyclon hydrolysate (Williams and Tjeerdema 2016). For this reaction to occur and for benzobicyclon hydrolysate to be formed, water must be present. Hence, it is imperative for rice producers to maintain a continuous flood throughout the growing season for benzobicyclon to perform optimally (Young et al. 2018). Additionally, flood depth has an impact on the efficacy of benzobicyclon. In a recent study, Davis et al. (2013) documented that benzobicyclon performed optimally when the flood depth was at least 10 cm. This is important because a majority of rice hectares in the Midsouth are drill-seeded and receive a continuous flood around the 5-leaf growth stage, which is maintained through plant maturity. Benzobicyclon controls a broad spectrum of problematic rice weeds including aquatics, broadleaves, grasses, and sedges, including those currently resistant to ALS herbicides (Young et al. 2017).

The addition of benzobicyclon to current rice weed control programs provides a new effective SOA for producers, thus enabling control of a broadened spectrum of weeds as well as providing some protection against weedy rice and other rice weeds evolving resistance to current herbicide options. Furthermore, the addition of benzobicyclon into current Midsouth rice herbicide programs will provide producers with a non-traited, postflood weedy rice control option on those populations sensitive to the herbicide.

In order to protect the current traited technologies available in rice for further herbicide resistance development in weedy rice, the objective of this research was to determine if the addition of benzobicyclon to quizalofop- or imidazolinone-resistant rice herbicide programs will provide comparable or improved weedy rice control versus a standard program in these systems.

MATERIALS AND METHODS

Benzobicyclon-containing Programs for Weedy Rice Control in Quizalofop- and Imidazolinone-Resistant Rice. Field experiments were conducted in 2018 and 2019 on a Calloway silt loam (Fine-silty, mixed, active, thermic Aquic Fraglossudalfs) at the Pine Tree Research Station (PTRS) near Colt, AR, and in 2019 on a Dewitt silt loam (Fine, smectitic, thermic Typic Albaqualfs) at the Rice Research and Extension Center (RREC) near Stuttgart, AR. The experimental design for these experiments was a randomized complete block with a nontreated control and four replications.

Herbicide trade names, manufacturers, and herbicide common names for the experiments are listed in Table 2.1. The herbicide treatment combinations evaluated for the quizalofop-resistant rice experiment conducted in 2018 are listed in Table 2.2, and the herbicide treatment combinations evaluated for the quizalofop-resistant experiments conducted in 2019 are listed in Table 2.3. The herbicide treatment combinations evaluated for the imidazolinone-resistant rice experiment conducted in 2018 and 2019 are listed in Table 2.4.

Individual rice bays were used to prevent movement of benzobicyclon among treatments. Rice bays consisted of a continuous flood being held within man-made levees beginning at the 5-leaf stage of rice. Each non-benzobicyclon-containing plot was placed in a separate bay than benzobicyclon-containing treatments. This setup ensured that non-benzobicyclon-containing plots were not contaminated by benzobicyclon. Plots measured 1.8 by 5.2 m and were planted using a 9-row cone drill on May 14, 2018, at Pine Tree, April 24, 2019, at Stuttgart, and May 17, 2019, at Pine Tree. The quizalofop-resistant (Provisia™ Rice System, BASF Corporation, Research Triangle Park, NC 27709) cultivar 'PVL01', and the IMI-resistant (Clearfield® Rice, BASF Corporation, Research Triangle Park, NC 27709) cultivar 'CL153' were drill-seeded at a 2-cm depth at a seeding rate of 73 seeds m^{-1} of row, and a 1-m alley was established between plots.

A broadcast application of clomazone (Command® herbicide, FMC Corporation, Philadelphia, PA) at 336 g ai ha^{-1} and halosulfuron + prosulfuron (Gambit® herbicide, Gowan Company, Yuma, AZ) at 53 g ai ha^{-1} and 31 g ai ha^{-1}, respectively, was made at planting. All experiments were fertilized prior to flooding with nitrogen (N) at 155 kg N ha^{-1} and otherwise managed for non-evaluated weeds according to University of Arkansas Extension recommendations (Roberts et al. 2018; Scott et al. 2018). All treatments were applied with a CO_2-pressurized backpack sprayer utilizing a handheld four-nozzle boom equipped with 110015

AIXR nozzles (Teejet Technologies, Springfield, IL) calibrated to deliver 140 L ha^{-1} at 276 kPa. All postflood applications were made within 3 days following flooding.

Assessments. For all quizalofop- and imidazolinone-resistant rice experiments, herbicide efficacy was assessed by means of weedy rice control ratings at 28 days after delayed preemergence (DPRE) applications and at 14 and 28 days after postflood (POST) applications. At the 28 days after DPRE evaluation timing, all DPRE and early postemergence (EPOST) (1-leaf and 3-leaf) applications had been made. At the 14 and 28 days after POST evaluation timing, all applications prior to flooding and postflood benzobicyclon applications had been made. Control ratings were based on a scale of 0 to 100%, with 0% being no control relative to the nontreated check and 100% being complete control of weedy rice within the plots. Additionally, crop injury ratings were taken simultaneously with weedy rice control ratings. Injury ratings were based on a scale of 0 to 100%, with 0% being no crop injury relative to the nontreated check and 100% being complete crop death (Frans and Talbert 1977). For all field experiments, experimental plots were machine harvested using a small-plot combine to determine rough rice yield at an adjusted moisture of 12%.

Statistical Analyses. All data were analyzed using SAS 9.4 (SAS Institute Inc., Cary, NC). Crop injury and weedy rice control data were subjected to analysis of variance (ANOVA) and analyzed as repeated measures with a beta distribution (values of 0 were adjusted to 0.001 to avoid exclusion) using PROC GLIMMIX in SAS (Gbur et al. 2012). Crop injury and weedy rice control data were analyzed using multiple different covariance structures, then the analysis with the most appropriate covariance structure was chosen for reporting based on the smallest Akaike's information criterion (AICC) value (Burnham and Anderson 2002; Brewer et al. 2016). When analyzing crop injury and weedy rice control data, block was considered random, and herbicide treatment and time were fixed. Rough rice yield data were subjected to ANOVA using PROC GLIMMIX in SAS. When analyzing rough rice yield data, block was considered a random effect and herbicide treatment was fixed. A gamma distribution was used to analyze rough rice yield data. For both the quizalofop- and imidazolinone-resistant rice, each site year was analyzed separately for each response variable. Each site year was analyzed separately because combining site years and analyzing these data using a repeated measures analysis yielded results that were not conducive to reporting. Means were separated using Fisher's protected LSD at P=0.05. P-values of ANOVA are displayed in Table 2.5.

For the quizalofop-resistant rice experiments, analyses containing the variance components (VC) covariance structure were chosen for crop injury data at Pine Tree in 2018 and at Stuttgart in 2019, and the analysis containing the first order autoregressive [AR (1)] covariance structure was chosen for crop injury data at Pine Tree in 2019. The analyses containing the VC covariance structure were chosen for weedy rice control data at Pine Tree in 2018 and 2019. The analysis containing the AR (1) covariance structure was chosen for weedy rice control data at Stuttgart in 2019.

For the imidazolinone-resistant rice experiments, the analysis containing the VC covariance structure was chosen for crop injury data at Pine Tree in 2018, and the analyses containing the compound symmetry (CS) covariance structure were chosen for crop injury data at Pine Tree and Stuttgart in 2019. The analysis containing the VC covariance structure was chosen for weedy rice control data at Pine Tree in 2018, and the analyses containing the CS covariance structure were chosen for weedy rice control data at Pine Tree and Stuttgart in 2019.

RESULTS AND DISCUSSION

Quizalofop-Resistant Rice

Weedy Rice Control. One application of quizalofop, either at the 1-leaf rice stage or at preflood, followed by benzobicyclon applied postflood, provided comparable weedy rice control to two sequential applications of quizalofop across site years (Table 2.6). At Pine Tree and Stuttgart in 2019, both treatments containing one application of quizalofop followed by benzobicyclon postflood provided weedy rice control ≥95% at 28 days after the postflood application. Two sequential applications of quizalofop is the current standard herbicide program in a quizalofop-resistant rice system (Barber et al. 2020). With the treatments evaluated, it is not possible to conclude whether a single quizalofop application was as effective as the current standard, but considering the previously reported activity of benzobicyclon on weedy rice (Young et al. 2018; Mann and Yerkes 2018), it is believed that benzobicyclon contributes to the high level of control obtained in this research.

The addition of benzobicyclon to the current standard program has tremendous value for Midsouth rice growers for many reasons. For example, using an additional herbicide SOA for weedy rice control while also decreasing the total annually applied amount of quizalofop will provide some protection against weedy rice evolving resistance to quizalofop. The addition of benzobicyclon to a quizalofop-based weed control program broadens the spectrum of control, specifically removing many aquatics and rice flatsedge (*Cyperus iria* L.) (Sandoski et al. 2014; Young et al. 2017). The ability to effectively control weedy rice while using two herbicide SOA and control a more diverse weed spectrum will likely aid adoption of benzobicyclon in Midsouth rice production systems following registration.

Acetochlor, a very-long chain fatty acid (VLCFA)-inhibiting herbicide, is not currently labeled for use in rice (Norsworthy et al. 2019). If eventually labeled, acetochlor could be used in many rice technology systems because it does not require a specific tolerance trait by the crop. At Pine Tree in 2018 and Stuttgart in 2019, pendimethalin + thiobencarb applied DPRE followed by two sequential EPOST applications of acetochlor followed by benzobicyclon postflood provided comparable or improved weedy rice control when compared to all quizalofop-containing treatments (Table 2.6). Based on these findings, it is suggested that a “non-traited” herbicide program including acetochlor, with the addition of benzobicyclon, could potentially be a viable option for weedy rice control if acetochlor were labeled for use in rice.

There is an imperative need for an additional effective postemergence weedy rice control option in the Midsouth. Weedy rice is an extremely competitive weed and can be difficult to control in a cultivated rice system (Burgos et al. 2014). In many instances, it can negatively impact rice production to the point of complete crop failure (Burgos et al. 2006; Diarra et al. 1985). Herbicide resistance poses many challenges for Midsouth rice producers. Although quizalofop, or Provisia/Highcard herbicide, is currently an effective option for controlling weedy rice, the evolution of herbicide resistance in weedy rice is inevitable. To mitigate the further evolution of resistance to the already limited herbicide options, the implementation of weedy rice control strategies such as using multiple SOA for season-long weed control (Norsworthy et al. 2012) is paramount.

Rice Injury. The recent successful registration of benzobicyclon in rice and potential use in quizalofop-resistant rice requires every facet of the new chemistry to be understood. In order to effectively control weeds and potentially maximize yields while using benzobicyclon in conjunction with other herbicides in a system that employs quizalofop, the risk of crop injury must be assessed.

At Pine Tree and Stuttgart in 2019, when compared to all other treatments, the treatment containing pendimethalin + thiobencarb applied DPRE followed by two sequential EPOST applications of acetochlor followed by benzobicyclon postflood was much more injurious (≥41%) to the rice when evaluated at 14 days after the postflood application (Table 2.7). This severe level of injury was likely because of the phytotoxic effects elicited by acetochlor on the rice, which rendered the crop more susceptible to the benzobicyclon application. Findings from previous research indicated that when a single microencapsulated (ME) acetochlor application was made EPOST, rice injury was tolerable (Fogleman et al. 2019). In this experiment, when ME acetochlor was applied EPOST, rice injury was beyond allowable limits (19 to 65%). Furthermore, when benzobicyclon was subsequently applied, crop injury seemed to be exacerbated. These findings suggest that injury to rice caused by acetochlor can be variable from year to year and that sequential applications increase the likelihood for severe injury. Additional research would be needed to better understand the extent that soil moisture and rainfall differences among site years contribute to increased risk for injury from ME acetochlor.

Across site years, treatments containing quizalofop or quizalofop followed by benzobicyclon injured the rice ≤5% at 28 days after the postflood application, and these results were consistent whether quizalofop was applied at a low rate (77 g ai ha^{-1}) or the standard rate (120 g ai ha^{-1}) (Table 2.7). From these findings, it appears that the addition of benzobicyclon to either a standard two sequential quizalofop application or a single quizalofop application will not increase the likelihood for injury to rice.

