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Evaluation of Insecticide Seed Treatments to Protect Rice (Oryza sativa) Against Various Herbicides

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Evaluation of Insecticide Seed Treatments to Protect Rice (*Oryza sativa*) Against Various Herbicides

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Abstract

The increase in herbicide-resistant weeds in Arkansas crop fields has led to the need for new herbicide modes of action for use in all crops. This need has led to the introduction of technologies that can be devastating to conventional rice crops. Field observation, noted that insecticide seed treatments used in rice could potentially reduce the effects of off-target movement of herbicides onto rice crops and possibly reduce the negative effects of some herbicides applied directly to rice. Research was conducted to determine if insecticide seed treatments could reduce the harmful effects of drift from imazethapyr and glyphosate onto conventional rice, and if so, which insecticide seed treatments provided adequate protection. In addition, research was conducted to determine if thiamethoxam, a popular insecticide seed treatment, could reduce the negative effects of some acetolactate synthase (ALS)-inhibiting, preemergence and postemergence herbicides for better or future use in rice. The use of insecticide seed treatments containing thiamethoxam and clothianidin resulted in less rice injury, more groundcover, and increased grain yields following simulated herbicide drift events compared to a fungicide-only seed treatment. Thiamethoxam seed treatment also reduced the amount of injury caused by ALS-inhibiting herbicides applied to imidazolinone-resistant varieties of rice. In addition, thiamethoxam reduced injury from the preemergence and postemergence herbicides; however, individual interactions were observed in terms of yield for the herbicides. Overall, this research confirms the hypothesis that insecticide seed treatments can provide some safening from low rates of harmful herbicides and reduce some of the negative effects of injurious herbicides commonly used in rice production.

Acknowledgements

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Literature Review

Rice Production. Rice (*Oryza sativa* L.) was first grown in Arkansas in 1905. Since then, rice has become one of the most important commodities in Arkansas (Hardke 2012). Since its introduction into the United States, rice production reached an all-time high in 2010 with over 1.4 million hectares harvested. In 2013, the Arkansas rice crop was valued at more than 1.2 billion U.S. dollars (NASS 2017a). Production in Arkansas increased from 1905 until 1955 when the government limited the amount of rice to around 200,000 hectares. In 1974, this ban was lifted and once again the number of rice acres in Arkansas began to increase (Hardke 2012). During this time, new varieties of rice were being developed that yielded much higher than varieties in the past. Most of the current Arkansas rice acres lie in eastern Arkansas with Poinsett, Arkansas, and Lawrence counties being the three largest rice-producing counties in the state (Hardke 2012). Most rice in Arkansas is grown in a silt or clay loam, or a clay soil, which accounts for 96% of all rice grown in Arkansas (Hardke 2014). About 61% of rice in Arkansas is grown using conventional tillage, which involves both fall and spring tillage before planting in April and May. Rice is typically flooded at the four- to five-leaf growth stages, which usually occurs at the end of May or beginning of June. Rice harvest usually begins in mid-August and continues through the early parts of November (Hardke 2012).

Insecticide Seed Treatments. In Arkansas, most rice is grown in a flooded environment to help suppress weeds (Smith and Fox 1973). However, along with the benefits of the flood, come some negative aspects. The rice water weevil (*Lissorhoptrus oryzophilus* Kuschel), one of the biggest threats to a rice crop, is attracted to the flood (Way 1990). After 2005 when fipronil was voluntarily removed from the market, there were not many options to control rice water weevils besides draining the fields and letting the soil dry until it cracked (Lorenz et al. 2012a). In 2010, chlorantraniliprole (Dermacor® X-100) and thiamethoxam (Cruiser® 5FS) received labels for use in rice. The following year thiamethoxam had a fungicide mixed with it and became known as CruiserMaxx Rice®. In 2012, clothianidin (NipsIt INSIDE®) received a label for rice production. Since the release of these insecticides, insecticide seed treatments were the easiest and most efficient method of controlling rice water weevil. Foliar insecticides are effective but timing is much more critical (Lorenz et al. 2012b). In 2013, 61% of the total rice acres in Arkansas received an insecticide seed treatment (Hardke 2014). In Louisiana, insecticide seed treatments showed a significant decrease in rice water weevil larvae in rice crops from 2008 until 2011 with chlorantraniliprole being significantly better than thiamethoxam in 2010 and 2011 (Hummel et al. 2014). A similar study was conducted in Arkansas to determine the efficacy of seed treatments over different seeding rates of conventional, Clearfield, and hybrid rice cultivars, which yielded similar results (Taillon et al. 2012). A significant decrease in rice water weevils for all seed treatments in all seeding rates of conventional and Clearfield varieties was observed but only at the 25.7 and 31.4 kg ha^{-1} seeding rates of hybrid rice (Taillon et al. 2012). In a large block study conducted in Arkansas in 2009 and 2010, a significant reduction in rice water weevils and a significant increase in yield were seen with the use of insecticide seed treatment (Plummer et al. 2012). While chlorantraniliprole, thiamethoxam, and clothianidin all seem to be effective in drill-seeded rice, only chlorantraniliprole can be applied to water-seeded rice. Hence, chlorantraniliprole seems to remain an effective method for rice water weevil control regardless of the seeding method for rice (Lanka et al. 2014).

Drift Concerns in Rice. In Arkansas, the most widely planted crop is soybean (*Glycine max* L. Merr.) with over 1.4 million hectares grown each year. Of these hectares, more than 97% are genetically modified to tolerate applications of glyphosate, dicamba, or glufosinate with a majority being glyphosate resistant (NASS 2017b), which results in frequent drift of glyphosate to adjacent rice fields. Soybean and rice are commonly rotated on the same fields and are grown in close proximity to each other. Another common occurrence is imazethapyr drift from imidazolinone-resistant (Clearfield®) rice fields to neighboring fields seeded with conventional rice varieties. In 2011, crop consultants in Arkansas and Mississippi rice reported that 64% of rice hectares that year were planted to imidazolinone-resistant varieties (Norsworthy et al. 2013). With 55% of rice hectares in Arkansas still in conventional rice and most soybean fields being treated with glyphosate, herbicide drift is a major concern (Hardke 2016).

The sensitivity of rice to glyphosate varies by growth stage. Rice injury up to 94% from glyphosate at 140 g ae ha^{-1} (1/6X rate) was observed when applied at the two- to three-leaf growth stage (Ellis et al. 2003). The same herbicide rate applied at panicle differentiation caused no more than 35% injury. A two- to three-leaf application of glyphosate to rice caused 56% yield reduction whereas the later application at panicle differentiation caused 31% yield loss. In other research, the same rate of glyphosate caused a maximum of 35% injury to rice when applied at panicle initiation (Kurtz and Street 2003). This same study however showed a maximum injury rating of 45% for the same rate of glyphosate applied at the three- to four-leaf growth stage whereas the greatest yield loss occurred when glyphosate was applied at the boot stage (Kurtz and Street 2003).

Similar studies have also been conducted to determine the effects of imazethapyr drift on conventional rice. In an experiment evaluating rice response to simulated imazethapyr drift at 1/8 and 1/16X rates, injury was greatest early in the season when the drift event occurred on one-tiller rice yet yield loss was greatest when the drift events occurred at the boot stage (Hensley et al. 2012).

A major development in rice technology was the release of imidazolinone-resistant rice in 2002 (Burgos et al. 2008). Imidazolinone-resistant varieties offer added benefits with herbicide resistance, making this system an excellent option for areas where red rice (*Oryza sativa* L.) and dense populations of barnyardgrass (*Echinochloa crus-galli* L. Beauv.) occur (Hardke 2012). In addition to conventional rice remaining a relevant crop, a large number of rice hectares are sprayed using agriculture aircrafts, which also leads to an increased concern of drift (Hardke 2012).

Herbicide/Insecticide Interactions

Numerous interactions have been noted previously between herbicides and insecticides. One of the earliest discovered interactions was inhibition of cytochrome P450 by organophosphate and carbamate insecticides, which led to injury to rice when propanil was tank-mixed with carbaryl or applied in close proximity to the insecticide (Bowling and Hudgins 1966). Guthion, phosphamidon, dylox, malathion, and naled also caused increased injury to rice when tank-mixed with propanil (Bowling and Hudgins 1966). Later research revealed that these insecticides also inhibited aryl acylamidase, the enzyme that detoxifies propanil in rice; hence, the reason for rice injury from propanil (Frear and Still 1968). Similarly, injury to soybean has occurred when mixing bentazon or thifensulfuron with organophosphate and carbamate insecticides (Campbell and Penner 1982; Ahrens 1990). In corn, several experimental herbicides, primisulfuron, and nicosulfuron caused increased injury or yield reduction when mixed with the insecticide turbufos (Biediger et al. 1992; Frazier et al. 1993; Holshouser et al. 1991; Kapusta and Krausz 1992; Morton et al. 1991, 1993, 1994). Cotton plants have also been subject to injurious combinations of insecticides and herbicides. Both diuron and monuron can cause plant mortality after germination when combined with disyston or phorate insecticides (Hacskaylo et al. 1964).

Some insecticides have been found to reduce or alleviate injury caused by certain herbicides. For example, use of phorate or disulfoton applied in-furrow in cotton was found to reduce injury caused by preemergence-applied clomazone and increase cotton stands over clomazone alone (York et al. 1991; York and Jordan 1992). Following this research, clomazone (Command®) received registration in cotton under the stipulation that disulfoton or phorate be applied in-furrow at time of planting (Anonymous 2014).

In previous research, Scott et al. (2014) and Miller et al. (2016) found that the use of thiamethoxam can safen rice when exposed to drift rates of imazethapyr and glyphosate. The use of thiamethoxam helped alleviate injury and quicken recovery from the drift rates of herbicides. Thiamethoxam also protected the yield of the rice after the simulated drift event of both glyphosate and imazethapyr.

Postemergence (POST) Contact Herbicides in Rice. ***Saflufenacil (Sharpen).*** Saflufenacil is a relatively new rice herbicide that previously has only been used for burndown applications prior to planting crops. However, saflufenacil is now labeled for use in rice as a POST-applied herbicide at a rate of 24.7 g ai ha^{-1}. Since saflufenacil is a relatively new herbicide in rice, research is ongoing to determine the best method of use for saflufenacil. In recent research, injury ratings were significantly greater with methylated seed oil (MSO) compared to a crop oil concentrate (COC) (Dickson et al. 2014). The rice recovered from the injury and no yield loss occurred compared to the nontreated check (Dickson et al. 2014). Some plots treated with saflufenacil yielded higher than the nontreated checks possibly due to a reduction in weed pressure. Camargo et al. (2012) found similar results in a separate study. In their study, there was also a significant amount of injury to the rice after the application of saflufenacil; likewise, there was also no reduction in yield in this trial (Camargo et al. 2012). However, in other research, rice yield loss has occurred following a saflufenacil application (Fickett et al. 2012). Overall, saflufenacil provides good broadleaf weed control, but there is a significant amount of rapid leaf necrosis from the herbicide application.