Rough Rice Yield. At Pine Tree in 2018, rice in both treatments containing a single application of quizalofop followed by benzobicyclon yielded comparably to the treatment containing two sequential applications of quizalofop - a standard herbicide program for quizalofop-resistant rice (Table 2.8). At Stuttgart in 2019, rice in both treatments containing a single application of quizalofop followed by benzobicyclon yielded greater than that in the treatment containing two sequential applications of quizalofop (Table 2.8). Although the quizalofop-resistant rice cultivar PVL01 in 2018 and 2019 yielded >1000 kg ha^{-1} less than many of the other rice cultivars commonly planted in Arkansas (Hardke 2019), the addition of benzobicyclon to a herbicide program for quizalofop-resistant rice can provide better or comparable yields than the current standard herbicide program in quizalofop-resistant rice. The ability to maintain cultivar yield potential while also utilizing more than one SOA and providing a broader spectrum of control seems to emphasize that the use of benzobicyclon will be a viable option for rice growers moving forward.

Imidazolinone-Resistant Rice

Weedy Rice Control. Widespread weedy rice resistance to IMI-herbicides such as imazethapyr, which is labeled for use in imidazolinone-resistant rice, poses many challenges for Midsouth rice producers. The overuse and poor stewardship of these IMI-herbicides has led to extreme herbicide resistance issues, and as a result, they are no longer an effective option for controlling weedy rice and other weeds like barnyardgrass in the Midsouth (Norsworthy et al. 2012). Currently, effective postemergence herbicide options for controlling weedy rice are limited. Hence, the goal of this experiment was to investigate the viability of the addition of benzobicyclon into a current imidazolinone-resistant rice herbicide program as well as investigating benzobicyclon included in “non-traited” herbicide programs, relative to a standard imidazolinone-resistant rice herbicide program.

Across all three site years, at 28 days after the postflood application of benzobicyclon, all treatments containing a full-season herbicide program followed by benzobicyclon postflood provided comparable or improved weedy rice control when compared to two sequential EPOST applications of imazethapyr, which is a standard imidazolinone-resistant rice postemergence herbicide program (Table 2.9). Many of the treatments contained DPRE-applied pendimethalin + thiobencarb followed by single and/or multiple applications of EPOST-applied acetochlor. These treatments do not contain imazethapyr and can be considered “non-traited” herbicide programs. However, these programs do include acetochlor, meaning they could be utilized for weedy rice control in different rice technologies in the event that acetochlor were to become labeled for use in rice.

At Pine Tree in 2018 and Stuttgart in 2019, the treatment containing postflood-applied benzobicyclon alone was often one of the least effective treatments for weedy rice control. Control increased if benzobicyclon followed a full-season herbicide program (Table 2.9). These results indicate that benzobicyclon is not to be used as a stand-alone herbicide program for weedy rice control. Rather, it should be used in combination with early-season herbicides to make a complete full-season herbicide program in order to effectively control weedy rice. Size of weedy rice at application of benzobicyclon greatly impacts the likelihood of success with the herbicide (Brabham et al. 2021).

Rice Injury. Benzobicyclon was safe for use in IMI-resistant rice when it was not preceded by injury elicited from applications of other herbicides prior to flooding. Across all three site years, at 28 days after the postflood application of benzobicyclon applied without previous herbicides, rice was injured ≤1% (Table 2.10). The observed injury on ‘CL153’, a rice cultivar with *japonica* background, are consistent with findings reported by Young et al. (2017) in which IMI-resistant rice cultivars and other rice cultivars with *japonica* backgrounds were injured ≤7%. Conversely, the *indica* cultivars ‘Rondo’ and ‘Purple Maker’ were severely injured and high levels of chlorosis were observed when assessed two weeks after treatment (Young et al. 2017). Increased tolerance to benzobicyclon in *japonica* rice cultivars is important because a vast majority of rice cultivars planted in the U.S. are of *japonica* origin as opposed to *indica* origin (Burgos et al. 2014). In general, when injury did occur, benzobicyclon tended to exacerbate injury observed from acetochlor-containing applications prior to flood establishment. As expected, the standard imidazolinone-resistant rice herbicide program of two sequential EPOST applications of imazethapyr did not injure the rice.

Rough Rice Yield. At Pine Tree in 2018, the addition of benzobicyclon to weed control programs, except when following sequential acetochlor applications, resulted in improved rice yields over the standard treatment of two sequential EPOST imazethapyr applications (Table 2.11). Likewise, rice yields for some, but not all, benzobicyclon-containing treatments at Pine Tree in 2019 had greater yields than were harvested from plots for the standard two-application imazethapyr alone program (Table 2.11). In no instance, in any of the three sites years, were rice yields lower for benzobicyclon-treated plots compared to the two-application imazethapyr alone program.

Practical Implications. Findings from this research indicate that the use of benzobicyclon in current standard quizalofop- and imidazolinone-resistant rice herbicide programs provides tremendous utility for Midsouth rice producers. In both of these production systems, the addition of benzobicyclon to the respective standard herbicide programs resulted in comparable or improved weedy rice control compared to the standard program alone. Additionally, minimal injury was observed from treatments containing the current standard herbicide program followed by the post-flood application of benzobicyclon.

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TABLES

Table 2.1. Product name, common name, and manufacturing company of evaluated herbicides for the quizalofop- and imidazolinone-resistant rice experiments in 2018 and 2019.

Product name	Common name	Manufacturer
Prowl H_20	Pendimethalin	BASF Corp., Research Triangle Park, NC 27709
Bolero	Thiobencarb	Valent U.S.A Corp., Walnut Creek, CA 94596
Warrant	Acetochlor	Monsanto Company, St. Louis, MO 63167
Provisia	Quizalofop	BASF Corp., Research Triangle Park, NC 27709
Newpath	Imazethapyr	BASF Corp., Research Triangle Park, NC 27709
Rogue	Benzobicyclon	Gowan Company, Yuma, AZ 85364

Table 2.2. List of herbicide treatments, application timings, and rates for the quizalofop-resistant rice experiment in 2018.

Herbicide treatment[a]	Application timing	Rate
		g ai ha^{-1}
Nontreated	--	--
quizalofop + COC	3 lf	120
quizalofop + COC	Preflood	120
pendimethalin + thiobencarb	DPRE	1120 + 3360
acetochlor	1 lf	1051
acetochlor	3 lf	1051
benzobicyclon + MSO	Postflood	371
quizalofop + COC	3 lf	120
benzobicyclon + MSO	Postflood	371
quizalofop + COC	Preflood	120
benzobicyclon + MSO	Postflood	371

[a] Abbreviations: COC – crop oil concentrate at 1% v/v; MSO – methylated seed oil at 1% v/v; DPRE – delayed preemergence; 1 lf – 1-leaf crop stage; 3 lf – 3-leaf crop stage

Table 2.3. List of herbicide treatments, application timings, and rates for the quizalofop-resistant rice experiment in 2019.

Herbicide treatment[a]	Application timing	Rate
		g ai ha^{-1}
nontreated	--	--
quizalofop + COC	3 lf	120
quizalofop + COC	Preflood	120
low-rate quizalofop + COC	3 lf	77
low-rate quizalofop + COC	Preflood	77
low-rate quizalofop + COC	Postflood	77
quizalofop + COC	3 lf	120
quizalofop + COC	Preflood	120
benzobicyclon + MSO	Postflood	371
pendimethalin + thiobencarb	DPRE	1120 + 3360
acetochlor	1 lf	1051
acetochlor	3 lf	1051
benzobicyclon + MSO	Postflood	371
quizalofop + COC	3 lf	120
benzobicyclon + MSO	Postflood	371
quizalofop + COC	Preflood	120
benzobicyclon + MSO	Postflood	371
low-rate quizalofop + COC	3 lf	77
low-rate quizalofop + COC	Preflood	77
low-rate quizalofop + COC	Postflood	77
benzobicyclon + MSO	Postflood	371

[a] Abbreviations: COC – crop oil concentrate at 1% v/v; MSO – methylated seed oil at 1% v/v; DPRE – delayed preemergence; 1 lf – 1-leaf crop stage; 3 lf – 3-leaf crop stage

Table 2.4. List of herbicide treatments, application timings, and rates for the imidazolinone-resistant rice experiment in 2018 and 2019.

Herbicide treatment[a]	Application timing	Rate
		g ai ha^{-1}
nontreated	--	--
pendimethalin + thiobencarb	DPRE	1120 + 3360
acetochlor	1 lf	1051
acetochlor	3 lf	1051
imazethapyr + COC	3 lf	70
imazethapyr + COC	preflood	70
benzobicyclon + MSO	postflood	371
acetochlor	1 lf	1051
benzobicyclon + MSO	postflood	371
acetochlor	1 lf	1051
acetochlor	3 lf	1051
benzobicyclon + MSO	postflood	371
pendimethalin + thiobencarb	DPRE	1120 + 3360
acetochlor	1 lf	1051
acetochlor	3 lf	1051
benzobicyclon + MSO	postflood	371
pendimethalin + thiobencarb	DPRE	1120 + 3360
acetochlor	1 lf	1051
benzobicyclon + MSO	postflood	371
pendimethalin + thiobencarb	DPRE	1120 + 3360
acetochlor	3 lf	1051
benzobicyclon + MSO	postflood	371
pendimethalin + thiobencarb	DPRE	1120 + 3360
benzobicyclon + MSO	postflood	371

[a] Abbreviations: COC – crop oil concentrate at 1% v/v; MSO – methylated seed oil at 1% v/v; DPRE – delayed preemergence; 1 lf – 1 leaf crop stage; 3 lf – 3 leaf crop stage

Table 2.5. The p-values from ANOVA for the quizalofop- and imidazolinone-resistant rice experiments for rough rice yield, crop injury, and weedy rice control at Pine Tree in 2018 and at Pine Tree and Stuttgart in 2019.

		ANOVA					
Response variable tested	Factors evaluated	Pine Tree 2018		Pine Tree 2019		Stuttgart 2019	
		imi-res[a]	quiz-res	imi-res	quiz-res	imi-res	quiz-res
		-------------------------------------p-values----------------------------------					
Rough rice yield	herbicide treatment	<0.0001	<0.0001	0.0370	0.1658	0.5424	<0.0001
Crop injury	herbicide treatment	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	time	<0.0001	0.0026	<0.0001	0.0002	<0.0001	0.1201
	herbicide treatment*time	<0.0001	0.7336	<0.0001	<0.0001	0.0067	<0.0001
Weedy rice control	herbicide treatment	<0.0001	0.0036	<0.0001	<0.0001	<0.0001	0.1681
	time	<0.0001	<0.0001	<0.0001	0.0001	<0.0001	0.0369
	herbicide treatment*time	<0.0001	0.0060	0.0564	0.0071	<0.0001	0.4524

[a] Abbreviations: imi-res – imidazolinone-resistant rice experiment; quiz-res – quizalofop-resistant rice experiment

Table 2.6. Estimates of weedy rice control relative to the nontreated check 28 days after delayed preemergence applications, 14 days after postflood applications, and 28 days after postflood applications for the quizalofop-resistant rice experiment at Pine Tree in 2018 and at PineTree and Stuttgart in 2019. Site years were analyzed separately.

	Weedy rice control								
	Pine Tree 2018			Pine Tree 2019			Stuttgart 2019		
Herbicide treatment[abc]	28 DPRE[d]	14 POST[e]	28 POST[f]	28 DPRE	14 POST	28 POST	28 DPRE	14 POST	28 POST
	----------%	----------%	----------%	----------%	%	%----------	%----------	%----------	%----------
quizalofop (3 lf) fb quizalofop (preflood)	49 e[g]	99 a	86 c	99 a	99 a	99 a	96	97	97
quizalofop (3 lf) fb benzobicyclon (postflood)	79 cd	99 a	81 cd	98 a	99 a	99 a	96	91	95
quizalofop (preflood) fb benzobicyclon (postflood)	--[h] --	93 b	78 cd	-- --	96 b	99 a	--	93	98
quizalofop (3 lf) fb quizalofop (preflood) fb benzobicyclon (postflood)	-- --	-- --	-- --	99 a	99 a	99 a	97	94	97
low-rate quizalofop (3 lf) fb low-rate quizalofop (preflood) fb low-rate quizalofop (postflood)	-- --	-- --	-- --	98 a	98 a	99 a	96	98	98
low-rate quizalofop (3 lf) fb low-rate quizalofop (preflood) fb low-rate quizalofop + benzobicyclon	-- --	-- --	-- --	98 a	99 a	99 a	97	93	96
pendimethalin + thiobencarb (dpre) fb acetochlor (1 lf) fb acetochlor (3 lf) fb benzobicyclon (postflood)	73 d	99 a	94 b	21 d	61 c	59 c	97	95	96

[a] Abbreviations: lf – leaf; fb – followed by; dpre – delayed preemergence

[b] Quizalofop-containing treatments also included crop oil concentrate at 1% v/v; benzobicyclon-containing treatments also included methylated seed oil at 1% v/v

[c] Low-rate quizalofop treatments received 77 g ai ha^{-1} instead of the standard rate of 120 g ai ha^{-1}

[d,e,f] Evaluations were recorded 28 days after delayed preemergence applications; 14 days after postflood applications; 28 days after postflood applications

[g] Letters are used to separate means. Means that are significantly different are represented by letter separation by site year; means without the same letter in each site year are significantly different according to Fisher's protected LSD (α=0.05).

[h] Evaluations with "–" were either not included in that site year, or had not been evaluated at that timing

Table 2.7. Estimates of crop injury relative to the nontreated check 28 days after delayed preemergence applications, 14 days after postflood applications, and 28 days after postflood applications for the quizalofop-resistant rice experiment at Pine Tree in 2018 and at Pine Tree and Stuttgart in 2019. Site years were analyzed separately.

	Crop injury								
	Pine Tree 2018			Pine Tree 2019			Stuttgart 2019		
Herbicide treatment[abc]	28 DPRE[d]	14 POST[e]	28 POST[f]	28 DPRE	14 POST	28 POST	28 DPRE	14 POST	28 POST
	%								
quizalofop (3 lf) fb quizalofop (preflood)	6	11	5	10 b-e[g]	0 h	0 h	0 c	1 b	1 b
quizalofop (3 lf) fb benzobicyclon (postflood)	3	13	5	4 efg	4 d-g	4 g	1 b	0 c	0 c
quizalofop (preflood) fb benzobicyclon (postflood)	--[h]	8	3	-- --	1 g	0 h	-- --	0 c	0 c
quizalofop (3 lf) fb quizalofop (preflood) fb benzobicyclon (postflood)	--	--	--	9 b-e	15 bc	4 d-g	1 b	1 b	1 b
low-rate quizalofop (3 lf) fb low-rate quizalofop (preflood) fb low-rate quizalofop (postflood)	--	--	--	8 c-f	0 h	0 h	0 c	0 c	0 c
low-rate quizalofop (3 lf) fb low-rate quizalofop (preflood) fb low-rate quizalofop + benzobicyclon	--	--	--	3 fg	8 c-f	0 h	1 b	1 b	0 c
pendimethalin + thiobencarb (dpre) fb acetochlor (1 lf) fb acetochlor (3 lf) fb benzobicyclon (postflood)	66	85	78	19 abc	41 a	23 ab	65 a	46 a	40 a

[a] Abbreviations: lf – leaf; fb – followed by; dpre – delayed preemergence

[b] Quizalofop-containing treatments also included crop oil concentrate at 1% v/v; benzobicyclon-containing treatments also included methylated seed oil at 1% v/v

[c] Low-rate quizalofop treatments received 77 g ai ha^{-1} instead of the standard rate of 120 g ai ha^{-1}

[d,e,f] Evaluations were recorded 28 days after delayed preemergence applications; 14 days after postflood applications; 28 days after postflood applications

[g] Letters are used to separate means. Means that are significantly different are represented by letter separation by site year; means without the same letter in each site year are significantly different according to Fisher's protected LSD (α=0.05).

[h] Evaluations with “--" were either not included in that site year, or had not been evaluated at that timing

Table 2.8. Rough rice yield for the quizalofop-resistant rice experiment at Pine Tree in 2018 and at Pine Tree and Stuttgart in 2019. Site years were analyzed separately.

	Rough rice yield				
Herbicide treatment[abc]	Pine Tree 2018		Pine Tree 2019	Stuttgart 2019	
	-------------------kg ha^{-1}	--------------------			
Nontreated	1867	b[d]	4844	4945	cd
quizalofop (3 lf) fb quizalofop (preflood)	4996	a	4693	5904	bc
quizalofop (3 lf) fb benzobicyclon (postflood)	6308	a	4441	7519	a
quizalofop (preflood) fb benzobicyclon (postflood)	5349	a	4491	7468	a
quizalofop (3 lf) fb quizalofop (preflood) fb benzobicyclon (postflood)	--	--	4643	7367	a
low-rate quizalofop (3 lf) fb low-rate quizalofop (preflood) fb low-rate quizalofop (postflood)	--	--	3482	4289	d
low-rate quizalofop (3 lf) fb low-rate quizalofop (preflood) fb low-rate quizalofop + benzobicyclon (postflood)	--	--	4743	7367	a
pendimethalin + thiobencarb (dpre) fb acetochlor (1 lf) fb acetochlor (3 lf) fb benzobicyclon (postflood)	2018	b	4844	6308	ab

[a] Abbreviations: lf – leaf; fb – followed by; dpre – delayed preemergence

[b] Quizalofop-containing treatments also included crop oil concentrate at 1% v/v; benzobicyclon-containing treatments also included methylated seed oil at 1% v/v

[c] Low-rate quizalofop treatments received 77 g ai ha^{-1} instead of the standard rate of 120 g ai ha^{-1}

[d] Letters are used to separate means. Data within columns containing the same letter are not significantly different according to Fisher's protected LSD (α=0.05).

Table 2.9. Estimates of weedy rice control relative to the nontreated check 28 days after delayed preemergence applications, 14 days after postflood applications, and 28 days after postflood applications for the imidazolinone-resistant rice experiment at Pine Tree in 2018 and at Pine Tree and Stuttgart in 2019. Site years were analyzed separately.

	Weedy rice control								
	Pine Tree 2018			Pine Tree 2019			Stuttgart 2019		
Herbicide treatment[ab]	28 DPRE[c]	14 POST[d]	28 POST[e]	28 DPRE	14 POST	28 POST	28 DPRE	14 POST	28 POST
	%								
imazethapyr (3 lf) fb imazethapyr (preflood)	78 abc[f]	66 b-f	56 d-g	19	69	63	68 i	96 a	96 ab
pendimethalin + thiobencarb (dpre) fb acetochlor (1 lf) fb acetochlor (3 lf)	79 ab	74 bcd	50 fgh	2	59	51	89 b-f	91 a-f	94 a-d
pendimethalin + thiobencarb (dpre) fb acetochlor (1 lf) fb benzobicyclon (postflood)	66 b-f	64 b-f	66 b-f	19	66	59	69 i	89 c-f	96 ab
pendimethalin + thiobencarb (dpre) fb acetochlor (3 lf) fb benzobicyclon (postflood)	68 b-f	59 d-g	66 b-f	20	75	68	83 e-h	88 d-g	94 a-d
pendimethalin + thiobencarb (dpre) fb acetochlor (1 lf) fb acetochlor (3 lf) fb benzobicyclon (postflood)	73 b-e	74 bcd	86 a	17	73	69	87 d-g	92 a-e	96 abc
pendimethalin + thiobencarb (dpre) fb benzobicyclon (postflood)	53 fgh	40 gh	40 gh	8	65	54	89 c-f	87 d-g	95 a-d
acetochlor (1 lf) fb benzobicyclon (postflood)	49 fgh	49 fgh	55 efg	11	66	59	34 j	74 hi	93 a-d
acetochlor (1 lf) fb acetochlor (3 lf) fb benzobicyclon (postflood)	65 b-f	63 c-f	74 bcd	12	73	67	30 j	82 fgh	96 ab
benzobicyclon (postflood)	--[g] --	9 i	34 h	--	54	40	-- --	8 k	77 ghi

[a] Abbreviations: lf – leaf; fb – followed by; dpre – delayed preemergence

[b] Imazethapyr-containing treatments also included crop oil concentrate at 1% v/v; benzobicyclon-containing treatments also included methylated seed oil at 1% v/v

[c,d,e] Evaluations were recorded 28 days after delayed preemergence applications, 14 days after postflood applications, and 28 days after postflood applications, respectively

[f] Letters are used to separate means. Means with the same letter in each site year are not significantly different according to Fisher's protected LSD (α=0.05).

[g] Evaluations with "--" had not been evaluated at that timing

Table 2.10. Estimates of crop injury relative to the nontreated check 28 days after delayed preemergence applications, 14 days after postflood applications, and 28 days after postflood applications for the imidazolinone-resistant rice experiment at Pine Tree in 2018 and at Pine Tree and Stuttgart in 2019. Site years were analyzed separately.

	Crop injury								
	Pine Tree 2018			Pine Tree 2019			Stuttgart 2019		
Herbicide treatment[ab]	28 DPRE[c]	14 POST[d]	28 POST[e]	28 DPRE	14 POST	28 POST	28 DPRE	14 POST	28 POST
	---%								---
imazethapyr (3 lf) fb imazethapyr (preflood)	0 k[f]	0 k	0 k	1 i	1 i	1 i	1 k	1 k	1 k
pendimethalin + thiobencarb (dpre) fb acetochlor (1 lf) fb acetochlor (3 lf)	30 cde	38 a-d	21 def	5 efg	18 bcd	1 ghi	28 abc	39 a	5 ghi
pendimethalin + thiobencarb (dpre) fb acetochlor (1 lf) fb benzobicyclon (postflood)	25 c-f	20 def	13 fgh	11 de	18 bcd	2 f-i	12 efg	11 e-h	2 ijk
pendimethalin + thiobencarb (dpre) fb acetochlor (3 lf) fb benzobicyclon (postflood)	25 c-f	23 def	5 hij	15 bcd	49 a	21 bcd	16 c-f	14 def	5 hij
pendimethalin + thiobencarb (dpre) fb acetochlor (1 lf) fb acetochlor (3 lf) fb benzobicyclon (postflood)	48 abc	55 ab	58 ab	14 cd	54 a	26 b	24 bcd	33 ab	30 ab
pendimethalin + thiobencarb (dpre) fb benzobicyclon (postflood)	14 efg	6 g-j	4 ij	1 i	22 bc	4 fgh	2 ijk	2 ijk	1 k
acetochlor (1 lf) fb benzobicyclon (postflood)	20 def	21 def	8 ghi	2 f-i	40 a	15 bcd	10 fgh	10 fgh	2 jk
acetochlor (1 lf) fb acetochlor (3 lf) fb benzobicyclon (postflood)	36 bcd	61 a	59 a	1 hi	41 a	5 ef	20 b-f	21 b-e	5 g-j
benzobicyclon (postflood)	--[g] --	3 j	0 k	-- --	5 e-h	1 i	-- --	1 k	1 k

[a] Abbreviations: lf – leaf; fb – followed by; dpre – delayed preemergence

[b] Imazethapyr-containing treatments also included crop oil concentrate at 1% v/v; benzobicyclon-containing treatments also included methylated seed oil at 1% v/v

[c,d,e] Evaluations were recorded 28 days after delayed preemergence applications, 14 days after postflood applications, and 28 days after postflood applications, respectively

[f] Letters are used to separate means. Means with the same letter in each site year are not significantly different according to Fisher's protected LSD (α=0.05).

[g] Evaluations with "--" had not been evaluated at that timing

Table 2.11. Rough rice yield for the imidazolinone-resistant rice experiment at Pine Tree in 2018 and at Pine Tree and Stuttgart in 2019. Site years were analyzed separately.

	Rough rice yield				
Herbicide treatment[ab]	Pine Tree 2018		Pine Tree 2019		Stuttgart 2019
	---------------------kg ha^{-1}----------------------				
Nontreated	1815	e[c]	5933	c	7200
imazethapyr (3 lf) fb imazethapyr (preflood)	3242	d	5877	c	7674
pendimethalin + thiobencarb (dpre) fb acetochlor (1 lf) fb acetochlor (3 lf)	5278	a	6349	bc	7529
pendimethalin + thiobencarb (dpre) fb acetochlor (1 lf) fb benzobicyclon (postflood)	5215	ab	6063	c	7297
pendimethalin + thiobencarb (dpre) fb acetochlor (3 lf) fb benzobicyclon (postflood)	5064	ab	7198	ab	8384
pendimethalin + thiobencarb (dpre) fb acetochlor (1 lf) fb acetochlor (3 lf) fb benzobicyclon (postflood)	3545	cd	6543	abc	7587
pendimethalin + thiobencarb (dpre) fb benzobicyclon (postflood)	4615	abc	6709	abc	7588
acetochlor (1 lf) fb benzobicyclon (postflood)	5174	ab	6084	c	7277
acetochlor (1 lf) fb acetochlor (3 lf) fb benzobicyclon (postflood)	3399	cd	6581	abc	7443
benzobicyclon (postflood)	3809	bcd	7485	a	6634

[a] Abbreviations: lf – leaf; fb – followed by; dpre – delayed preemergence

[b] Imazethapyr-containing treatments also included crop oil concentrate at 1% v/v; benzobicyclon-containing treatments also included methylated seed oil at 1% v/v

[c] Letters are used to separate means. Data within columns containing the same letter are not significantly different according to Fisher's protected LSD (α=0.05).