Propanil. Propanil is a POST-applied herbicide that has been used in rice since the 1960's (Smith 1965). Historically, propanil has been used on a majority of rice acres in Arkansas (Carey et al. 1995). Resistance to propanil has been found in barnyardgrass in Arkansas; however, propanil still remains an effective weed control measure in rice production due to its broad-spectrum activity on other weeds (Carey et al. 1995). Like saflufenacil, propanil use in rice can cause injury to the crop soon after application. Leaf tip necrosis to rice amounting to 30% injury has been reported following a propanil application (Baltazar and Smith 1994).

Some insecticides when used in combination with propanil result in elevated levels of injury to rice caused by propanil (Khosro et al. 1986). This injury to rice comes from the use of carbamate and organophosphate insecticides in tank-mixture or close proximity to propanil use. These insecticides inhibit aryl acylamidase, the enzyme in rice that metabolizes propanil. Aryl acylamidase in rice breaks down propanil into propionic acid and 3,4-dichloroaniline which are both non-toxic to the rice (Frear and Still 1968). This enzyme is found at low levels in propanil-susceptible barnyardgrass, but its activity is elevated in resistant biotypes of barnyardgrass. Hence, the herbicide is detoxified (Hoagland et al. 2004). Barnyardgrass or other weed species that do not contain high levels of aryl acylamidase are easily controlled by propanil, which makes propanil a very useful broad-spectrum herbicide in rice (Frear and Still 1968).

Carfentrazone (Aim). Carfentrazone is a POST-applied, broadleaf herbicide labeled for use in rice. The use of carfentrazone in rice can cause slight leaf chlorosis or necrosis to the plants (Anonymous 2015). Even with this leaf injury there is no loss of yield with the use of carfentrazone (Pellerin et al. 2004). In a study conducted by Montgomery et al. (2014), the use of carfentrazone applied POST to two- to three-leaf rice caused no injury to the crop.

Preemergence (PRE)-Applied Herbicides that Injure Rice. ***Clomazone (Command).*** Clomazone is labeled for use as a residual herbicide in rice. Clomazone controls multiple grass species and is safe to soybean as a rotational crop with rice (Webster et al. 1999). Clomazone has been adopted as one of the main herbicides for barnyardgrass control and consistently provides a high level of barnyardgrass control while not affecting the yield of rice (Webster et al. 1999; Norsworthy et al. 2007). Although clomazone does not affect yield, injury often occurs in rice fields treated with clomazone (personal observation). Injury consists of pigment bleaching and can reach up to 50% or more injury in some instances. Across several rice varieties, there was no yield loss from the use of clomazone even though injury was upwards of 50% for some varieties (Zhang et al. 2004). This bleaching effect on rice usually occurs on coarse-textured (silt and sandy loam) soils and is not as common on clay soils (Hardke 2012). Injury is also increased following a rainfall event where the herbicide is fully activated in the soil (Norsworthy et al. 2008).

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Chapter I

Insecticide Seed Treatments Partially Safen Rice (*Oryza sativa*) to Low Rates of Glyphosate and Imazethapyr

Abstract

Each year there are multiple reports of drift occurrences in rice. With a large percentage of crops being glyphosate-resistant and approximately 50% of Arkansas rice hectares being non-Clearfield® (imidazolinone-resistant), the majority of drift complaints in rice are from imazethapyr or glyphosate. In 2014 and 2015, multiple field experiments were conducted at the Rice Research and Extension Center near Stuttgart, Arkansas (hereafter referred to as Stuttgart), and at the University of Arkansas Pine Bluff farm near Lonoke, Arkansas (hereafter referred to as Lonoke), to evaluate whether insecticide seed treatments would reduce injury from glyphosate or imazethapyr drift or decrease the recovery time of the rice following exposure to a low rate of these herbicides. In the 'seed treatment study,' the conventional rice cultivar 'Roy J' was planted, and imazethapyr at 10.5 g ai ha^{-1} or glyphosate at 126 g ae ha^{-1} was applied to each plot. Each plot had either a seed treatment of thiamethoxam, clothianidin, chlorantraniliprole, or no insecticide seed treatment. The herbicides were applied at the two- to three-leaf growth stage. Crop injury was assessed 1, 3, and 5 weeks after application. Rice water weevil samples were taken 3 weeks after flood in 2015. Averaged over site years, thiamethoxam-treated rice had less injury than the non-treated rice at each rating along with an increased yield over the non-treated. Similarly, clothianidin-treated rice had an increased yield over the non-treated, but the reduction in injury for both herbicides was less pronounced than the thiamethoxam-treated plots. Overall, chlorantraniliprole was generally the least effective of the three insecticides evaluated in reducing injury from either herbicide and protecting rice yield potential. A second experiment conducted at Stuttgart was aimed to determine whether damage to rice from glyphosate and imazethapyr was influenced by the timing (15, 30, and 45 days after planting) of exposure to herbicides for thiamethoxam-treated and non-treated rice. There was an overall reduction in injury with the use of thiamethoxam, but the reduction in injury was not dependent on the timing of the drift event. Reduction in damage from physical drift of glyphosate and imazethapyr as well as increased yields over the absence of an insecticide seed treatment appear to be an added benefit for rice producers.

Nomenclature: glyphosate; imazethapyr; rice water weevil, *Lissorhoptrus oryzophilus* Kuschel; rice, *Oryza sativa* L.

Key words: herbicide drift, rice injury, off-target movement

Introduction

Conventional rice is often grown in close proximity to glyphosate-resistant soybean [*Glycine max* (L.) Merr.] and imidazolinone-resistant rice in Midsouth cropping systems. This along with poor herbicide application techniques can lead to off-target movement of herbicides onto conventional rice, especially glyphosate and imazethapyr. Several factors such as wind speed, distance from targeted area, droplet size, and application method determine the severity of the drift event and the concentration of herbicide drift (Smith et al. 2000). Glyphosate drift of 800 m can occur from a 3.46 m s^{-1} wind when applied with an airplane as opposed to less than 100 m when properly sprayed with a ground sprayer during similar wind (Yates et al. 1978). Depending on rice growth stage, concentration, and herbicide, injury can range from barely noticeable to complete necrosis and plant death (Ellis et al. 2003; Kurtz and Street 2003).

Glyphosate use has increased significantly since the release of glyphosate-resistant crops (Benbrook 2016). Glyphosate is a non-selective systemic herbicide that causes chlorosis followed by necrosis that eventually leads to plant death. Glyphosate inhibits 5-enolpyruvyl-shikimate-3-phosphate synthase, preventing the production of amino acids that are necessary for plant growth (Senseman 2007). Since the introduction of glyphosate-resistant crops in 1996, glyphosate has been primarily used as a postemergence-applied herbicide to control a wide range of both broadleaf and grass weeds. The widespread adoption of glyphosate-resistant crops in the Midsouth includes soybean, corn (*Zea mays* L.), and cotton (*Gossypium hirsutum* L.). Adoption of genetically modified rice was never accepted globally, causing other herbicide options to be utilized in rice production.

In rice production, an imidazolinone-resistant line, developed through conventional breeding techniques, has been widely adopted since introduction in 2002 (Croughan 1994). The most widespread herbicide used in the imidazolinone-resistant rice is imazethapyr. Imazethapyr is an acetolactate synthase (ALS) inhibitor that primarily ceases production of isoleucine, leucine, and valine (Shaner 1991). Symptomology caused by imazethapyr usually consists of chlorosis in the meristematic region followed by chlorosis and necrosis throughout the plant within 7 to 14 days after exposure (Shaner 1991).

In the southern U.S., rice is an important agronomic crop in Arkansas, Louisiana, Mississippi, Missouri, and Texas. These states account for a majority of the rice hectares produced in the United States. Arkansas is the largest producer of rice in the United States with more than 50% of the rice hectares often planted to imidazolinone-resistant varieties (Norsworthy et al. 2013; NASS 2016). Arkansas also ranks 11th in U.S. soybean production with nearly 1.3 million hectares planted in 2015. Nearly 98% of these planted hectares were herbicide-resistant, with most being glyphosate resistant (NASS 2016).

Glyphosate and imazethapyr drift onto a conventional rice crop can cause adverse effects (Ellis et al. 2003; Kurtz and Street 2003; Hensley et al. 2012). Rice injury up to 94% has been reported from glyphosate at 140 g ae ha^{-1} when applied at the two- to three-leaf growth stage, subsequently leading to a 56% yield reduction (Ellis et al. 2003). The same glyphosate rate applied at panicle differentiation caused no more than 35% visible injury and 31% yield reduction. In another study, a similar rate of glyphosate caused up to 35% injury when applied at panicle initiation and 45% injury when applied at the three- to four-leaf growth stage (Kurtz and Street 2003).

Similar studies have been conducted to determine the effects of imazethapyr drift onto conventional rice. In an experiment evaluating rice response to simulated imazethapyr drift at 1/8 and 1/16 of the 70 g ai ha^{-1} rate, injury was greatest early in the season when the drift event occurred on one-tiller rice, yet yield loss was greatest when simulated drift occurred at the boot stage (Hensley et al. 2012).

Although studies have been conducted to determine the effects of low rates of imazethapyr and glyphosate onto rice and some have determined that thiamethoxam can partially safen rice to glyphosate and imazethapyr drift (Miller et al. 2016), further research is needed to understand if safening occurs across insecticide seed treatments. The objective of this research was to determine if three commercially available insecticide seed treatments would lessen rice injury from low rates of glyphosate and imazethapyr and whether possible injury reduction would be influenced by time after planting.

Materials and Methods

Two field studies were conducted in the summers of 2014 and 2015 to determine the effects of glyphosate and imazethapyr drift onto conventional rice. The first experiment evaluated different insecticide seed treatments (referred to as the seed treatment study). The second experiment evaluated the timing of rice exposure to low rates of glyphosate and imazethapyr (referred to as the drift timing study).