CHAPTER 3

EFFECT OF RICE LEAF STAGE ON TOLERANCE TO BENZOBICYCLON IN A DRILL-SEEDED PRODUCTION SYSTEM

ABSTRACT

Effective postflood herbicide options for rice producers in the Midsouth are limited, thus, there is an imperative need for the commercialization of a new effective postemergence rice herbicide. Benzobicyclon is a new postflood-applied 4-hydroxyphenylpyruvate dioxygenase-inhibiting herbicide that was registered for use in U.S. rice in 2021 by Gowan® Company. Some rice cultivars, depending on genealogical lineage, are sensitive to benzobicyclon. Therefore, for benzobicyclon to be a viable weed control option for Midsouth rice growers, research must be conducted to evaluate varietal tolerances of many commonly grown rice cultivars to the application of benzobicyclon. In 2018 and 2019, field experiments were conducted at the Rice Research and Extension Center (RREC) near Stuttgart, AR. The objectives were to evaluate the influence of growth stage on rice varietal tolerance to benzobicyclon, and to evaluate pure line and hybrid rice tolerance to benzobicyclon following repeated use of acetolactate synthase-inhibiting herbicides. The experiments were implemented as a randomized complete block design with a split-plot arrangement of treatments. In one of two years, rice growth stage (leaf number) at application impacted tolerance to benzobicyclon. In that year, the 2-leaf application of benzobicyclon was generally more injurious to the rice cultivars, ‘CL153’, ‘Diamond’, ‘PVL01’, and ‘CLXL745’ than when applied at 4-leaf or tillering growth stages. In the second year, all rice cultivars, except ‘Rondo’, were not injured by benzobicyclon applied at any growth stage. In both years, the application of benzobicyclon on the rice cultivar ‘Rondo’ elicited ≥97%

crop injury, regardless of application timing. Findings from these experiments suggest that rice cultivar tolerance can vary across environments and that smaller-sized rice will be more prone to injury than when applications occur at a more typical timing for a postflood-applied herbicide. In general, 4-leaf and tillering rice will exhibit sufficient tolerance to benzobicyclon. It is especially not recommended to apply benzobicyclon on rice cultivars that have a predominant *indica*-type genealogical background. Benzobicyclon following repeated applications of acetolactate synthase-inhibiting herbicides to the pure line cultivar ‘CL153’ and the hybrid cultivar ‘CLXL745’ did not pose increased risk for injury to rice.

Nomenclature: benzobicyclon; rice, *Oryza sativa* L.

Keywords: crop injury; shoots; varietal tolerance; ALS-inhibiting herbicide; pure line rice; hybrid rice

INTRODUCTION

Rice production throughout many parts of the world serves as one of the most important and primary food sources for vast amounts of people. Similar to many international countries, the adult population in the United States (U.S.) is responsible for consuming a significant amount of rice. In the U.S., over the last several decades, rice consumption has increased (Batres-Marquez and Jensen 2005). Consequently, research objectives are invariably geared towards increasing the nutritional value of cultivated rice as well as improving yields. In an effort to vie with increasing consumption needs, many rice cultivars possessing rice herbicide tolerance, improved yields, and overall superior resiliency have been developed.

Present-day rice producers in the Midsouth have more cultivar options, with many having resistance to a particular herbicide. The implementation of imidazolinone herbicide (IMI)-resistant (Clearfield® BASF Corporation, Research Triangle Park, NC and Fullpage® RiceTec, Alvin, TX) rice and quizalofop-resistant (Provisia® Rice System, BASF Corporation, Research Triangle Park, NC and Max-Ace® Cropping Solution, RiceTec, Alvin, TX) rice has enabled Midsouth producers to make postemergence herbicide applications for the control of weeds with minimal risk for crop injury. Clearfield and Fullpage technologies enable producers to use IMI herbicides such as imazethapyr or imazamox. Imazethapyr, a Group 2 acetolactate synthase (ALS)-inhibiting herbicide, under the trade names Newpath® and Preface®, has strong herbicidal activity on a broad-spectrum of weeds when applied either preemergence or postemergence, and can provide season-long control when mixed with other herbicides (Sudianto et al. 2013). The Provisia® Rice System and Max-Ace® Cropping Solution enables producers to use quizalofop, a Group 1 acetyl CoA carboxylase (ACCase)-inhibiting herbicide, under the trade names Provisia® and Highcard™, for the control of gramineous weeds such as weedy rice (*Oryza sativa* L.) or barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.] (Lancaster 2017). Quizalofop is not phytotoxic to broadleaf weeds or sedges; therefore, it must be mixed with other herbicides to achieve broad-spectrum control.

In order to provide safety against the evolution of herbicide resistance, the use of multiple effective sites of action (SOA) is crucial for maintaining the longevity of herbicide effectiveness, and the over-reliance on a single herbicide SOA can lead to rapid widespread resistance (Norsworthy et al. 2007, 2012, 2013). The extensive adoption of herbicide-resistant rice cultivars enabled producers to effectively control problematic weeds, and these cultivars played a vital role in increasing the productivity of rice farming operations throughout the Midsouth. Total IMI-resistant rice hectares exponentially increased from the time of commercialization to the late 2000's. As a result, Midsouth rice producers were over-reliant on Clearfield technology, which ultimately led to the evolution of herbicide resistance in barnyardgrass and weedy rice (Burgos et al. 2008, 2014; Heap 2020). The increase of IMI-resistant rice hectares influenced widespread outcrossing with weedy rice and now a majority of weedy rice in the Midsouth is ALS-resistant (Norsworthy 2020, personal communication). This poses a real problem for Midsouth rice producers because now they are tasked with controlling ALS-resistant weedy rice with limited postemergence herbicide options.

Benzobicyclon, a 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibiting herbicide, is a new postflood-applied herbicide recently registered in Midsouth U.S. rice by Gowan® Company (Rogue® SC Herbicide, Gowan Company, Yuma, AZ 85364). Benzobicyclon can effectively control a broad spectrum of grasses, broadleaves, sedges, and aquatics (Komatsubara et al. 2009). Benzobicyclon is a pro-herbicide; therefore, it does not directly inhibit HPPD enzymes in plants (Komatsubara et al. 2009). For benzobicyclon to exhibit herbicidal activity on plants, the chemical must undergo a non-enzymatic hydrolysis reaction in the presence of water. During this reaction, benzobicyclon is converted to benzobicyclon hydrolysate, which is the potent and phytotoxic compound responsible for herbicidal activity (Williams and Tjeerdema 2016). Since the presence of water is required for benzobicyclon to perform optimally, it is imperative for producers to maintain a continuous flood throughout the growing season (Young et al. 2018).

The addition of benzobicyclon to Midsouth rice weed control programs will provide tremendous utility for controlling some of the most problematic weeds in rice. However, the development and commercialization of a new herbicide is a long and exorbitant task for chemical companies. In many cases, this process can take 10+ years at a cost of ≥$250 million (Green 2014). During the development process, and before a new herbicide can be commercially sold, extensive varietal tolerance testing must be conducted on the crop(s) for which the herbicide will be registered. Thus, for benzobicyclon to be a viable weed control option for Midsouth rice growers, research must be conducted to evaluate varietal tolerances of many commonly grown rice cultivars to the application of benzobicyclon.

Previous studies were conducted in Korea to evaluate the differences in sensitivity to HPPD-inhibiting herbicides among rice cultivars (Kim et al. 2012; Kwon et al. 2012). Findings from these studies conclude that some rice cultivars, depending on their genealogical lineage, are extremely susceptible to benzobicyclon and other HPPD-inhibiting herbicides. In the study conducted by Kwon et al. (2012), applications of benzobicyclon at different timings and different rates were made to multiple transplanted rice cultivars. Key symptomology of HPPD-inhibiting herbicides (bleaching and necrosis) were seen on many of the *indica*-type rice cultivars. As reported by Kwon et al. (2012), *japonica*-type rice cultivars show much better crop safety to benzobicyclon than *indica*-type or *japonica* x *indica*-type.

Increased tolerance to benzobicyclon in *japonica* rice cultivars is important because a vast majority of rice cultivars planted in the U.S. are of *japonica* origin as opposed to *indica* origin (Burgos et al. 2014). Similar to results observed by Kwon et al. (2012), Young et al. (2017) reported that out of 19 planted *japonica*-type cultivars, at two different locations in the Midsouth, no injury was observed at one week after the application of benzobicyclon and halosulfuron when applied at 494 g ha^{-1} and 72 g ha^{-1}, respectively. Conversely, the *indica* cultivars Rondo and Purple Maker were severely injured and high levels of chlorosis were observed when assessed two weeks after treatment (Young et al. 2017). Given the findings by Kwon et al. (2012) and Young et al. (2017), conclusions can be drawn that *indica*-type rice cultivars, or rice cultivars that have a predominant *indica*-type genealogical background, will not provide adequate crop safety to applications of benzobicyclon.

There are numerous different rice cultivars, both hybrid and pure line, that have been bred to possess IMI herbicide resistance. In a study conducted in Mississippi evaluating hybrid vs pure line rice cultivar sensitivity to treatments containing imazethapyr followed by imazamox, Bond et al. (2011) reported minimal (≤2%) crop injury on all evaluated cultivars when labeled applications were made. But, when application timing or incorrect rates were intentionally applied, the hybrid rice cultivars exhibited a slight delay in heading. The pure line rice cultivar was tolerant and did not exhibit any negative effects from herbicide applications. These findings indicate that there can be differences, albeit slight, in herbicide tolerance between pure line and hybrid rice cultivars.

Acetolactate synthase-inhibiting herbicides have been a foundational component of weed control in Midsouth rice for the past two decades, but in present-day, herbicide resistance is well documented. Each year, ALS-inhibitor-resistant weeds such as barnyardgrass, weedy rice (*Oryza* spp.), and rice flatsedge (*Cyperus iria* L.) become more and more problematic for Midsouth rice growers and consultants (Norsworthy et al. 2013). Although the occurrence of ALS-inhibitor-resistant rice weeds has become widespread, in 2019, 37% of Arkansas rice growers still relied on the use of IMI-resistant rice in conjunction with IMI herbicides for the control of various problematic weeds (Hardke 2019). In an IMI-resistant rice system, the herbicide recommendation is two sequential applications of imazethapyr applied either preemergence and early postemergence, or both sequential applications postemergence (Hardke and Goforth 2018). Hence, IMI herbicides will continue to be used early in the growing season and will likely be followed by subsequent postflood applications of benzobicyclon. Thus, research must be conducted to evaluate the risk for crop injury from benzobicyclon on pure line and hybrid rice at various growth stages and following repeated use of ALS herbicides.

MATERIALS AND METHODS

Influence of Growth Stage on Rice Varietal Tolerance to Benzobicyclon. Field experiments were conducted in 2018 and 2019 on a Dewitt silt loam (Fine, smectitic, thermic Typic Albaqualfs) at the Rice Research and Extension Center (RREC) near Stuttgart, AR. The experimental design for these experiments was a randomized complete block design with a split-plot arrangement of treatments. The whole-plot factor was herbicide application timing, and the split-plot factor was rice cultivar. All experiments had a nontreated control and all treatments were replicated four times.

Individual rice bays were used to prevent movement of benzobicyclon among treatments. Rice bays consisted of a continuous flood being held within man-made levees constructed with a tractor-mounted levee plow. In each rice bay, three grain drill passes were made at staggered dates – one for each of the applications differing by rice growth stage. Each experimental plot contained rows of five different rice cultivars spaced 38 cm apart and 11.2 m in length. In each experimental plot, rice was drill-seeded using a small-plot grain drill at a 1.5-cm depth at a seeding rate of 73 seeds m^{-1} of row, and a 1-m alley was established between plots.

In 2018, rice was drill-seeded on April 19, May 11, and May 16. These planting were staggered so each planting pass would contain rice at three different growth stages at the time of application. In 2019, rice was drill-seeded on April 1, April 23, and May 7. The rice cultivars planted were: ‘CL153’ (Clearfield® Rice, BASF Corporation, Research Triangle Park, NC 27709), ‘PVL01’ (Provisia™ Rice System, BASF Corporation, Research Triangle Park, NC 27709), ‘Rondo’ (Yan and McClung 2010), ‘Diamond’ (Moldenhauer 2018), and ‘CLXL745’ (Clearfield® Rice, BASF Corporation, Research Triangle Park, NC 27709).

A broadcast application of clomazone (Command® Herbicide, FMC Corporation, Philadelphia, PA) at 336 g ai ha^{-1} was made at planting in each year. Prior to flooding, all experimental plots were fertilized with nitrogen (N) at 155 kg N ha^{-1}. Additionally, all experimental plots were kept weed-free with herbicides according to recommendations by the University of Arkansas Extension Service (Scott et al. 2018). All maintenance herbicide applications made prior to flooding were applied with a CO_2-pressurized backpack sprayer utilizing a handheld four-nozzle boom equipped with 110015 AIXR nozzles (Teejet Technologies, Springfield, IL) calibrated to deliver 140 L ha^{-1} at 276 kPa. In 2018, the postflood applications of benzobicyclon were made utilizing identical parameters to applications made prior to flooding. In 2019, postflood benzobicyclon applications were made with a two-person, 7.6-m wide, boom capable of covering the entire rice bay in one swath. Applications parameters were the same as for the four-nozzle boom application. Herbicide treatments evaluated consisted of benzobicyclon (Gowan Company, Yuma, AZ 85364) at 751 g ai ha^{-1} and no benzobicyclon. Methylated seed oil was added to the benzobicyclon at 1% v/v. The application was made to rice at 2-leaf, 4-leaf, and tillering growth stages.

Assessments. Rice tolerance to herbicide applications was assessed by means of estimations of crop injury (injury ratings) at 14 and 21 days after the postflood applications of benzobicyclon. Injury ratings were based on a scale of 0 to 100%, with 0% being no crop injury relative to the nontreated check and 100% being complete crop death (Frans and Talbert 1977). Additionally, 2 m rice shoot counts were recorded 48 days after the postflood application of benzobicyclon.

Statistical Analyses. All data were analyzed using SAS 9.4 (SAS Institute Inc., Cary, NC) and were subjected to analysis of variance (ANOVA). Crop injury data were assumed to have a beta distribution (values of 0 were adjusted to 0.001 to avoid exclusion) and were analyzed using PROC GLIMMIX. Relative shoot count data were assumed to have a gamma distribution and were analyzed using PROC GLIMMIX. When analyzing crop injury and relative shoot count data, blocks were considered random, while application timing and cultivar were considered fixed. The 2018 and 2019 site years were analyzed separately for each response variable due to a significant site year effect being detected. Means were separated according to Fisher's protected least significant difference (LSD) at P=0.05. P-values of ANOVA are displayed in Tables 3.1 and 3.2.

Evaluation of Pure Line and Hybrid Rice Tolerance to Benzobicyclon Following Repeated Use of ALS-inhibiting Herbicides. Field experiments were conducted in 2018 and 2019 on a Dewitt silt loam (Fine, smectitic, thermic Typic Albaqualfs) at the RREC near Stuttgart, AR. The experimental design for these experiments was a randomized complete block design with a split-plot arrangement of treatments. The whole plot factor was site year, and the split-plot factors were rice cultivar (pure line and hybrid) and herbicide treatment. All experiments had a nontreated control and all treatments were replicated four times.

Rice bays containing the experimental plots were setup in a similar fashion to the rice cultivar tolerance experiment, ensuring that the movement of benzobicyclon between treatments was alleviated. Experimental plots measured 1.8 m wide by 5.2 m long, and within each plot rice was drill-seeded using a small-plot Almaco (ALMACO Custom Seed Research Equipment, Nevada, IA 50201) cone grain drill at a 1.5-cm depth at a seeding rate of 73 seeds m^{-1} of row for the pure line cultivar and 36 seeds m^{-1} of row for the hybrid cultivar. A 1-m nontreated alley was established between plots. In 2018, rice was drill-seeded on April 19, and in 2019, rice was drilled-seeded on May 13. The pure line rice cultivar used was ‘CL153’, and the hybrid rice cultivar used was ‘CLXL745’.

A broadcast application of clomazone at 336 g ai ha^{-1} was made at planting. The experiments were kept weed-free throughout the growing season by means of maintenance herbicide applications with labeled herbicides. All herbicide treatments were applied with a CO_2-pressurized backpack sprayer utilizing a handheld four-nozzle boom equipped with 110015 AIXR nozzles calibrated to deliver 140 L ha^{-1} at 276 kPa. The evaluated herbicide treatments are listed in Table 3.3.

Assessments. Pure line and hybrid rice cultivar tolerance to benzobicyclon following repeated use of ALS-inhibiting herbicides was visually assessed prior to flooding (before benzobicyclon application) and 14 and 21 days after the postflood application of benzobicyclon. Ratings were on a 0 to 100% scale, with 0% being no crop injury relative to the nontreated check and 100% being complete crop death (Frans and Talbert 1977). Once the rice reached the heading growth stage, each experimental unit was evaluated for date of 50% heading. Upon reaching physiological maturity, experimental plots were machine harvested using a small-plot combine to determine rough rice yield at an adjusted moisture of 12%.

Statistical Analyses. All data were analyzed using SAS 9.4 (SAS Institute Inc., Cary, NC) and were subjected to ANOVA. Crop injury data were assumed to have a beta distribution (values of 0 were adjusted to 0.001 to avoid exclusion) and were analyzed using PROC GLIMMIX (Gbur et al. 2020). Yield data were assumed to have a gamma distribution and were analyzed using PROC GLIMMIX (Gbur et al. 2020). When analyzing crop injury and yield, blocks were considered random, and herbicide, cultivar, and site year were fixed. There were no interactions with site year; hence, only the effects of herbicide and cultivar are shown. Means were separated according to Fisher's protected least significant difference (LSD) at α=0.05. P-values of ANOVA are displayed in Table 3.4.

RESULTS AND DISCUSSION

Influence of Growth Stage on Rice Varietal Tolerance to Benzobicyclon.

Rice tolerance – crop injury

In 2018, rice growth stage at the time of the benzobicyclon application significantly influenced observed crop injury, regardless of rice cultivar. At 14 and 21 days after treatment

(DAT), when benzobicyclon was applied to tillering rice (V5 growth stage) (Counce et al. 2000), all rice cultivars except ‘Rondo’ exhibited increased tolerance to benzobicyclon compared to applications to 2- or 4-leaf rice (Table 3.5). These findings were expected and are consistent with other research denoting increased susceptibility to herbicides as a function of small plants at application (Johnson et al. 2007; Brabham et al. 2021).

Benzobicyclon acts differently than other herbicides with respect to plant uptake. According to Brabham et al. (2019), benzobicyclon is almost exclusively taken up through the submersed shoot and is almost entirely reliant upon the presence of flood water. Conclusions from their experiment elucidate that when benzobicyclon is applied to only the foliage of weedy rice, which is the same species as cultivated rice, control was 2% with no added adjuvant and 9% when mixed with methylated seed oil. When benzobicyclon was applied only to the flood water or both the plant foliage + the flood water, control was 75 and 88%, respectively. In this experiment, rice plants at the 2-leaf growth stage were mainly submerged under flood water whereas more than 50% of the tillering rice plants were not submerged. Since the 2-leaf rice plants had more of the shoot and foliage submerged, more of the herbicide was likely taken up, eliciting increased levels of injury compared to the tillering rice. In other work, it has also been shown that control of weedy rice plants that are of a *HIS1/HIS1* genotype is a function of size at application, with 1- to 2-leaf plants, regardless of accession, often being controlled >60% with benzobicyclon at 371 g ha^{-1} whereas control diminished to <20% when applications were made to 4-leaf or larger plants (Brabham et al. 2021).

Results for rice tolerance to benzobicyclon were vastly different in the summer of 2019. All treatments, or combinations of application timing/rice cultivar were not injurious to rice at 14 and 21 DAT, regardless of size at application (Table 3.6). One possible explanation for the difference between years is a result of precipitation following application. According to climatological observation records (USDC-NOAA 2021), multiple rainfall events at the location of the experiment occurred within four days following application in 2019. Over the four days following application, these rainfall events deposited approximately 7 cm of water, which would have resulted in loss of benzobicyclon-containing water from the levee gates as well as dilution of the benzobicyclon concentration within each treated bay. Assuming that within each rice bay there was a consistent flood at a 7-cm depth, the addition of 7 more cm would reduce the concentration to 50% of the original application rate if none of the benzobicyclon was lost from the bay.

Even with benzobicyclon lost from the bays in 2019, there was still sufficient concentration to injure the severely sensitive cultivar Rondo. In 2018 and 2019, the application of benzobicyclon elicited ≥97% injury on Rondo at 14 and 21 DAT, regardless of application timing (Tables 3.5 and 3.6). These findings are consistent with studies conducted by Kwon et al. (2012) and Young et al. (2017) that concluded that rice cultivars with an *indica*-type background will be severely injured by applications of benzobicyclon over a range of rates. Therefore, it is not recommended to apply benzobicyclon on rice cultivars that have a predominant *indica*-type background because of the increased likelihood the cultivar has a sensitive *HIS1* gene (Brabham et al. 2021).

Shoot Counts

Rice shoot counts were conducted 48 DAT to provide quantitative data to aid in evaluating the effects of growth stage on rice varietal tolerance to benzobicyclon. In 2018, rice shoot count results closely aligned with crop injury results – all treatment combinations of application timing and rice cultivar, except for ‘Provisia’ rice (PVL01) applied at 4-leaf and tillering growth stages, reduced above-ground vegetative growth compared to the nontreated (Table 3.7). An additional observation from these results is that when benzobicyclon was applied at 2-leaf, all cultivars exhibited a reduction in above-ground vegetative growth compared to when benzobicyclon was applied at tillering growth stages.

In recent years, the cultivation of hybrid rice cultivars has become almost as commonplace as pure line cultivars in the Midsouth (McBride et al. 2018). Hybrid rice cultivars are superior to pure line cultivars in many ways. For example, many hybrid rice cultivars exhibit greater seedling vigor, vegetative growth, yield potential, and milling quality compared to pure line rice cultivars (Hardke et al. 2018). Since the cultivar 'CLXL745' is a hybrid, one would expect it to have increased shoot counts compared to the pure line cultivars. However, in this experiment, the 'PVL01' rice cultivar produced the highest number of tillers relative to the nontreated following the application of benzobicyclon at the tillering growth stage. These findings suggest that 'Provisia' rice tiller production may not be as adversely affected as other rice cultivars following the application of benzobicyclon at later growth stages.

Evaluation of Pure line and Hybrid Rice Tolerance to Benzobicyclon Following Repeated Use of ALS-inhibiting Herbicides.

Crop injury

In general, at 21 DAT, the evaluated pure line (CL153) and hybrid (CLXL745) rice cultivars were tolerant to the application of benzobicyclon + halosulfuron following repeated use of ALS-inhibiting herbicides (Table 3.8). When benzobicyclon + halosulfuron was applied alone, or after multiple applications of ALS-inhibiting herbicides, the hybrid rice cultivar was more tolerant than the pure line rice cultivar. Although observed levels of injury significantly differed between the pure line and hybrid rice cultivars, crop injury was <8% for all combinations of herbicide treatments and rice cultivars.

These results contradict findings reported by Bond and Walker (2011) where applications of imazamox, another ALS-inhibiting herbicide labeled for use in rice, delayed maturity of the hybrid rice cultivar ‘CLXL745’ and reduced rough rice yield compared to the pure line rice cultivar ‘CL161’. Variability in IMI hybrid rice response to ALS-inhibiting herbicides, particularly the Clearfield hybrids, is highly dependent upon environmental conditions surrounding applications and is also a result of resistance to the herbicide coming from the parent line of the rice cultivar (Wenefrida et al. 2004). Therefore, the most likely explanation for the decreased levels of tolerance in the pure line rice cultivar is the presence of benzobicyclon.

Yield

Yield response of rice from this experiment followed a similar trend compared to crop injury. While the interaction of rice cultivar and herbicide treatment was not significant, there was a significant main effect of rice cultivar on yield (Table 3.5). The hybrid rice cultivar ‘CLXL745’ yielded almost 100 kg ha^{-1} more than the pure line cultivar ‘CL153’, averaged over herbicide treatments (data not shown). The yield advantages of hybrid rice cultivars over pure line rice cultivars have been studied extensively, and these advantages can be attributed to many factors, most importantly hybrid vigor. Hybrid rice cultivars have a higher growth rate during early vegetative stages as a result of rapid leaf area expansion (Yamauchi 1994; Laza et al. 2001; Yang et al. 2007). Additionally, hybrid rice cultivars develop rice grains more efficiently than pure line cultivars, leading to increased yields (Song et al. 1990; Yang et al. 2007). Therefore, yield results from this experiment are consistent with many studies conducted in the past, even after considering the difference in tolerance between the hybrid and pure line rice cultivars.