The seed treatment study was conducted at the Rice Research and Extension Center located near Stuttgart, AR, (hereafter referred to as Stuttgart) and the University of Arkansas Pine Bluff farm located near Lonoke, AR (hereafter referred to as Lonoke). Studies at Stuttgart were conducted on a Dewitt silt loam soil (Fine, smectitic, thermic Typic Albaqualfs), while the studies at Lonoke were conducted on a Calhoun silt loam soil (Fine-silty, mixed, active, thermic Typic Glossaqualfs). Plot sizes at Stuttgart and Lonoke were 1.9 by 5.2 m and 1.9 by 7.6 m, respectively. Each plot contained 10 drill rows spaced 19 cm apart and was planted to ‘Roy J’ rice at 375 seed m^{-2}. Planting dates, herbicide application dates and permanent flood establishment dates are in Table 1. Plots were fertilized according to the University of Arkansas System Division of Agriculture recommendations for both locations (Hardke 2012). Plots were kept weed free throughout the growing season using conventional postemergence herbicides as shown in Table 2 to avoid any additional injury.

The experimental design was a randomized complete block with a two-factor factorial treatment arrangement with four replications. The two factors were herbicides and insecticide seed treatments. Herbicides evaluated were glyphosate (Roundup PowerMax®, Monsanto Company, St. Louis, MO) at 126 g ae ha^{-1} and imazethapyr (Newpath®, BASF Corporation, Research Triangle Park, NC) at 10.5 g ai ha^{-1} (1/10X rates for glyphosate-resistant soybean and imidazolinone-resistant rice), and a nontreated control. Herbicide applications were made at the two- to three-leaf (V2-V3) growth stage (Counce et al. 2000). Insecticide seed treatments included thiamethoxam, clothianidin, and chlorantraniliprole at rates listed in Table 3. All treatments including the non-treated control received fungicide seed treatments of azoxystrobin at 0.071 mg g^{-1} of seed, mefenoxam at 0.088 mg g^{-1} of seed, and fludioxonil at 0.015 mg g^{-1} of seed. A fungicide-only treatment (no insecticide) was used as the non-treated control. All herbicides were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} using a six-nozzle, 2.5-m spray boom, with AIXR 110015 nozzles.

Visual injury was evaluated 1, 3, and 5 weeks after the herbicide treatment (WAT) on a scale of 0 to 100, with 0 being no injury and 100 being plant death. Plots were compared to the non-treated herbicide plots with the same insecticide seed treatment. Rice groundcover was estimated using Sigma Scan Pro® (Systat Software, Inc., 501 Canal Blvd. Suite E, Point Richmond, CA 94804) by determining the percentage of green pixels in photographs of each plot. Photographs of each plot were taken 5 WAT using a 1.8-m monopod (Purcell 2000). Rice water weevil (*Lissorhoptrus oryzophilus* Kuschel) counts were taken in each plot 3 weeks after the permanent flood was established at both locations for 2015 only. Three 10-cm-diameter soil cores were taken from each plot and washed to count the number of rice water weevil larvae in each core. Plots were harvested at maturity using a small-plot combine, and rough rice yields were recorded at 12% moisture.

The drift timing study was conducted in a similar manner to the seed treatment study. The drift timing study was only conducted at Stuttgart in 2014 and 2015 with soil texture, planting dates (Table 4), plot size, and application equipment and setup similar to the seed treatment study. This study was also kept weed free in a similar manner as the seed treatment study.

The experimental design was a randomized complete block design with four replications; however, this study had three factors. The three factors were seed treatment, herbicide, and timing of the herbicide application. All insecticide-treated seed contained thiamethoxam at 1.405 mg g^{-1} of seed (referred to as "treated seed"). All seed, including the insecticide-treated seed, were treated with the fungicides azoxystrobin at 0.071 mg g^{-1} of seed, mefenoxam at 0.088 mg g^{-1} of seed, and fludioxonil at 0.015 mg g^{-1} of seed. The seed receiving only the fungicide seed treatments will be referred to as "non-treated seed." Herbicides remained the same as in the seed treatment study while herbicide applications were 15, 30, and 45 days after rice planting (DAP).

Visual injury was rated 1, 3, and 5 WAT for each herbicide timing along with Sigma Scan photos taken 5 weeks after the final herbicide treatment. Plots were harvested at maturity using a small-plot combine, and rough rice yields were recorded and adjusted to 12% moisture.

All data for the seed treatment study and drift timing study were analyzed in JMP Pro 12 (SAS Institute Inc., Cary, NC). Site-year and replication nested within site year were included in the model as random effects. Means were separated using Fisher's protected LSD test at $\alpha = 0.05$. P- Values for the seed treatment study and the drift timing study are provided in Tables 5 and 6 respectively.

Results and Discussion

Seed Treatment Study. Only rice water weevil numbers had a significant interaction between seed treatment and herbicide. For all other evaluations there was no significant interaction; however, the main effects of seed treatment and herbicide were significant.

Within one week of applying the herbicide treatments, injury symptoms began to occur. Plants in all insecticide seed treatment plots had at least 18% injury 1 WAT averaged over glyphosate and imazethapyr, but injury was less for all insecticide seed treatments than that observed in plots without an insecticide seed treatment (Table 7). At 1 WAT, thiamethoxam safened rice to a greater extent than did clothianidin or chlorantraniliprole. By 3 WAT rice treated with thiamethoxam and clothianidin (27 and 29% injury, respectively) were both injured less than the nontreated rice (39% injury). Injury to chlorantraniliprole-treated rice was comparable to the non-insecticide-treated rice. By 5 WAT rice plants had begun to recover from injury caused by the herbicides, with ranking of insecticide seed treatments similar to earlier ratings. Evaluation of green pixels in photographs taken 5 WAT also revealed a reduction in damage to the crop as indicated by greater groundcover for thiamethoxam- and clothianidin-treated rice than for plots without an insecticide seed treatment (Table 7). Thiamethoxam and clothianidin had 50 and 52% groundcover, respectively, compared to 42% groundcover for the fungicide-only seed treatment. The reduction in early-season damage to rice, averaged over herbicides, when seed were treated with thiamethoxam or clothianidin translated into a 700 to

810 kg ha^{-1} yield improvement over plots without an insecticide seed treatment that likewise received a low rate of the herbicides (Table 7). In addition to protecting yield, it is likely that the quicker canopy formation caused by the seed treatments would aid weed control because weed interference is largely a function of the rate of canopy formation (Miller et al. 2016).

The 1/10X rates of imazethapyr (10.5 g ai ha^{-1}) and glyphosate (126 g ae ha^{-1}) had different effects on the rice after application. Overall, glyphosate caused more injury than imazethapyr to the rice at all three ratings (Table 8). Damage to rice from glyphosate at 3 WAT averaged 42% over seed treatments, similar to the levels observed by Hensley et al. (2013) when applied to one-tiller rice. Rice injury was 24% following imazethapyr at 3 WAT averaged over insecticide seed treatments. Injury from glyphosate and imazethapyr seemed to have a direct effect on groundcover 5 WAT (Table 8). Glyphosate, which caused the most injury, resulted in rice having only 45% groundcover averaged over insecticide seed treatments while the imazethapyr-treated plots had 51% groundcover. In comparison, the plots that were not treated with herbicide averaged 59% groundcover. Based on previous neonictinoid research in Asian honey bees (*Apis cerana cerana*) (Ming et al. 2016), it is speculated that a possible upregulation of stress genes from the neonictinoids could be the reason for less herbicide injury and an overall healthier rice plant.

Rice water weevil samples were taken for both locations in 2015. Averaged across locations, rice water weevil numbers were greatest when rice was treated with a low rate of imazethapyr or glyphosate in the absence of an insecticide seed treatment (Table 9). All three insecticides performed equally well in reducing rice water weevil numbers. Research has shown that a decrease in groundcover can cause an increase in rice water weevil larvae (Stout et al.

2009), which may explain the high counts in the plots exhibiting the greatest damage in the absence of the insecticide.

Drift Timing Study. At 1 and 3 WAT, there was a significant interaction between herbicide and application timing (Table 10). For glyphosate 1 WAT, as application timing was delayed, injury to rice often increased, likely because the insecticide seed treatment was less effective at the later timings. However, imazethapyr caused the least amount of injury when applied 15 DAP while there was no difference when applied 30 or 45 DAP. At 3 WAT, there was no difference in any of the glyphosate applications. Imazethapyr applied 45 DAP had less injury than when applied 30 DAP but was no different than 15 DAP application. For both herbicides, injury increased from 1 WAT to 3 WAT for the 15 DAP application, while staying nearly the same for the 30 DAP and decreasing for the 45 DAP. At 5 WAT, herbicide was no longer significant and only application timing was significant. Applications 45 DAP had more injury than the 15 and 30 DAP applications.

Seed treatment also played a role in injury to the rice. At all three ratings, plots having the thiamethoxam-treated seed exhibited less injury than those without the insecticide seed treatment (Table 11), which is similar to findings in other research (Miller et al. 2016).

Groundcover images were taken 5 WAFT for all plots and later converted to percentage of green pixels using Sigma Scan. The main effects of timing and seed treatment had no effect on groundcover; however, the herbicides applied did have an effect. There was no difference between the herbicides; however, the herbicides did reduce groundcover when compared to plots that did not receive a herbicide. There was a 13 to 15 percentage point decrease in groundcover when either the drift rate of imazethapyr or glyphosate was applied (Table 12).

Similar to groundcover, the only factor that affected yield was the application of imazethapyr or glyphosate. Plots without any herbicide treatment yielded 11,670 kg ha^{-1} while the application of glyphosate and imazethapyr reduced yields to 10,610 and 10,810 kg ha^{-1}, respectively (Table 12).

Practical Implications. Rice plants receiving a thiamethoxam seed treatment showed reduced damage from glyphosate and imazethapyr along with some rice water weevil protection. This reduction in injury protected some of the yield potential of rice when the glyphosate or imazethapyr exposure occurred soon after planting. Clothianidin-treated seed reduced injury and provided yield protection in the presence of glyphosate or imazethapyr as well as rice water weevil protection. Chlorantraniliprole provided rice water weevil protection but did not provide significant protection against glyphosate or imazethapyr.

Even though rice exhibited injury at each of the evaluation timings, the safening from the insecticide seed treatments was generally comparable for thiamethoxam and clothianidin (both neonicotinoids) based on most injury evaluations, rice groundcover, and rough rice yield. It is important to note that the insecticide seed treatments did not completely alleviate the risk for injury from imazethapyr or glyphosate but instead reduced the damage and subsequent yield loss caused by early-season exposure of rice to these herbicides.

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Table 1. Planting dates, application dates of herbicides, and permanent flood dates for seed treatment experiment.

Location	Year	Planting date	Application date	Permanent Flood
Stuttgart, AR	2014	April 23	May 9	June 6
	2015	May 5	June 2	June 17
Lonoke, AR	2014	May 20	June 5	July 2
	2015	June 8	June 22	July 14

Table 2. Herbicides used to maintain weed-free plots.