Practical Implications

Results from this research indicate that benzobicyclon, with optimal application timing under the right conditions, will be safe for use in Midsouth rice. Findings from these experiments suggest that rice cultivar tolerance can vary across environments and that smaller-sized rice will be more prone to injury than when applications occur at timings characteristic for a postflood applied herbicide in the Midsouth. In general, 4-leaf and tillering rice will exhibit sufficient tolerance to benzobicyclon. However, regardless of growth stage at application, it is not recommended to apply benzobicyclon on the rice cultivar ‘Rondo’, or on rice cultivars that have a predominant *indica*-type background because of the increased likelihood of a sensitive *HIS1* gene.

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TABLES

Table 3.1. The p-values from ANOVA for the cultivar tolerance/growth stage experiment in 2018.

		ANOVA[a]	
Response variable tested	Factors evaluated	14 DAT	21 DAT
		-------------p-values------------	
Crop injury	application timing	<.0001	<.0001
	cultivar	<.0001	<.0001
	application timing*cultivar	0.0007	<.0001
Relative shoot counts	application timing	0.0023	
	cultivar	<.0001	
	application timing*cultivar	0.0031	

[a] Abbreviations: DAT – days after treatment

Table 3.2. The p-values from ANOVA for the cultivar tolerance/growth stage experiment in 2019.

		ANOVA[a]	
Response variable tested	Factors evaluated	14 DAT	21 DAT
		-------------p-values------------	
Crop injury	application timing	0.3273	0.6868
	cultivar	<.0001	<.0001
	application timing*cultivar	<.0001	<.0001
Relative shoot counts	application timing	0.8178	
	cultivar	0.0002	
	application timing*cultivar	0.2129	

[a] Abbreviations: DAT – days after treatment

Table 3.3. List of herbicide treatments, their respective growth stages at application, and rates applied for the experiments evaluating hybrid and pure line rice tolerance to benzobicyclon following repeated use of acetolactate synthase-inhibiting herbicides.

Cultivar[a]	Herbicide[b]	Application timing	Rate
			g ai ha^{-1}
Nontreated (Pure line)	--		--
Nontreated (Hybrid)	--		--
Pure line	imazosulfuron	PRE	336
	imazethapyr + NIS	2-leaf	105
	imazethapyr + NIS	preflood	105
	imazosulfuron	PRE	336
	imazethapyr + NIS	2-leaf	105
	imazethapyr + NIS	preflood	105
	benzobicyclon + halosulfuron + MSO	postflood	248 + 35
	benzobicyclon + halosulfuron + MSO	postflood	248 + 35
Hybrid	imazosulfuron	PRE	336
	imazethapyr + NIS	2-leaf	105
	imazethapyr + NIS	preflood	105
	imazosulfuron	PRE	336
	imazethapyr + NIS	2-leaf	105
	imazethapyr + NIS	preflood	105
	benzobicyclon + halosulfuron + MSO	postflood	248 + 35
	benzobicyclon + halosulfuron + MSO	postflood	248 + 35

[a] Pure line rice cultivar – CL153; Hybrid rice cultivar – CLXL745

[b] Abbreviations: MSO – methylated seed oil at 1% v/v; NIS – non-ionic surfactant at 0.25% v/v; PRE - preemergence

Table 3.4. The p-values from ANOVA for the hybrid/pure line rice tolerance to benzobicyclon after repeated use of acetolactate synthase-inhibiting herbicides. These values reflect both the 2018 and 2019 experiments combined as a result of non-significant site year effects.

		ANOVA[a]		
Response variable tested	Factors evaluated	@ flooding	14 POSTFLD	21 POSTFLD
		----------------------	p-values	-----------------------
Crop injury	cultivar	0.6181	0.1107	0.0499
	herbicide treatment	0.0054	0.5848	0.4511
	cultivar*herbicide treatment	0.2587	0.2120	0.0087
Yield	cultivar		0.0004	
	herbicide treatment		0.0548	
	cultivar*herbicide treatment		0.1611	

[a] Abbreviations: POSTFLD – postflood

Table 3.5. Estimates of crop injury relative to the nontreated check 14 and 21 days after treatment (DAT) for the rice tolerance/growth stage experiment in 2018. At 14 and 21 DAT, there was a significant interaction of application timing and rice cultivar.

		Crop injury	
Application timing	Cultivar	14 DAT[a]	21 DAT
		------------------%	------------------
2-leaf	CL153	54 b[b]	39 c
	Diamond	42 c	50 b
	PVL01	54 b	32 d
	Rondo	99 a	99 a
	CLXL745	39 cd	34 cd
4-leaf	CL153	32 cd	24 e
	Diamond	30 cd	51 b
	PVL01	25 d	11 f
	Rondo	99 a	99 a
	CLXL745	33 cd	55 b
Tillering	CL153	4 f	5 g
	Diamond	5 f	17 e
	PVL01	3 f	3 g
	Rondo	98 a	99 a
	CLXL745	10 e	17 e

[a] Abbreviations: DAT – days after treatment

[b] Letters are used to separate means. 14 DAT means with different letters are significantly different. 21 DAT means with different letters are significantly different. These analyses were conducted separately. All data were subjected to analysis of variance and means were separated according to Fisher's protected LSD (α=0.05).

Table 3.6. Estimates of crop injury relative to the nontreated check 14 and 21 days after treatment (DAT) for the rice tolerance/growth stage experiment in 2019. At 14 and 21 DAT, there was a significant interaction of application timing and rice cultivar.

		Crop injury	
Application timing	Cultivar	14 DAT[a]	21 DAT
		------------------%------------------	
2-leaf	CL153	0 c[b]	0 c
	Diamond	0 c	0 c
	PVL01	0 c	0 c
	Rondo	99 a	99 a
	CLXL745	0 c	0 c
4-leaf	CL153	0 c	0 c
	Diamond	0 c	0 c
	PVL01	0 c	0 c
	Rondo	99 a	99 a
	CLXL745	0 c	0 c
Tillering	CL153	0 c	0 c
	Diamond	0 c	0 c
	PVL01	0 c	0 c
	Rondo	96 b	97 b
	CLXL745	0 c	0 c

[a] Abbreviations: DAT – days after treatment

[b] Letters are used to separate means. 14 DAT means with different letters are significantly different. 21 DAT means with different letters are significantly different. These analyses were conducted separately. All data were subjected to analysis of variance and means were separated according to Fisher’s protected LSD (α=0.05).

Table 3.7. Shoot count response relative to the nontreated check from the interaction of application timing and rice cultivar for the rice tolerance/growth stage experiment in 2018. Data were collected 48 days after application.

Application timing	Cultivar	Shoots	
		% of nontreated[b]	
2-leaf	CL153	48	ef[a]
	Diamond	39	f
	PVL01	58	cde
	CLXL745	49	ef
4-leaf	CL153	40	f
	Diamond	54	de
	PVL01	100	ab
	CLXL745	80	b
Tillering	CL153	89	b
	Diamond	74	bcd
	PVL01	134	a
	CLXL745	80	bc

[a] Letters are used to separate means. Means with different letters are significantly different. All data were subjected to analysis of variance and means were separated according to Fisher's protected LSD (α=0.05).

[b] Nontreated plots for cultivars CL153, Diamond, PVL01, and CLXL745 from the 2-leaf growth stage planting had an average number of shoots/m of row of 144, 87, 118, and 307, respectively.

Nontreated plots for cultivars CL153, Diamond, PVL01, and CLXL745 from the 4-leaf growth stage planting had an average number of shoots/m of row of 183, 96, 184, and 320, respectively.

Nontreated plots for cultivars CL153, Diamond, PVL01, and CLXL745 from the tillering growth stage planting had an average number of shoots/m of row of 206, 131, 282, and 371, respectively.

Table 3.8. Estimates of crop injury relative to the nontreated check 21 days after treatment (DAT) for the rice tolerance to benzobicyclon following repeated use of acetolactate synthase-inhibiting herbicides experiment in 2018 and 2019. There was a significant interaction of rice cultivar and herbicide treatment. Data were averaged over site years.

Cultivar	Herbicide treatment[a]	Crop injury
		%
CL153	imazosulfuron fb imazethapyr (2LF) fb imazethapyr (preflood)	2 b[b]
	imazosulfuron fb imazethapyr (2LF) fb imazethapyr (preflood) fb benzobicyclon + halosulfuron	7 a
	benzobicyclon + halosulfuron	5 a
CLXL745	imazosulfuron fb imazethapyr (2LF) fb imazethapyr (preflood)	4 a
	imazosulfuron fb imazethapyr (2LF) fb imazethapyr (preflood) fb benzobicyclon + halosulfuron	1 b
	benzobicyclon + halosulfuron	0 b

[a] Abbreviations: fb – followed by; 2LF – 2-leaf rice application timing

[b] Letters are used to separate means. Means with different letters are significantly different. All data were subjected to analysis of variance and means were separated according to Fisher's protected LSD (α=0.05).

CHAPTER 4

EVALUATION OF CROP INJURY FROM REDUCED RATES OF BENZOBICYCLON AND OTHER COMMONLY APPLIED RICE HERBICIDES ON STS AND NON-STS SOYBEAN

ABSTRACT

Soybean and rice are commonly grown in close proximity to one another in the Midsouth. Many of the herbicides commonly used for weed control in rice can elicit severe phytotoxicity in soybean, even at extremely low rates of the herbicides. Gowan Company® recently registered benzobicyclon as a postflood herbicide option in rice. Benzobicyclon is a pro-herbicide that must be converted to its phytotoxic compound benzobicyclon hydrolysate. Thus, benzobicyclon will be applied postflood, likely while nearby soybean are actively growing. Therefore, the risks associated with off-target movement of benzobicyclon onto adjacent soybean fields must be evaluated and understood. In 2018 and 2019, field experiments were conducted at the Milo J. Shult Agricultural Research & Extension Center in Fayetteville, AR to evaluate the impact of lower-than-labeled rates of benzobicyclon and other commonly applied rice herbicides on sulfonylurea-tolerant soybean (STS) and non-STS soybean applied during early vegetative development. The experiments were implemented as randomized complete block designs with a split-plot treatment structure. Benzobicyclon, halosulfuron, benzobicyclon + halosulfuron, and florpyrauxifen-benzyl were applied to STS and non-STS soybean at 1/20 and 1/180X rates based on current or anticipated labels for rice. In 2018, when evaluated 14 days after treatment (DAT), vegetative soybean treated with a 1/20X rate of florpyrauxifen-benzyl were severely injured. In 2019, 14 DAT, both reduced rates of florpyrauxifen-benzyl were severely injurious to vegetative soybean. In both years, when evaluated 14 DAT, treatments containing benzobicyclon alone, regardless of reduced rate, injured soybean ≤8%. These findings indicate that benzobicyclon can be safely applied with minimal risk of off-target injury on adjacent soybean.

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

Keywords: crop injury, reduced rate, sulfonylurea-tolerant soybean

INTRODUCTION

Rice has been a staple of agricultural production in Arkansas since the early 1900's. Prior to 1973, California, Louisiana, and Texas planted and harvested nearly equal amounts of rice as the state of Arkansas (Talbert and Burgos 2007). In present-day, Arkansas produces approximately half of the total U.S. rice, and is the top rice-producing state. In 2020, U.S. rice farmers planted just under 1.2 million hectares of rice and of those total U.S. planted hectares, Arkansas was responsible for planting over 579,000 hectares (NASS 2020).

In Arkansas, soybean is often grown in close proximity to rice or planted in rotation with rice (Wilson et al. 2010; Schwartz-Lazaro et al. 2017). With the addition of new herbicide options for postemergence control of problematic weeds in rice, an understanding of how these herbicides affect adjacent crops is imperative. The use of many acetolactate synthase (ALS)-inhibiting herbicides in rice poses risks for off-target crop injury on adjacent soybean. In a recent study, Schwartz-Lazaro et al. (2017) investigated soybean crop injury elicited by applications of commonly applied ALS-inhibiting rice herbicides at low rates on V3 soybean. When 1/20x rates of bispyribac, penoxsulam, and halosulfuron were applied to V3 soybean, observed crop injury at 14 days after application was 36, 14, and 11%, respectively. When applied at 1/80x rates, observed injury for the same herbicides was 15, 8, and 7%, respectively (Schwartz-Lazaro et al. 2017). Additionally, soybean plants treated with bispyribac, which was the most injurious of the evaluated ALS-inhibiting herbicides, yielded 57% less than the nontreated when applied at the 1/20x rate at the V3 stage (Schwartz-Lazaro et al. 2017).