Herbicide trade name	Herbicide common name	Rate	Application timing	Manufacturer
		g ae or ai ha^{-1}		
Command 3 ME®	Clomazone	340	PRE[a]	FMC Corporation, Philadelphia, PA
Facet L®	Quinclorac	280	PRE	BASF Corporation, Research Triangle Park, NC
Ricestar HT®	Fenoxaprop	123	MPOST[b]	Bayer CropScience, Research Triangle Park, NC
Clincher®	Cyhalofop	314	LPOST[c]	Dow AgroSciences LLC, Indianapolis, IN
Permit®[d]	Halosulfuron	40	MPOST	Gowan Company, Yuma, AZ

[a] PRE application applied at planting
[b] MPOST application applied prior to establishing permanent flood
[c] LPOST application applied after establishment of permanent flood
[d] Only applied at Rice Research and Extension Center location.

Table 3. Insecticide seed treatments and rates evaluated in seed treatment experiment.

Seed treatment trade name	Insecticide common name	Rate	Manufacturer
		mg g^{-1} seed	
CruiserMaxx Rice®	Thiamethoxam	1.405	Syngenta Crop Protection, Greensboro, NC
NipIt INSIDE®	Clothianidin	0.75	Valent U.S.A. Corporation, Walnut Creek, CA
Dermacor X-100®	Chlorantraniliprole	1.0175	du Pont de Nemours and Company, Wilmington, Delaware

Table 4. Planting date and application dates of herbicides for drift timing experiment at the Rice Research and Extension Center near Stuttgart, AR.

Year	Planting date	Application date		
		15 DAP[a]	30 DAP	45 DAP
2014	April 24	May 9	May 20	June 3
2015	May 6	May 21	June 5	June 19

[a] Abbreviation: DAP, days after planting application

Table 5. P- Values for all evaluations in the seed treatment experiment

Factor	Injury 1 WAT[a]	Injury 3 WAT	Injury 5 WAT	Groundcover 5 WAT	Rice Water Weevil	Yield
Seed Treatment	0.0006	0.0001	0.0017	0.0001	0.0001	0.0059
Herbicide	0.0012	0.0001	0.0329	0.0091	0.0001	0.0001
Seed Treatment * Herbicide	0.5695	0.8237	0.8837	0.7983	0.0209	0.5163

[a] Weeks After Treatment

Table 6. P- Values for all evaluations in the drift timing study

Factor	Injury 1 WAT[a]	Injury 3 WAT	Injury 5 WAT	Groundcover 5 WAFT[b]	Yield
Seed Treatment	0.0364	0.0222	0.0453	0.7662	0.3167
Herbicide	0.0001	0.1375	0.3221	0.0001	0.0379
Timing	0.0001	0.3205	0.0436	0.4444	0.2501
Seed Treatment * Herbicide	0.2512	0.8926	0.8791	0.1791	0.5119
Seed Treatment * Timing	0.4862	0.9611	0.7093	0.9716	0.5488
Herbicide * Timing	0.0065	0.0382	0.5107	0.1155	0.0624
Seed Treatment * Herbicide * Timing	0.2521	0.7221	0.9313	0.9621	0.7813

[a] Weeks After Treatment
[b] Weeks After Final Treatment

Table 7. Main effect of insecticide seed treatment on visible injury, groundcover, and rough rice yield averaged over herbicides and the 2014 and 2015 growing seasons near Lonoke and Stuttgart, AR.

Insecticide seed treatment	Injury			Groundcover	
	1 WAT[a]	3 WAT	5 WAT	5 WAT	Yield
	------------------%------------------			%	kg ha^{-1}
Thiamethoxam	18	27	16	50	9600
Clothianidin	23	29	23	52	9490
Chlorantraniliprole	26	37	28	47	9040
Non-treated[b]	30	39	31	42	8790
LSD (0.05)[c]	4	9	9	7	510

[a] Abbreviation: WAT, weeks after treatment
[b] 'Non-treated seed' received a fungicide treatment of azoxystrobin at 0.071 mg g^{-1} of seed, mefenoxam at 0.088 mg g^{-1} of seed, and fludioxonil at 0.015 mg g^{-1} of seed.
[c] Fisher's protected LSD is for comparing means within a column.

Table 8. Main effect of herbicide on visible injury, groundcover, and rough rice yield for the seed treatment experiment, averaged over insecticide seed treatments and the 2014 and 2015 growing seasons near Lonoke and Stuttgart, AR.

	Injury			Groundcover	
Herbicide	1 WAT[a]	3 WAT	5 WAT	5 WAT	Yield
	-----------%--------			%	kg ha^{-1}
Glyphosate	27	42	28	45	8790
Imazethapyr	22	24	21	51	8940
Non-treated	-[b]	-	-	59	10000
LSD (0.05)[c]	3	6	6	5	460

[a] Abbreviation: WAT, weeks after treatment
[b] Data for the 'Non-treated' was not included in the injury analysis
[c] Fisher's protected LSD is for comparing means within a column.

Table 9. Average number of rice water weevil (RWW) larvae found per 10-cm-diameter core in 2015 seed treatment studies averaged over experiments near Lonoke and Stuttgart, AR.

Insecticide seed treatment	Glyphosate	Imazethapyr	None
	RWW larvae per core		
Thiamethoxam	22	21	9
Clothianidin	16	11	11
Chlorantraniliprole	14	10	8
Non-treated[a]	52	35	19
LSD (0.05)[b]	---------12---------		

[a] 'Non-treated seed' received a fungicide treatment of azoxystrobin at 0.071 mg g^{-1} of seed, mefenoxam at 0.088 mg g^{-1} of seed, and fludioxonil at 0.015 mg g^{-1} of seed
[b] Fisher's protected LSD is for comparing any two means.

Table 10. Effects of application timing and herbicide on visible injury to rice averaged over 2014 and 2015 at Stuttgart, AR.

	Injury				
	Glyphosate	Imazethapyr	Glyphosate	Imazethapyr	
Application timing	----------1 WAT[a]----------		----------3 WAT----------		5 WAT[b]
	------------------%				------------------
15 DAP[a]	13	7	31	26	25
30 DAP	35	32	32	34	20
45 DAP	67	39	41	20	38
LSD (0.05)[c]	----------10----------		----------12----------		7

[a] Abbreviations: DAP, days after planting; WAT, weeks after treatment
[b] Herbicide was not significant 5 WAT
[c] Fisher's protected LSD is for comparing means within a column.

Table 11. The effects of seed treatment on visual injury to rice averaged over 2014 and 2015 at Stuttgart, AR.

Insecticide seed treatment	Injury		
	1 WAT[a]	3 WAT	5 WAT
	----------------------	%	----------------------
Treated[b]	29	26	23
Non-treated[c]	35	36	33
LSD (0.05)[d]	6	7	6

[a] Abbreviation: WAT, weeks after treatment

[b] 'Treated seed' received an insecticide treatment of thiamethoxam at 1.405 mg g^{-1} along with a fungicide treatment of azoxystrobin at 0.071 mg g^{-1} of seed, mefenoxam at 0.088 mg g^{-1} of seed, and fludioxonil at 0.015 mg g^{-1} of seed.

[c] 'Non-treated seed' received a fungicide treatment of azoxystrobin at 0.071 mg g^{-1} of seed, mefenoxam at 0.088 mg g^{-1} of seed, and fludioxonil at 0.015 mg g^{-1} of seed.

[d] Fisher's protected LSD is for comparing means within a column.

Table 12. The effects of reduced herbicide rates on groundcover and rice yield averaged over insecticide seed treatment, application timing, and the 2014 and 2015 growing season at Stuttgart, AR.

Herbicide	Groundcover	Yield
	%	kg ha^{-1}
Glyphosate	53	10,610
Imazethapyr	55	10,810
None	68	11,670
LSD (0.05)[a]	6	660

[a] Fisher's protected LSD is for comparing means within a column.

Chapter II

Influence of a Thiamethoxam Seed Treatment on Acetolactate Synthase-Inhibiting Herbicide-Induced Injury to Inbred and Hybrid Imidazolinone-Resistant Rice

Abstract

The increased use of insecticide seed treatments in rice has raised many questions about the potential benefits of these products. In 2014 and 2015, a field experiment was conducted near Stuttgart and Lonoke, Arkansas, to evaluate whether an insecticide seed treatment could possibly lessen injury from acetolactate synthase (ALS)-inhibiting herbicides in ALS-resistant (Clearfield®) rice. Two imidazolinone-resistant (IR) cultivars were tested (a hybrid – CLXL745 and an inbred – CL152) with and without an insecticide seed treatment (thiamethoxam). Four different herbicide combinations were evaluated [a non-treated control, two applications of bispyribac-sodium (hereafter bispyribac), two applications of imazethapyr, and two applications of imazethapyr plus bispyribac]. The first herbicide application was to two- to three-leaf rice and the second immediately prior to establishing the permanent flood (five- to six-leaf rice). At both 2 and 4 weeks after final treatment (WAFT), the sequential applications of imazethapyr or bispyribac plus imazethapyr were more injurious to CLXL745 than CL152. This increased injury led to decreased groundcover 3 WAFT. Rice treated with thiamethoxam was less injured than nontreated rice and had improved groundcover and greater canopy heights. Even with up to 32% injury, the rice plants recovered by the end of the growing season, and yields within a cultivar were similar with and without a thiamethoxam seed treatment across all herbicide treatments. Based on these results, thiamethoxam can partially safen rice from injury caused by ALS-inhibiting herbicides as well as increase groundcover and canopy height; albeit, the injury to rice never negatively affected yield.

Nomenclature: bispyribac-sodium; imazethapyr; rice, *Oryza sativa* L.

Key words: herbicide tolerance, insecticide seed treatment, safener

Introduction

Season-long weed interference can cause significant yield loss in rice. Red rice (*Oryza sativa* L.) is particularly difficult to control and can cause up to 82% yield loss as well as reductions in quality (Diarra et al. 1985). In response to a lack of effective red rice control options, imidazolinone-resistant (IR) rice was released in 2002. After its release, IR rice acreage increased to 68% of total rice hectares in Arkansas in 2011 and since has decreased to less than 50% of planted hectares in recent years (Hardke and Wilson 2013; Hardke 2016).

Since the discovery of IR rice in 1993, some injury has been observed following application of acetolactate synthase (ALS)-inhibiting herbicides (Croughan 1994). Imazethapyr, an ALS-inhibiting herbicide labeled for use in IR rice, can cause crop injury following treatment, especially when applied to hybrid rice. Injury levels from 26 to 37% have been observed when imazethapyr was applied early POST at 70 g ai ha^{-1} to some cultivars (Webster and Masson 2001; Ottis et al. 2003; Levy et al. 2006). However, other cultivars and different application timings have resulted in less than 12% injury. The CL (Clearfield) inbred cultivar CL121 treated with imazethapyr at 70 g ha^{-1} at the one- to two-leaf stage had 37% injury 2 weeks after treatment (WAT) and only 12% injury when treated at the three- to four-leaf stage. CL161 had 6% and 5% injury when treated with imazethapyr at the one- to two-leaf and three- to four-leaf stages, respectively (Levy et al. 2006).

Substantial differences in sensitivity to imazethapyr exist among cultivars. Cultivars developed from the PWC-16 IR germplasm are more resistant to imazethapyr than cultivars developed from the original IR germplasm of 93-AS-3510 (Levy et al. 2006). Also with the development of hybrid IR rice cultivars, the level of resistance to imidazolinone herbicides appear to be less than that exhibited by inbred cultivars. The hybrid IR cultivars have only one copy of the resistance gene from the male parent (Anonymous 2008). Likewise, hybrid IR cultivars have a narrower application window for imazamox, another common herbicide used in IR rice (Anonymous 2015). Imazamox can be applied to inbred IR cultivars up to green ring plus 14 days while hybrid IR cultivars can only be treated with imazamox up to green ring, another indication of differences in sensitivity (Anonymous 2015).

Differences among rice cultivars in tolerance to other ALS-inhibiting herbicides exist. Since the introduction of bispyribac, rice injury, which can differ among cultivars, has been one of the major concerns with the use of this herbicide (Braverman and Jordan 1996; Zhang et al. 2005). Zhang et al. (2005) reported little to no injury in some cultivars and up to 33% injury in others following bispyribac applied at two- to three-leaf rice. Applications of bispyribac applied at 20 and 40 g ai ha^{-1} also resulted in decreased root and shoot growth in the cultivar 'Bengal' when applied at the two- to three-leaf growth stage. When applications were delayed until the three- to four-leaf growth stage there was no reduction in root or shoot weight compared to nontreated plants (Zhang and Webster 2002).

The combined use of insecticides and herbicides on crops has resulted in conflicting results in terms of crop injury. Rice tolerance to certain herbicides can be altered through the use of insecticides (Bowling and Hudgins 1966). Tank-mixes of propanil with carbamate or organophosphate insecticides, known inhibitors of aryl acylamidase – the enzyme response for metabolizing propanil, can cause increased injury to rice (Frear and Still 1968). Later research in cotton (*Gossypium hirsutum* L.) showed the opposite effect of herbicide interactions with insecticides. Clomazone, a herbicide that can severely injure cotton, was found to be safe to the crop when used in conjunction with phorate or disulfoton insecticides in-furrow (York et al. 1991; York and Jordan 1992). A similar positive benefit of an insecticide seed treatment on safening rice against herbicide drift was recently observed (Scott et al. 2014; Miller et al. 2016). In this research, thiamethoxam reduced injury to rice from simulated drift rates of imazethapyr. Injury was reduced from 63% without the use of thiamethoxam to 6% with thiamethoxam 42 days after applying imazethapyr at 8.75 g ai ha^{-1} (Miller et al. 2016).

Previous research indicates that injury to IR rice can occur from both labeled rates of imazethapyr and bispyribac, especially when applied from the one- to three-leaf growth stage (Braverman and Jordan 1996; Zhang et al. 2005). Research also suggests that the use of insecticides with some herbicides could reduce herbicidal injury. Therefore, the objective of this research was to determine if an insecticide seed treatment (thiamethoxam) could reduce injury to inbred and hybrid rice caused by imazethapyr and bispyribac.

Materials and Methods

Field experiments were conducted in 2014 and 2015 at the Rice Research and Extension Center (RREC) near Stuttgart, AR, (hereafter referred to as Stuttgart) and the University of Arkansas Pine Bluff (UAPB) farm near Lonoke, AR (hereafter referred to as Lonoke). Studies at Stuttgart were conducted on a Dewitt silt loam soil (Fine, smectitic, thermic Typic Albaqualfs), and studies at Lonoke were conducted on a Calhoun silt loam soil (Fine-silty, mixed, active, thermic Typic Glossaqualfs). Plot sizes at Stuttgart and Lonoke were 1.9 by 5.2 m and 1.9 by 7.6 m, respectively. Each plot contained 10 drill rows spaced 19 cm apart. Plots were fertilized according to the University of Arkansas recommendations for both locations (Hardke 2012). Plots were maintained weed free throughout the growing season using conventional rice herbicides. Clomazone (Command® 3 ME, FMC Corporation, Philadelphia, PA) plus quinclorac (Facet® L, BASF Corporation, Research Triangle Park, NC) were applied at both locations at a rate of 340 g ai ha^{-1} and 280 g ai ha^{-1}, respectively, at the time of planting. A POST application of fenoxaprop (Ricestar HT®, Bayer CropScience, Research Triangle Park, NC) at 123 g ai ha^{-1} and halosulfuron (Permit®, Gowan Company, Yuma, AZ) at 40 g ai ha^{-1} were applied to control grasses and sedges at both locations. Additional POST herbicides included 2,4-D at 560 g ae ha^{-1} and saflufenacil at 18.5 g ai ha^{-1} at Stuttgart in 2015 to control broadleaf weeds and acifluorfen at 140 g ai ha^{-1} at Lonoke in 2015.

The experimental design was a randomized complete block with a three-factor factorial treatment arrangement with four replications. The three factors were cultivar, herbicide program, and seed treatment. Rice cultivars were the inbred CL152 and the hybrid CLXL745. Herbicide programs consisted of two applications of imazethapyr at 105 g ha^{-1}, two applications of bispyribac at 37.5 g ha^{-1}, two applications of imazethapyr plus bispyribac (referred to as "Combined Treatment") at the previous mentioned rates, and a nontreated check. Treatments containing bispyribac also had an adjuvant (Dyne-A-Pak, Helena Chemical Company, Collierville, TN) at 2.5% v/v while a separate adjuvant (Induce, Helena Chemical Company, Collierville, TN) at 0.5% v/v was added to all imazethapyr-containing treatments. The first application was applied at the two- to three-leaf (V2-V3) growth stage of rice while the sequential application was applied at the five- to six-leaf (mid-tillering) growth stage (Counce et al. 2000).

Herbicide programs were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} using a six-nozzle, 2.5-m spray boom, with AIXR 110015 nozzles. All insecticide-treated seed contained thiamethoxam at 1.405 mg g^{-1} of seed (referred to as "treated seed"). All seed, including the insecticide-treated seed, were treated with the fungicides azoxystrobin at 0.071 mg g^{-1} of seed, mefenoxam at 0.088 mg g^{-1} of seed, and fludioxonil at

0.015 mg g^{-1} of seed. Dates for planting, herbicide treatments, and harvest are provided in Table 1.

Visible estimates of injury were recorded 2 and 4 weeks after the final herbicide application (WAFT) on a scale of 0 to 100% compared to the non-treated check for the same seed treatment and cultivar, with 0% being no injury and 100% being plant death. Rice groundcover was estimated using Sigma Scan Pro® (Systat Software, Inc., 501 Canal Blvd. Suite E, Point Richmond, CA 94804) to determine the percentage of green pixels in photographs of each plot. Photographs of each plot were taken 3 WAFT using a 1.8-m monopod (Purcell 2000). Canopy height was also determined 3 WAFT for each treatment and converted to a relative height based on the non-treated check. Plots were harvested at maturity using a small-plot combine, and rough rice yields were recorded and adjusted to 12% moisture.

All data were analyzed in JMP Pro 12 (SAS Institute Inc., Cary, NC) using the MIXED procedure. Site-year and replication nested within site-year were included in the model as random effects. Means were separated using Fisher's protected LSD test at $\alpha = 0.05$. P- Values for all evaluation are included in Table 2.

Results and Discussion

Injury. For both evaluations after final treatment, the two-way interaction of cultivar and herbicide program along with the main effect of seed treatment were significant for visible estimates of injury to rice. By 2 WAFT, injury symptoms began to occur in all plots receiving a herbicide treatment. Injury symptoms consisted of chlorosis around the leaf tip and margin. At 2 WAFT, injury from the combined treatment of imazethapyr and bispyribac was less than 10% for CL152 when averaged across seed treatments (Table 3). For CLXL745, only the bispyribac treatment had less than 10% injury. Imazethapyr alone treatment caused 17% injury 2 WAFT in CLXL745. With the combined treatment, injury increased to 32% in CLXL745. By 4 WAFT, rice plants had begun to recover from the herbicide applications; however, injury was still higher for the CLXL745 than for CL152.

When averaged across cultivar and herbicide programs, seed treatment had an effect on rice injury. Rice injury for the treated seed was nearly half that of the non-treated seed at both 2 and 4 WAFT, evidence of the safening associated with the insecticide seed treatment (Table 4). Based on previous cytochrome P450 gene expression research with thiamethoxam in the Asian honey bee (*Apis cerana cerana*) (Ming et al. 2016), it is speculated that safening of rice may be a result of upregulation of stress genes caused by the insecticide seed treatment, in turn resulting in a greater rate of metabolism of the ALS-inhibiting herbicides.

When considering only visible injury, CLXL745 was more prone to injury from imazethapyr alone and the combined treatment compared to CL152 (Table 3). Additionally, CLXL745 tended to recover from injury slower than CL152. Cultivar differences such as those seen here have also been noted previously for injury to rice in response to bispyribac (Braverman and Jordan 1996; Zhang et al. 2005).

Canopy Height. There were no significant interactions for canopy height, and only the main effects were significant. At 3 WAFT, the canopy height, averaged over cultivars and herbicides, was 2 cm greater in the plots with an insecticide seed treatment and follows the same trend as injury, with the treated plants being slightly healthier (Table 4). Additionally, when averaged over seed treatments and herbicides, CLXL745 was 45 cm tall at 3 WAFT while CL152 was only 43 cm tall (data not shown). These height differences between cultivars was expected because previous research has shown that CLXL745 is 10 cm taller than CL152 at maturity

(Sater et al. 2014). When herbicide programs were compared for effect on height, the imazethapyr alone and bispyribac alone treatments were equal to the non-treated control (Table 5). However, the combined program of imazethapyr plus bispyribac did reduce canopy height by 4 cm.

Groundcover. There was a significant two-way interaction between rice cultivar and herbicide program for groundcover at 3 WAFT (Table 3). Likewise, the main effect of seed treatment was significant (Table 3).

Rice groundcover at 3 WAFT followed some of the same trends observed in the rice injury data. There was a significant reduction in groundcover of both imazethapyr-containing treatments applied to the hybrid cultivar whereas the inbred cultivar had reduced groundcover only when treated twice with imazethapyr plus bispyribac (Table 3). This trial was conducted under weed-free conditions; however, in a commercial field, it is possible that the delay in groundcover (i.e., canopy formation) caused by the ALS-inhibiting herbicides could contribute to greater opportunity for weed growth and interference with the rice crop, especially those weeds tolerant to the herbicides applied.