With many ALS-inhibiting herbicides having a significant role in weed control programs in Midsouth rice and the capacity that ALS-inhibiting herbicides have activity on soybean, the risk for damage associated with off-target movement is high (Nandula et al. 2009; Rana et al.

2014). Sulfonylurea-tolerant soybean (STS) were commercialized to allow growers to apply sulfonylurea herbicides mid-season in their soybean crops and to reduce the risk of injury from off-target physical drift and carryover from previous herbicide applications (Albrecht et al. 2017; Anderson and Simmons 2004). Sulfonylurea-tolerant soybean cultivars may provide additional options for weed control, but due to the overreliance on ALS-inhibiting herbicides, many problematic weed species have evolved resistance to the site of action (Norsworthy et al. 2013). As a result, other sites of action are commonly used for weed control in soybean, and non-STS soybean cultivars are predominantly planted.

In recent years, off-target movement, or drift, of synthetic auxin herbicides has become a major concern for agriculture (Riar et al. 2013). The term "drift" encompasses two different ways that herbicide active ingredients can migrate away from the intended target: primary and secondary drift. Primary drift, also referred to as physical, particle, or droplet drift, occurs when herbicide droplets migrate away from the intended target at the time of application (Maybank et al. 1978). The occurrence of primary drift is largely dependent on the mechanical properties of the sprayer, spray boom height above the target area, spray droplet size, wind speed, and atmospheric turbulence (Maybank et al. 1978). Since many rice herbicides, including synthetic auxin herbicides, are applied in proximity to soybean, there is potential risk of these herbicide droplets migrating onto adjacent sensitive soybean.

Synthetic auxin herbicides have been the foundation that many herbicide programs have been built upon for the past several decades. When applied at low doses, in some plants, synthetic auxin herbicides have stimulated plant growth, but at high concentrations, plant growth is disrupted, and lethal damage can be caused (Grossmann 2010). In 2017, florpyrauxifen-benzyl (Loyant® Herbicide, Dow AgroSciences LLC, Indianapolis, IN 46268), a synthetic auxin herbicide, was commercialized to combat many rice weeds possessing evolved herbicide resistance to ALS-inhibitors, acetyl Coenzyme A carboxylase (ACCase)-inhibitors, glyphosate, propanil, and quinclorac chemistries (Anonymous 2020). Florpyrauxifen-benzyl provides Midsouth rice growers with a new effective postemergence site of action for the control of broadleaves, grasses, and sedges (Schwartz-Lazaro et al. 2017). In recent studies, when applied at much lower-than-labeled rates, florpyrauxifen-benzyl was very injurious to soybean. When applied on V3 soybean at 1/20x and 1/80x rates, Schwartz-Lazaro et al. (2017) reported soybean injuries of 78 and 40%, respectively, at 14 days after treatment (DAT). In a similar study, when florpyrauxifen-benzyl was applied to R1 soybean at 1/20x and 1/160x rates, Miller and Norsworthy (2018) reported injuries of 66 and 12%, respectively, at 14 DAT. Per the EPA approved label, florpyrauxifen-benzyl can legally be applied postemergence in rice (Anonymous 2017), which likely increases risk for off-target movement onto sensitive soybean. Therefore, reduced rates of florpyrauxifen-benzyl were evaluated in order to compare crop injury from a rice herbicide that is well-documented to be severely injurious on soybean to other commonly applied rice herbicides.

Discovered in the 1980s, 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibiting herbicides belong to one of the newest herbicide sites of action (Lee et al. 1997). HPPD-inhibiting herbicides have activity on problematic weeds by blocking an enzyme within the plant that is responsible for forming carotenoids, which protect chlorophyll from powerful ultraviolent light (Dunne 2012). Although HPPD-inhibiting herbicides tend to be most phyto-active on broadleaves or dicots, they also control some grasses. The triketone herbicide family, specifically, directly inhibits the HPPD enzyme.

Gowan Company® recently obtained registration of benzobicyclon, a Group 27 HPPD-inhibiting herbicide, as a postflood herbicide option in rice. It is the first commercially available HPPD-inhibiting herbicide in Midsouth rice production. Benzobicyclon is a pro-herbicide and does not directly inhibit HPPD enzymes in plants (Komatsubara et al. 2009). In order to have phytotoxic effects on plants, benzobicyclon must undergo a non-enzymatic hydrolysis reaction in the presence of water to be converted to benzobicyclon hydrolysate (Williams and Tjeerdema 2016). Because benzobicyclon requires the presence of water to convert to benzobicyclon hydrolysate, it is imperative that a continuous flood be present. Additionally, flood depth has an impact on the efficacy of benzobicyclon. Davis et al. (2013) documented that benzobicyclon performed optimally when at least a 10-cm flood depth was present.

In Arkansas, approximately 90% of rice hectares are drill-seeded and grown in a continuously flooded paddy rice system (Hardke and Chlapecka 2019). Therefore, due to benzobicyclon requiring the presence of water to be converted to the active compound, and most Arkansas acres being grown in paddy rice, benzobicyclon will be an additional potentially viable herbicide option for growers. Although triketone herbicides readily persist in the soil and can potentially elicit damage in subsequently planted crops (Riddle et al. 2013; Norsworthy and Young 2020) reported that subsequently planted soybean yields were not affected by benzobicyclon residues from the previous year’s application. Additionally, since benzobicyclon requires a continuous flood to be active, it is unlikely to injure actively growing adjacent soybean.

In order to fully understand the risk of applying benzobicyclon in Midsouth rice, all likely scenarios where the herbicide will be used must be evaluated, including effects on adjacent crops such as soybean. Thus, the objective of this research was to determine if benzobicyclon applied at reduced rates will elicit injury on STS and non-STS soybean cultivars, relative to other commonly applied rice herbicides. Both STS and non-STS cultivars are used in this study because benzobicyclon is likely to be applied in combination with the sulfonylurea herbicide halosulfuron to rice.

MATERIALS AND METHODS

General Setup. Field experiments were conducted in the summers of 2018 on a Captina silt loam (Fine-silty, siliceous, active, mesic Typic Fragiudults) and again in 2019 on a Cleora fine sandy loam (Coarse-loamy, mixed, active, thermic Fluventic Hapludolls) at the Milo J. Shult Agricultural Research & Extension Center in Fayetteville, AR. All experimental plots were fertilized according to University of Arkansas extension recommendations (Slaton et al. 2013). Herbicide applications were made on soybean in early vegetative development (V3). The experimental design for these experiments was a randomized complete block design with a split-plot treatment arrangement. The whole-plot factors were herbicide and rate, and the split-plot factor was soybean cultivar. All experiments had a nontreated control, and all treatments were replicated four times.

Herbicide trade names, manufacturers, and common names used in the experiments are listed in Table 4.1. The herbicide treatments evaluated for the experiments conducted in 2018 and 2019 are listed in Table 4.2. Each experimental plot contained four rows spaced 91 cm apart resulting in an overall plot size of 3.6 m wide by 6 m long. In each experimental plot, two rows of a STS cultivar, and two rows of a non-STS cultivar were planted using a 4-row planter at a 2.5-cm depth at a seeding rate of 345,800 seeds ha^{-1}, and a 1.5 m alley was established between experimental plots. In 2018, the STS soybean cultivar ‘DGSTS47’ (Dyna-Gro® Seed, Nutrien Ag Solutions, Loveland, CO 80538) and the non-STS soybean cultivar ‘P47T76’ (Pioneer® Hi-Bred, Johnston, IA 50131) were planted on May 5, 2018. In 2019, the STS soybean cultivar ‘CZ 4548’ (Credenz® Soybean Seed, BASF Corporation, Research Triangle Park, NC 27709) and the non-STS soybean cultivar ‘CZ 4540’ (Credenz® Soybean Seed, BASF Corporation, Research Triangle Park, NC 27709) were planted on June 6, 2019.

In 2018, a broadcast application of flumioxazin (Valor® SX Herbicide, Valent USA, Walnut Creek, CA 94596) at 72 g ai ha^{-1} was made at planting. In 2019, a broadcast application of glyphosate (Roundup PowerMax® Herbicide, Monsanto Company, St. Louis, MO 63167) at 1927 g ai ha^{-1} and sulfentrazone + *S*-metolachlor (BroadAxe® XC Herbicide, Syngenta Crop Protection LLC, Greensboro, NC 27419) at 153 g ai ha^{-1} and 1380 g ai ha^{-1}, respectively, was made at planting. In 2018, the herbicide application made at planting effectively controlled weeds until just before canopy closure, when some minor hand-weeding was required. In 2019, an early postemergence application of quizalofop (Assure® II Herbicide, AMVAC Chemical Corporation, Newport Beach, CA 92660) at 77 g ai ha^{-1}, glufosinate (Liberty® 280 SL Herbicide, Bayer CropScience, Research Park Triangle, NC 27709) at 656 g ai ha^{-1}, and *S*-metolachlor (Dual Magnum® Herbicide, Syngenta Crop Protection LLC, Greensboro, NC 27419) at 1068 g ai ha^{-1} was made to control weeds that had emerged prior to the V3 application. This maintenance application was made two days prior to the application of evaluated treatments.

All herbicide treatments were applied to the center two rows containing one STS and one non-STS soybean cultivar, and applications were made with a CO_2-pressurized backpack sprayer utilizing a handheld four-nozzle boom equipped with 110015 AIXR nozzles (Teejet Technologies, Springfield, IL 62703) calibrated to deliver 140 L ha^{-1} at 276 kPa. During application, spray shields were used on both sides of the center two rows to mitigate herbicide injury from physical drift onto the adjacent non-treated rows.

Assessments. Crop injury ratings were taken at 7, 14, 21, and 28 days after the V3 application. Ratings were based on a scale of 0 to 100, with 0 being no crop injury relative to the nontreated check and 100 being complete crop death (Frans and Talbert 1977). Each treated row in each experimental plot from the field experiments in 2018 were machine harvested separately using a small-plot combine following physiological maturity to determine soybean grain yield at an adjusted moisture of 13%. Yield data were not collected for the vegetative growth stage experiment and the reproductive growth stage experiment in 2019 because all experimental plots were accidentally destroyed via mowing late in the season by an employee at the Milo J. Shult Agricultural Research & Extension Center.

Statistical analyses. All data were analyzed using SAS 9.4 (SAS Institute Inc., Cary, NC) and were subjected to analysis of variance (ANOVA). Crop injury data were assumed to have a beta distribution (values of 0 were adjusted to 0.001 to avoid exclusion) and were analyzed using PROC GLIMMIX. Relative yield data were assumed to have a gamma distribution and were analyzed using PROC GLIMMIX (Gbur et al. 2020). When analyzing crop injury and relative yield data, blocks were considered random and herbicide, rate, and cultivar were fixed. Each site year was analyzed separately for each response variable because a significant site year effect was detected when data from each year were analyzed together. Means were separated according to Fisher’s protected least significant difference (LSD) at P=0.05. P-values of ANOVA are displayed in Table 4.3.

RESULTS AND DISCUSSION

Crop Injury. In 2018, there was a significant three-way interaction (P=0.0462) of herbicide, rate, and cultivar for the 14 days after treatment (DAT) evaluation. The highest rate (1/20X) of florpyrauxifen-benzyl was severely injurious (>80%) to soybean regardless of whether the cultivar possessed tolerance to sulfonylurea herbicides, and the observed injury was greater than all other treatments (Table 4.4). These findings are consistent with research conducted by Schwartz-Lazaro et al. (2017), where they found that at 14 DAT florpyrauxifen-benzyl elicited similar levels of injury to soybean (78%). At the lowest rate (1/180X), on either soybean cultivar, observed injury from florpyrauxifen-benzyl (24-29%) was greater than all other herbicides applied at that rate; however, injury from florpyrauxifen-benzyl applied at the 1/180X rate was not different than injury from halosulfuron (23%) and benzobicyclon + halosulfuron (20%) when applied at the 1/20X rate (Table 4.4). These findings suggest that if soybean is exposed to a 1/20X rate of florpyrauxifen-benzyl, intolerable levels of crop injury are to be expected at 14 days after exposure.