Additionally, plants from insecticide-treated seed showed more groundcover at 3 WAFT than the non-treated seed (Table 4). There was an eight-percentage point increase in groundcover when an insecticide seed treatment was used, further evidence that the seed treatment results in a more robust rice plant. Rice water weevil (*Lissorhoptrus oryzophilus* Kuschel) populations were not determined in this research, but depending upon their presence and density at these four sites, this improvement in crop growth may be partially a result of the insecticide since all other factors would be comparable between treated and non-treated seed. In an adjacent but separate experiment at both locations each year, the insecticide seed treatment did reduce rice water weevil numbers (G. Lorenz, nonpublished data).

Yield. The use of an insecticide seed treatment or the use of differing herbicide programs had no effect on rough rice yield. The only significant main effect was the rice cultivar, with the hybrid IR cultivar CLXL745 producing an average rough rice yield of 11,570 kg ha^{-1}, while the inbred IR cultivar CL152 averaged 8,080 kg ha^{-1} (data not shown). Although injury was observed from the use of ALS-inhibiting herbicides on IR rice, the injury did not result in any yield loss as observed in other research (Ottis et al. 2004).

Practical Implications. Growing a healthy rice crop is paramount to reducing weed interference and maximizing yield potential. Pest control (insects, diseases, and weeds) is vital to minimizing variability in crop yields among fields and across years. Troublesome weeds such as barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] and red rice leads many growers to choose to plant IR rice, enabling greater use of ALS-inhibiting herbicides (Ottis et al. 2003; Ottis et al. 2004; Masson et al. 2001). However, it should be noted that even then some ALS-inhibiting herbicides can still cause severe injury to the crop (Webster and Masson 2001; Ottis et al. 2003; Levy et al. 2006). Today, approximately 75% of the Arkansas rice hectares is treated with an insecticide seed treatment with thiamethoxam being the most common (Lorenz, nonpublished data). While insect control will remain one of the major reasons for applying an insecticide seed treatment, this research shows use of thiamethoxam provided increased crop growth or less damage associated with multiple applications of ALS-inhibiting herbicides, especially in fields where hybrid rice is grown.

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Table 1. Planting dates and herbicide application dates

Location	Year	Planting date	Application date	
			Two- to three-leaf rice	Five- to six-leaf rice [a]
Stuttgart, AR	2014	April 23	May 15	June 3
	2015	May 5	May 19	June 10
Lonoke, AR	2014	May 20	June 5	June 17
	2015	June 8	June 22	July 6

[a] Applied immediately prior to establishing the permanent flood

Table 2. P- values for all evaluations

Factor	Injury 2 WAFT[a]	Injury 4 WAFT	Groundcover 3 WAFT	Canopy Height 3 WAFT	Yield
Seed Treatment	0.0001	0.0071	0.0001	0.0002	0.4148
Variety	0.0001	0.0001	0.0001	0.0028	0.0001
Herbicide	0.0001	0.0001	0.0001	0.0001	0.3024
Seed Treatment * Variety	0.1792	0.3822	0.9673	0.9884	0.9706
Seed Treatment * Herbicide	0.1276	0.1008	0.6922	0.4251	0.1570
Variety * Herbicide	0.001	0.0463	0.0244	0.5596	0.9252
Seed Treatment * Herbicide * Variety	0.9179	0.7826	0.8992	0.4784	0.6183

[a] Weeks After Final Treatment

Table 3. Interaction of herbicide program and rice cultivar on visible estimates of injury 2 and 4 weeks after final treatment (WAFT) and groundcover 3 WAFT, averaged across seed treatments and site years.

	Injury				Groundcover	
	2 WAFT[a]		4 WAFT		3 WAFT	
Herbicide program	CL 152	CLXL 745	CL 152	CLXL 745	CL 152	CLXL 745
	%					
Imazethapyr fb[b] Imazethapyr	6	17	1	11	72	61
Bispyribac fb bispyribac	7	8	1	7	68	66
Combined[d]	13	32	7	22	62	51
None	-[c]	-	-	-	72	69
LSD (0.05)[e]	7		5		6	

[a] Weeks After Final Treatment
[b] Followed by
[c] Injury data for the 'None' herbicide program was not included in the analysis 2 or 4 WAFT.
[d] Imazethapyr plus bispyribac applied to two- to three-leaf rice and subsequently to five- to six-leaf rice.
[e] Fisher's protected LSD is for comparing means with a shared LSD

Table 4. Main effect of seed treatment on visible estimates of rice injury 2 and 4 weeks after final treatment (WAFT) along with groundcover and canopy height 3 WAFT, averaged across cultivar, herbicide program, and site years.

Insecticide seed treatment	Injury		Groundcover	Canopy height
	2 WAFT	4 WAFT	---------------3 WAFT---------------	
	------------------------%-------------------------			cm
Treated[a]	9	6	70	45
Nontreated	18	10	62	43
LSD (0.05)[b]	4	3	3	1

[a] The insecticide thiamethoxam was applied to 'treated' seed prior to planting.
[b] Fisher's protected LSD is for comparing means within a column.

Table 5. Main effect of herbicide program on rice canopy height 3 weeks after final treatment, averaged across cultivar, seed treatment, and site years.

Herbicide program	Canopy height
	cm
None	45
Imazethapyr	45
Bispyribac	45
Combined	41
LSD (0.05)[a]	2

[a] Fisher's protected LSD is for comparing means within a column.

Chapter III

Effect of Thiamethoxam on Injurious Herbicides in Rice

Abstract

Increases in the number of herbicide-resistant weeds in rice has led to the need for new herbicides and modes of action to control these troublesome weeds. Previous research has indicated that insecticide seed treatments can safen rice from herbicide drift. In 2014 and 2015, two field experiments were conducted at the Rice Research and Extension Center (RREC) near Stuttgart, Arkansas, and at the University of Arkansas Pine Bluff (UAPB) farm near Lonoke, Arkansas, to determine if insecticide seed treatments could prevent unacceptable levels of herbicide injury from preemergence (PRE)- and postemergence (POST)-applied herbicides that are typically injurious to rice. Both studies were planted with the imidazolinone-resistant, inbred variety CL151. 'Treated' plots contained the insecticide seed treatment thiamethoxam while 'nontreated' plots contained no insecticide seed treatment. Seven herbicides were evaluated in the PRE experiment: clomazone, pethoxamid, fluridone, *S*-metolachlor, thiobencarb, clethodim, and quizalofop to determine crop injury, stand counts, groundcover, and rough rice yield with and without an insecticide seed treatment compared to plots with no herbicide treatments. Overall, an insecticide seed treatment provided increased rice stands and less herbicide injury than the 'nontreated' seed while increasing yield by 500 kg ha^{-1}. Of the herbicides tested, clomazone-, thiobencarb-, clethodim-, and quizalofop-treated plots had equivalent yields to the no-herbicide plots. The POST experiment evaluated propanil, saflufenacil, carfentrazone, and acifluorfen in various tank-mixtures and application timings. Similar to the PRE experiment, plants from treated seed had less herbicide injury 1 and 5 weeks after treatment (WAT) along with an increased canopy height and groundcover percentage. Plants having treated seed also had increased yields when used with some herbicide programs. Overall, the use of an insecticide seed

treatment can give the added benefit of less injury from injurious herbicides as well as increased groundcover.

Nomenclature: thiamethoxam; clomazone; thiobencarb; pethoxamid; fluridone; *S*-metolachlor; thiobencarb; clethodim; quizalofop; propanil; saflufenacil; carfentrazone; acifluorfen; rice, *Oryza sativa* L.

Key words: herbicide tolerance, insecticide seed treatment, safener

Introduction

Effectively controlling weeds is an important factor in growing a successful rice crop. Some of the most troublesome weeds in rice include barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.], red rice (*Oryza sativa* L.), broadleaf signalgrass [*Urochloa platyphylla* (Nash)], Palmer amaranth [*Amaranthus palmeri* (S.) Wats], and jointvetch (*Aeschynomene* spp.) (Webster 2012). If left uncontrolled, these weeds can cause significant yield loss in rice crops. Red rice left uncontrolled can cause up to 82% yield loss while other grasses such as barnyardgrass and broadleaf signalgrass can reduce yields up to 70 and 32%, respectively (Smith 1988). Control of barnyardgrass has been achieved through the use of propanil and imazethapyr among other herbicides (Smith 1961; Klingaman et al. 1992; Masson et al. 2001; Webster and Masson 2001). Since the introduction of propanil and imazethapyr, resistant biotypes of barnyardgrass have evolved to both herbicides (Heap 2016). In addition, resistance to clomazone, cyhalofop, quinclorac, and fenoxaprop has been documented in rice-producing regions of the US (Heap 2016). With barnyardgrass evolving resistance to multiple modes of action, new herbicides and programs are needed.

Tank mixtures and herbicide programs that utilize multiple modes of action are recommended for control of troublesome weeds of rice (Riar et al. 2013). Research has shown increases in weed control when herbicide programs or tank mixtures with multiple modes of action are used. When propanil was added to a herbicide program of two applications of imazethapyr alone, an increase of up to 31 percentage points was observed in red rice control and up to 36 percentage points in barnyardgrass control (Carlson et al. 2011). Increased barnyardgrass and broadleaf signalgrass control was also observed when quinclorac was added to an imazethapyr-alone herbicide program (Norsworthy et al. 2011). The addition of saflufenacil, carfentrazone, bentazon, and acifluorfen to imazethapyr can also aid in broadleaf weed control (Pellerin et al. 2003; Montgomery et al. 2015).

Additional herbicide modes of action are needed in rice, especially with the multiple resistance that is increasingly common throughout the Midsouth (Norsworthy et al. 2013). Currently, there are no WSSA group 15 herbicides labeled for use in rice. Bararpour et al. (2013, 2014) recently screened three group 15 herbicides (acetochlor, pyroxasulfone, and *S*-metolachlor) for rice tolerance to POST applications. Acetochlor applied at the two- or four-leaf growth stage caused a maximum of 18% injury and did not cause any yield loss. *S*-metolachlor applied at the same time caused up to 35% injury and yields were inconsistent among rates and application timing (Bararpour et al. 2013). Pyroxasulfone caused up to 60% injury and reduced yields. Injury also was more profound when applied to spiking rice, which led to greater yield reductions at this timing. Injury to rice from these herbicides was generally greater on a silt loam than on a clay soil (Bararpour et al. 2014). Pethoxamid, another group 15 herbicide, is currently being evaluated for use in Midsouth rice production systems. Pethoxamid may offer another option for rice growers, with little injury depending on timing of application (Godwin 2017).

With the evaluation of some new herbicides for use in rice and some already registered rice herbicides causing crop injury, interactions with other pesticides need to be evaluated. Increased rice injury from propanil occurs when carbamate or organophosphate insecticides, known inhibitors of aryl acylamidase – the enzyme response for metabolizing propanil -- are used in tank-mixes with propanil (Frear and Still 1968). Other herbicides such as saflufenacil can cause injury to rice; however, there have been no reports of interactions with insecticides (Montgomery et al. 2014; Dickson et al. 2014). Also, clomazone, a common PRE herbicide used in rice, can cause injury to seedling rice plants. For example, clomazone at 340 g ai ha^{-1} can cause up to 27% injury to rice (Scherder et al. 2004; O'Barr et al. 2007). Like saflufenacil, little research has been conducted to determine if an insecticide seed treatment could be used to safen rice against possible injury from herbicides currently registered in-crop use or those for which tolerance is currently being evaluated. It is known that insecticide seed treatments help to lessen the injury to rice caused by drift rates of imazethapyr and glyphosate (Miller et al. 2016). Therefore, the objective of this research was to assess whether an insecticide seed treatment would reduce crop injury caused by a 1X rate of currently registered and non-registered herbicides.

Materials and Methods

Two field experiments were conducted in 2014 and 2015, with the first experiment using herbicides applied PRE (hereafter referred to as the PRE experiment). The second experiment consisted of herbicides that were applied after rice emergence (hereafter referred to as the POST experiment).

The PRE experiment was conducted at the Rice Research and Extension Center (RREC) located near Stuttgart, AR, and the University of Arkansas Pine Bluff (UAPB) farm located near Lonoke, AR. Studies at the RREC were conducted on a Dewitt silt loam soil (Fine, smectitic, thermic Typic Albaqualfs), while the studies at UAPB were conducted on a Calhoun silt loam soil (Fine-silty, mixed, active, thermic Typic Glossaqualfs). Plot sizes at the RREC and UAPB were 1.9 by 5.2 m and 1.9 by 7.6 m, respectively. Each plot contained 10 drill rows spaced 19 cm apart and was planted with the imidazolinone-resistant, inbred variety CL 152 at 83 kg ha^{-1}. Planting and herbicide application dates are shown in Table 1. Plots were fertilized according to the University of Arkansas recommendations for both locations (Hardke 2012). Plots were kept weed free throughout the growing season using the conventional POST herbicides shown in Table 2.

The experimental design was a randomized complete block with a two-factor factorial treatment arrangement with four replications. The two factors were herbicides and seed treatments. All herbicides and rates evaluated are listed in Table 3. All insecticide-treated seed contained thiamethoxam at 1.405 mg g^{-1} of seed (referred to as "treated seed"). All seed, including the insecticide-treated seed, were treated with the fungicides azoxystrobin at 0.071 mg g^{-1} of seed, mefenoxam at 0.088 mg g^{-1} of seed, and fludioxonil at 0.015 mg g^{-1} of seed. The seed receiving only the fungicide seed treatments will be referred to as "non-treated seed." All herbicide programs for the PRE experiment were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} using a six-nozzle, 2.5-m spray boom, with AIXR 110015 nozzles immediately after planting.

Injury was evaluated 2, 4, and 7 weeks after emergence (WAE) on a scale of 0 to 100% compared to the non-treated check with the same seed treatment, with 0% being no injury and 100% being plant death. Rice density per meter of row was counted for each plot 2 WAE and compared to the herbicide non-treated. Rice groundcover was estimated using Sigma Scan Pro® (Systat Software, Inc., 501 Canal Blvd. Suite E, Point Richmond, CA 94804) to determine the percentage of green pixels in photographs of each plot. Photographs of each plot were taken 2, 4, and 7 WAE using a 1.8-m monopod (Purcell 2000). Canopy height was also determined 6 WAE for each treatment and converted to a relative height based on the herbicide non-treated check. The center five drill rows of each plot were harvested at crop maturity using a small-plot combine, and rough rice yields were recorded. Yields were adjusted to a standard of 12% moisture.

The POST experiment was conducted in similar fashion to the PRE experiment. The POST experiment was conducted only at the RREC near Stuttgart with soil texture, planting dates, plot size, and application equipment and setup similar to the PRE experiment. Planting and herbicide application dates are shown in Table 4. Herbicide applications were made at the 2-lf, 4-lf, and 6-lf (V2, Early tillering, and Mid-tillering, respectively) growth stages (Counce et al. 2000). The POST experiment was also kept weed free throughout the growing season using conventional rice herbicides as shown in Table 2.

The experimental design was a randomized complete block with a two-factor factorial treatment arrangement with four replications. The two factors for the POST experiment were also herbicides and seed treatment. Seed treatments remained the same as the PRE experiment with “treated seed” and “non-treated seed.”

Visual injury was evaluated 1, 5, and 11 weeks after herbicide treatment (WAT). Photos of all plots were taken at 8 WAT, and groundcover was determined using Sigma Scan Pro. Three canopy height measurements were taken per plot 11 WAT. The five center rows of each plot was harvested at crop maturity using a small-plot combine, and rough rice yields were recorded and adjusted to 12% moisture.

All data were analyzed in JMP Pro 11(SAS Institute Inc., Cary, NC). Site years and replications nested within site years were included in the model as random effects for the PRE experiment. Site years for the POST experiment were analyzed separately. Means were separated using Fisher’s protected LSD test at $\alpha = 0.05$. P- Values for all evaluations in the PRE and POST experiments are listed in Table 5 and 6 respectively.

Results and Discussion

PRE Experiment. For all evaluations in the PRE experiment, the interaction of herbicide and insecticide seed treatment was not significant ($p > 0.05$). However, the main effects of herbicide and insecticide seed treatment were significant for all evaluations (Table 5).

Herbicide Effect. About a week after planting, rice plants began to emerge and injury symptoms began to occur by 2 WAT (Table 7). All of the group 15 herbicides, pyroxasulfone, *S*-metolachlor, and pethoxamid, caused at least 65% injury at 2 WAT. The group 1 ACCase-inhibiting herbicides, clethodim and quizalofop, injured rice 48 and 43%, respectively, even though these herbicides are typically applied POST in other crops. Fluridone and thiobencarb caused 32 and 30% injury, respectively, whereas clomazone, a standard for comparison, injured rice 19% at 2 WAT.

By 4 WAT, rice treated with some herbicides began to recover while other plots continued to worsen (Table 7). Thiobencarb, which is currently labeled for use as a delayed PRE herbicide in rice, was the only treatment that did not differ from clomazone for visible injury to rice at both 4 and 7 WAT. Although injury from fluridone at 4 WAT was comparable to clomazone, flooding the field at 5 to 6 WAT caused crop damage from fluridone to increase, likely because of greater availability of the herbicide.

Stand counts were also evaluated 2 WAT to determine if rice densities in each herbicide-treated plot were comparable to the non-treated check. Clomazone, thiobencarb, and fluridone had rice densities comparable to the non-treated check, which had 111 plants per 3 m of row (Table 7). *S*-metolachlor had the least number of plants emerge.

In conjunction with the last injury rating, groundcover photos were taken at 7 WAT. At 7 WAT, rice groundcover percentage varied greatly among treatments and followed the same trend as injury 7 WAT. Stand reductions and increased injury led to the pyroxasulfone- and *S*-metolachlor-treated plots having only 3 and 5% groundcover, respectively, 7 WAT (Table 7). Clomazone remained the best herbicide option, having 83% groundcover, with thiobencarb and fluridone remaining similar to the non-treated check. Overall, the percent of groundcover in each plot depended upon the amount of injury and number of plants per plot.

Rice yields following the PRE herbicides ranged from 9,000 kg ha^{-1} for the clomazone treatment to 2150 kg ha^{-1} for pyroxasulfone and *S*-metolachlor (Table 7). Only rice treated with clomazone, thiobencarb, clethodim, or quizalofop had yield comparable to the non-treated check (8,200 kg ha^{-1}).

Insecticide Seed Treatment Effect. Averaged over herbicides and site-years, the insecticide seed treatment lessened injury compared to its absence at 2, 4, and 7 WAT (Table 8). The use of an insecticide seed treatment also increased the number of emerged plants 2 WAT and improved rice groundcover at 7 WAT. It is unknown whether this improvement in crop growth caused by the insecticide seed treatment is partially a function of insecticide efficacy on rice water weevil (*Lissorhoptrus oryzophilus* Kuschel). Rice water weevil pressure was not determined in this research and, depending on the population, could have an effect on the parameters evaluated. It is obvious that insecticide-treated plots showed less injury and more plants, which eventually led to increased yield. The insecticide-treated plots yielded 500 kg ha^{-1} better than the non-treated plots, which is similar to that seen in other research when an elevated population of insects were present in the field (Plummer et al. 2012).

POST Experiment. For the POST experiment, there was a significant interaction between years; therefore, data were analyzed separately for 2014 and 2015. The interaction of herbicide program and insecticide seed treatment was significant only for rough rice yield both years; however, the main effects of herbicide program and insecticide seed treatment were significant for all other assessments such as visible injury, canopy height, and groundcover (Table 6).

Herbicide Effect. Herbicides were applied according to Table 4, while injury ratings were recorded 1, 5, and 11 weeks after the final herbicide treatment (WAT). At 1 WAT, injury ranged from 12% to 87% in 2014 (Table 9). Both programs containing carfentrazone had at least 65% injury while all other programs had 25% injury or less. At both 5 and 7 WAT only the carfentrazone alone program had significantly more injury than all other treatments (Table 9). Injury trends for the 2015 growing season were similar to the results from the 2014 growing season, although overall levels of injury were greater in 2015. Once again, 1 WAT both carfentrazone-containing programs had increased injury over all other treatments. However, rice plants in both treatments never recovered through 11 weeks of evaluation. At the 11-week evaluation, only the single application of propanil along with the propanil + saflufenacil treatments had less than 15% injury (Table 9).

In addition to injury ratings, groundcover percentages were taken for both years, but groundcover was significant only in 2014. Groundcover percentages ranged from 9% to 66% for the herbicide programs (Table 9). The percent groundcover generally followed the trend of visual injury. Plots with the least amount of injury generally had the highest amount of groundcover.

As with groundcover percentages, only data from 2014 were statistically different for canopy heights. Only two herbicide programs showed significant stunting when compared to the numerically tallest program (saflufenacil, 64 cm). Rice treated with propanil followed by (fb) propanil and carfentrazone alone was shorter than the 64 cm of the tallest program (Table 9). The carfentrazone alone program also had the most visual injury 11 WAT; however, the two applications of propanil had injury levels similar to most other programs.