In the same site year, when evaluated at 28 DAT, regardless of the rate of florpyrauxifen-benzyl applied to soybean at the V3 growth stage, observed crop injury on STS and non-STS soybean cultivars were 23 and 27%, respectively (Table 4.4). All other evaluated herbicides, regardless of rate, injured both soybean cultivars <2% (Table 4.4). These findings indicate that although soybean injury from florpyrauxifen-benzyl is intolerable at 28 DAT, all other evaluated herbicides, when applied during early vegetative development, will not injure soybean to an extent that it cannot recover by 28 DAT, assuming conditions are suitable for recovery.

In 2019, there was no significant three-way interaction, but there was an interaction between herbicide and soybean cultivar for the 14 DAT evaluation (P=0.0252) and the 28 DAT evaluation (P=0.0086); thus, data were averaged across rate (Table 4.3). At 14 DAT, applications of florpyrauxifen-benzyl during early vegetative development were very injurious to both soybean cultivars across both rates (82 to 95%) (Table 4.5). Furthermore, at 14 DAT, regardless of applied rate, all herbicides except benzobicyclon were injurious to vegetative non-STS soybean at levels ranging from 27 to 90% (Table 4.5). The absence of observed crop injury from benzobicyclon applications can likely be attributed to benzobicyclon being a pro-herbicide, which requires the sufficient water for it to be converted into its phytotoxic form, benzobicyclon hydrolysate (Williams and Tjeerdema 2016). Treatments of halosulfuron and benzobicyclon + halosulfuron injured STS soybean <4% (Table 4.5) because halosulfuron is a sulfonylurea herbicide and the STS soybean cultivar exhibited tolerance to the herbicide applications.

At 28 DAT in 2019, regardless of rate, florpyrauxifen-benzyl was severely injurious (72-80%) to both soybean cultivars (Table 4.5). Additionally, observed injury from halosulfuron-containing treatments on both soybean cultivars were <9% at 28 DAT (Table 4.5). These findings suggest that when either soybean cultivar was exposed to low rates of sulfonylurea herbicides during early reproductive development, they were able to recover almost entirely by 28 DAT. Results from this evaluation are consistent with findings reported by Schwartz-Lazaro et al. (2017), where they reported that halosulfuron at a 1/20X rate injured soybean 7 and 2% at 21 and 35 DAT, respectively.

Yield. In 2018, when averaged across soybean cultivars, florpyrauxifen-benzyl applied during early vegetative development at a 1/20X rate elicited a 19% reduction in yield relative to the nontreated (Table 4.6). This reduction in yield can likely be attributed to the severe levels of injury observed at 14 DAT (90%) and 28 DAT (72%) (Table 4.6). Florpyrauxifen-benzyl is a synthetic auxin herbicide, and it is well documented that herbicides in this family affect growth in broadleaf plants, even at sublethal doses (Grossman 2010; Solomon and Bradley 2014; Wax et al. 1969). Hence, soybean plants were not able overcome the injury induced by applications of the herbicide during early vegetative development. This injury likely persisted throughout the growing season, ultimately negatively affecting yield.

Practical Implications. Findings from this research indicate that benzobicyclon can be safely applied with minimal risk of off-target crop injury on adjacent soybean. Also, a continuous flood is required for benzobicyclon to be phyto-active; therefore, it is unlikely to injure actively growing soybean. The use of benzobicyclon in Midsouth rice production systems could be a viable rice weed control option while also providing safety against off-target crop injury on soybean, but additional years of research are needed to validate this conclusion.

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TABLES

Table 4.1. Product name, common name, and manufacturing company of evaluated herbicides for all experiments.

Product name	Common name	Manufacturer
Rogue	benzobicyclon	Gowan Company, Yuma, AZ 85364
Permit	halosulfuron	Gowan Company, Yuma, AZ 85364
Loyant	florpyrauxifen-benzyl	Corteva Agriscience, Wilmington, DE 19805

Table 4.2. List of herbicide treatments, reduced rates, and application rates for the soybean experiment in 2018 and 2019.

Herbicide treatment[a]	Reduced rate	Application rate[b]
		g ai ha^{-1}
Nontreated	--	--
benzobicyclon + COC	1/180X	1.4
	1/20X	12.3
benzobicyclon + halosulfuron + COC	1/180X	1.4 + 0.2
	1/20X	12.3 + 1.8
halosulfuron + COC	1/180X	0.2
	1/20X	1.8
florpyrauxifen-benzyl + MSO	1/180X	0.2
	1/20X	1.5

[a] Abbreviations: COC – crop oil concentrate at 1% v/v; MSO – methylated seed oil at 1% v/v; Dyne-A-Pak – non-ionic surfactant blend at 2.5% v/v

[b] 1X rates for benzobicyclon, benzobicyclon + halosulfuron, halosulfuron, and florpyrauxifen-benzyl were 252, 252 + 36, 36, and 30 g ai ha^{-1}, respectively

Table 4.3. The p-values from ANOVA for crop injury and relative yield in 2018 and 2019.

		ANOVA			
		2018		2019	
Response variable tested	Factors evaluated	14 DAT	28 DAT	14 DAT	28 DAT
Crop injury	herbicide	<0.0001	<0.0001	<0.0001	<0.0001
	rate	<0.0001	0.0226	<0.0001	<0.0001
	cultivar	0.1074	0.7300	0.0235	0.1289
	herbicide*rate	0.0006	<0.0001	0.7537	0.0052
	cultivar*herbicide	0.0781	0.0002	0.0252	0.0086
	cultivar*rate	0.0583	0.0039	0.7032	0.8596
	cultivar*herbicide*rate	0.0462	0.2072	0.8106	0.6875
Yield	herbicide	0.4893		--	
	rate	0.0061		--	
	cultivar	0.3650		--	
	herbicide*rate	0.0201		--	
	cultivar*herbicide	0.4872		--	
	cultivar*rate	0.1223		--	
	cultivar*herbicide*rate	0.1620		--	

[a] Abbreviations: DAT – days after treatment

Table 4.4. Estimates of crop injury relative to the nontreated check 14 and 28 days after treatment (DAT) for the V3-applied soybean experiment in 2018. At 14 DAT, there was a significant three-way interaction of cultivar, herbicide, and rate. At 28 DAT, there was a significant interaction of herbicide and cultivar, thus data were combined across rate.

		Crop injury							
		14 DAT				28 DAT			
Cultivar[a]	Herbicide[b]	1/180X		1/20X		1/180X	1/20X	combined	
		------------------------------%-------------------------------------							
Non-STS	benzobicyclon	3	cd	3	cd	0	0	0	e
	benzobicyclon + halosulfuron	3	cd	20	b	0	0	0	e
	halosulfuron	2	d	23	b	0	2	1	cd
	florpyrauxifen-benzyl	29	b	88	a	5	75	27	a
STS	benzobicyclon	4	cd	8	c	2	1	1	c
	benzobicyclon + halosulfuron	4	cd	5	cd	1	0	1	de
	halosulfuron	1	d	3	cd	0	0	0	e
	florpyrauxifen-benzyl	24	b	82	a	5	61	23	b

[a] Abbreviations: STS – sulfonylurea-tolerant soybean; DAT – days after treatment

[b] benzobicyclon- and halosulfuron-containing treatments also included crop oil concentrate at 1% v/v; penoxsulam- and florpyrauxifen-benzyl-containing treatments also included methylated seed oil at 1% v/v; bispyribac-containing treatments also included a non-ionic surfactant blend at 2.5% v/v

[c] Letters are used to separate means. 14 DAT means with different letters are significantly different. 28 DAT means with different letters are significantly different. These analyses were conducted separately. All data were subjected to analysis of variance and means were separated according to Fisher’s protected LSD (α=0.05).

Table 4.5. Estimates of crop injury relative to the nontreated 14 and 28 days after treatment (DAT) for the V3-applied soybean experiment in 2019. There was a significant interaction of herbicide and cultivar, thus data were combined across rate.

Cultivar[a]	Herbicide[b]	Crop injury 14 DAT		Crop injury 28 DAT	
		----------------------%		-----------------------	
Non-STS	benzobicyclon	1	cd	0	c
	benzobicyclon + halosulfuron	27	b	2	bc
	halosulfuron	39	b	8	b
	florpyrauxifen-benzyl	90	a	72	a
STS	benzobicyclon	0	d	0	c
	benzobicyclon + halosulfuron	3	c	1	c
	halosulfuron	1	cd	0	c
	florpyrauxifen-benzyl	92	a	80	a

[a] Abbreviations: STS – sulfonylurea-tolerant soybean; DAT – days after treatment

[b] benzobicyclon- and halosulfuron-containing treatments also included crop oil concentrate at 1% v/v; penoxsulam- and florpyrauxifen-benzyl-containing treatments also included methylated seed oil at 1% v/v; bispyribac-containing treatments also included a non-ionic surfactant blend at 2.5% v/v

[c] Letters are used to separate means. Means with different letters within a column are significantly different. All data were subjected to analysis of variance and means were separated according to Fisher's protected LSD (α=0.05).

Table 4.6. Soybean yield relative to the nontreated check for the V3-applied soybean experiment in 2018. There was a significant interaction of herbicide and rate, thus data were combined across cultivar.

Rate	Herbicide[a]	Grain yield	
		% of nontreated[b]	
1/20X	benzobicyclon	114	ab
	benzobicyclon + halosulfuron	95	bcd
	halosulfuron	86	cd
	florpyrauxifen-benzyl	81	d
1/180X	benzobicyclon	106	abc
	benzobicyclon + halosulfuron	102	bcd
	halosulfuron	110	abc
	florpyrauxifen-benzyl	136	a

[a] benzobicyclon- and halosulfuron-containing treatments also included crop oil concentrate at 1% v/v; penoxsulam- and florpyrauxifen-benzyl-containing treatments also included methylated seed oil at 1% v/v; bispyribac-containing treatments also included a non-ionic surfactant blend at 2.5% v/v

[b] Nontreated plots for the non-STS and STS cultivars yielded 2890 and 2360 kg ha^{-1}, respectively

[c] Letters are used to separate means. Means with different letters within a column are significantly different. All data were subjected to analysis of variance and means were separated according to Fisher's protected LSD (α=0.05).

GENERAL CONCLUSIONS

Controlling weedy rice postemergence is challenging for rice producers in the United States because of the lack of herbicide options. Weedy rice is genetically similar to cultivated rice, thus making it difficult to control with mid-season postemergence herbicide applications without also damaging the crop. Hence, there is a need for a new effective postemergence weedy rice control herbicide. Findings from this research indicate that the use of benzobicyclon in current standard quizalofop- and imidazolinone-resistant rice herbicide programs provides tremendous utility for Midsouth rice producers. In both of these production systems, the addition of benzobicyclon to the respective standard herbicide programs resulted in comparable or improved weedy rice control compared to the standard program alone. Additionally, minimal injury was observed from treatments containing the current standard herbicide program followed by the postflood application of benzobicyclon.

To validate that benzobicyclon is a viable weed control option for rice growers, research was conducted to evaluate varietal tolerances of commonly grown rice cultivars to the application of benzobicyclon. Plants are typically more sensitive to herbicides when they are small, and that sensitivity tends to decrease as the plant produces more vegetative growth. In the first year of this research, 4-leaf and tillering rice exhibited sufficient tolerance to benzobicyclon, whereas 2-leaf rice did not. However, in the second year, all treatments, or combinations of application timing/rice cultivar were not injurious to rice, which was partially attributed to loss of the herbicide from the field as a result of a rainfall event. Some rice cultivars, depending on genealogical lineage, are extremely susceptible to benzobicyclon and other 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibiting herbicides. More specifically, *japonica*-type rice cultivars show much better crop safety to benzobicyclon than *indica*-type or *japonica*- x *indica*-type. In this research, the *indica*-type rice cultivar ‘Rondo’ was severely injured, regardless of benzobicyclon application timing.

Since benzobicyclon is a pro-herbicide, it does not directly inhibit HPPD enzymes in plants. Rather, benzobicyclon must undergo (in the presence of water) a non-enzymatic hydrolytic reaction to be converted to the potent and phytotoxic compound benzobicyclon hydrolysate. Therefore, since benzobicyclon requires the presence of water to be phyto-active, it must be applied postflood, and applications will likely occur in proximity to actively growing soybean. In this research, treatments containing benzobicyclon alone, regardless of reduced rate applied, injured soybean ≤8% at 14 days after treatment, indicating that benzobicyclon can be safely applied to rice near soybean with minimal risk for injury to the adjacent crop.