Insecticide Seed Treatment Effect. Averaged over herbicide programs, an insecticide seed treatment had a significant effect on injury, canopy height, and groundcover in 2014. The use of an insecticide seed treatment helped reduce herbicide injury at all ratings. Overall, there was 5 to 6% less injury when the rice seed was treated with an insecticide (Table 10), similar to that observed in other research (Miller et. al 2016). The insecticide-treated seed also produced plants 3 cm taller than untreated along with an additional 7 percentage points of groundcover (Table 10). In 2014, the insecticide-treated seed produced an overall healthier rice plant than in 2015.

Yield. There was a significant interaction between herbicide program and seed treatment for both the 2014 and 2015 growing season. Among herbicide programs in 2014, rough rice yields were increased in herbicide programs containing propanil, with the exception of the propanil plus saflufenacil program, with the use of an insecticide seed treatment. Among treated seed, only the carfentrazone alone program had reduced yields when compared to the check. However, among non-treated seed, all herbicide programs without saflufenacil had reduced yields compared to the check without an insecticide seed treatment (Table 11). There was also no statistical difference between the non-treated checks with or without the insecticide seed treatment in 2014 or 2015. Among herbicide programs, yields were increased in the propanil fb propanil plus acifluorfen program along with both programs containing only saflufenacil with an insecticide seed treatment in 2015. In comparison to the non-treated check, all herbicide programs, both treated and non-treated seed, had reduced yields, with the exception of the non-treated seed in the propanil plus saflufenacil program.

In both years, increased yields were observed when acifluorfen was combined with propanil and was used with an insecticide seed treatment. Depending on year, other herbicide programs that included propanil and saflufenacil had some yield benefit from the insecticide seed treatment. In all herbicide programs, there was never a yield loss from using the insecticide seed treatment.

Practical Implications. A healthy rice crop is often necessary to optimize yield. With increased weed resistance, more herbicides and multiple modes of actions are required to keep a clean field. Some herbicides, although labeled for use in rice, can injure the crop (Montgomery et al. 2014; Dickson et al. 2014). Increased injury can also lead to increased chance for potential yield loss. However, with the use of insecticide seed treatments some injury can be alleviated, while protecting the potential rice yield when used in conjunction with some herbicides. It is speculated that a possible upregulation of stress genes caused by the neonicotinoid seed treatment could reduce herbicide injury in rice (Ming et al. 2016). Consequently, if left unattended, weed pressure can cause a significant yield loss as well (Smith 1988).

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Table 1. Planting dates and application dates for PRE experiment.

Location	Year	Planting date	Application date
Stuttgart, AR	2014	April 23	April 25
	2015	May 6	May 8
Lonoke, AR	2014	May 20	May 20
	2015	June 8	June 8

Table 2. Herbicides used to maintain weed-free plots.

Herbicide trade name	Herbicide common name	Rate	Manufacturer
		$g\ ha^{-1}$	
Newpath	Imazethapyr	105 ai	BASF Corporation, Research Triangle Park, NC
Command 3 ME[a]	Clomazone	340 ai	FMC Corporation, Philadelphia, PA
Facet[a]	Quinclorac	280 ai	BASF Corporation, Research Triangle Park, NC
Ricestar HT	Fenoxaprop	123 ai	Bayer CropScience, Research Triangle Park, NC
Ultra Blazer[b]	Aciflurofen	140 ai	United Phosphorus, Inc., King of Prussia, PA
Clincher	Cyhalofop	314 ai	Dow AgroSciences LLC, Indianapolis, IN
Permit[c]	Halosulfuron	40 ai	Gowan Company, Yuma, AZ
Weedar 64	2,4-D	560 ae	Nufarm Inc., Alsip, IL

[a] Herbicide used only in the POST experiment
[b] Herbicide used only at Lonoke location
[c] Herbicide used only at Stuttgart location

Table 3. Herbicides and rates evaluated for the PRE experiment.

Herbicide trade name	Herbicide common name	Rate	Manufacturer
		g ae or ai ha^{-1}	
Command	Clomazone	673	FMC Corporation, Philadelphia, PA
Pethoxamid	Pethoxamid	560	FMC Corporation, Philadelphia, PA
Brake	Fluridone	224	SePro, Carmel, IN
Zidua	Pyroxasulfone	120	BASF Corporation, Research Triangle Park, NC
Dual II Magnum	*S*-metolachlor	1071	Syngenta Crop Protection, Greensboro, NC
Bolero	Thiobencarb	6720	Valent U.S.A. Corporation, Walnut Creek, CA
SelectMax	Clethodim	135	Valent U.S.A. Corporation, Walnut Creek, CA
Targa	Quizalofop	120	Gowan Company, Yuma, AZ

Table 4. Planting date and application dates for POST experiment based on rice growth stage.

			Application date		
Location	Year	Planting date	Two-leaf rice	Four-leaf rice	Six-leaf rice
Stuttgart	2014	April 23	May 16	May 20	June 3
	2015	May 6	May 27	June 2	June 11

Table 5. P- Values for all evaluations in the PRE experiment

Factor	Injury 2 WAT[a]	Injury 4 WAT	Injury 7 WAT	Groundcover 7 WAT	Stand Counts	Yield
Seed Treatment	0.0083	0.0024	0.0012	0.0187	0.0408	0.048
Herbicide	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Seed Treatment * Herbicide	0.8740	0.6889	0.6446	0.5642	0.7045	0.926

[a] Weeks After Treatment

Table 6. P- Values for all evaluations in POST experiment

Factor	2014						2015					
	Injury 1 WAT[a]	Injury 5 WAT	Injury 11 WAT	Groundcover 54 DAP	Canopy Height 79 DAP	Yield	Injury 1 WAT	Injury 5 WAT	Injury 11 WAT	Groundcover 58 DAP[b]	Canopy Height 80 DAP	Yield
Seed Treatment	0.0024	0.0127	0.0061	0.0283	0.0408	0.0479	0.1158	0.1514	0.1678	0.2176	0.0804	0.0398
Herbicide	0.0001	0.0001	0.0001	0.0009	0.0001	0.0016	0.0001	0.0001	0.0007	0.0943	0.2764	0.0001
Seed Treatment * Herbicide	0.9274	0.7105	0.6562	0.4813	0.8510	0.0433	0.4812	0.3313	0.7049	0.8149	0.9995	0.0414

[a] Weeks After Treatment
[b] Days After Planting

Table 7. Main effect of herbicide on visable injury, stand counts, groundcover, and rough rice yield for the PRE experiment averaged over site years and seed treatments.

	Injury			Stand counts	Groundcover	
Herbicide	2 WAT[a]	4 WAT	7 WAT	2 WAT	7 WAT	Yield
	----------------%---------------			Plants 3 m^{-1} of row	%	kg ha^{-1}
Clomazone	19	12	8	112	83	9,000
Pethoxamid	65	61	42	65	55	7,200
Fluridone	32	18	25	98	73	7,200
Pyroxasulfone	78	95	90	68	3	2,150
S-metolachlor	78	98	93	44	5	2,150
Thiobencarb	30	19	17	95	68	8,200
Clethodim	48	36	29	75	60	8,200
Quizalofop	43	40	33	72	63	7,300
Check	-[b]	-	-	111	75	8,200
LSD(0.05)[c]	10	10	11	20	9	950

[a] Abbreviation: WAT, weeks after treatment
[b] Data for the 'Check' was not included in the injury analysis.
[c] Fisher's protected LSD is for comparing means within a column.

Table 8. Main effect of insecticide seed treatment on visable injury, stand counts, groundcover and rough rice yield for the PRE experiment.

Insecticide seed treatment	Injury			Stand counts	Groundcover	
	2 WAT[a]	4 WAT	7 WAT	2 WAT	7 WAT	Yield
	--------------------%--------------------			Plants 3 m^{-1} of row	%	kg ha^{-1}
Treated[b]	45	43	37	85	54	6,900
Nontreated	53	51	47	72	48	6,400
LSD(0.05)[c]	5	5	6	10	4	450

[a] Abbreviation: WAT, weeks after treatment

[b] 'Treated seed' received thiomethoxam.

[c] Fisher's protected LSD is for comparing means within a column.

Table 9. Main effect of herbicide program on visible injury, canopy height, and groundcover for 2014 and 2015 for the POST experiment.

			Injury						Canopy height	Groundcover
			2014			2015			2014	
Herbicide	Rate	Timing	1 WAT[a]	5 WAT	11 WAT	1 WAT	5 WAT	11 WAT	79 DAP[a]	54 DAP
	g ai ha^{-1}		---------------	---------------	---------------	%	---------------	---------------	cm	%
Propanil	6,720	2-lf[a]	25	16	7	11	9	6	61	54
Propanil fb[a]	4,480	2-lf	24	25	13	21	31	28	56	34
propanil	4,480	4-lf								
Propanil fb	4,480	2-lf	21	22	7	14	24	36	59	45
propanil	4,480	6-lf								
Propanil fb	4,480	2-lf	12	4	3	21	19	23	64	66
propanil +	4,480	6-lf								
acifluorfen	224	6-lf								
Saflufenacil fb	25	2-lf	12	19	9	19	34	36	63	57
saflufenacil	25	6-lf								
Propanil +	4,480	2-lf	21	11	7	25	19	11	63	59
saflufenacil	25	2-lf								
Carfentrazone	560	2-lf	87	59	42	65	58	50	52	9
Propanil +	4,480	2-lf	65	27	15	74	68	69	60	45
carfentrazone	560	2-lf								
LSD(0.05)[b]			6	10	9	15	20	27	6	10

[a] Abbreviations: WAT, weeks after treatment; DAP, days after planting; fb, followed by; lf, leaf

[b] Fisher's protected LSD is for comparing means within a column.

Table 10. Main effect of insecticide seed treatment on injury, canopy height, and groundcover for the POST experiment in 2014.

Insecticide seed treatment	Injury			Canopy height	Groundcover
	1 WAT[a]	5 WAT	11 WAT	79 DAP[a]	54 DAP
		%		cm	%
Treated	31	20	16	61	50
Nontreated	36	26	10	58	43
LSD(0.05)[b]	3	5	5	2	5

[a] Abbreviations: WAT, weeks after treatment; DAP, days after planting
[b] Fisher's protected LSD is for comparing means within a column.

Table 11. Interaction of herbicide program and insecticide seed treatment on rough rice yield for 2014 and 2015.

			Yield			
			2014		2015	
Herbicide	Rate	Timing	Treated[a]	Nontreated	Treated[a]	Nontreated
	g ai ha^{-1}		---------------------------kg ha^{-1}---------------------------			
Propanil	6,720	2-lf[b]	7,050	6,450	7,950	8,100
Propanil fb[b]	4,480	2-lf	6,750	6,300	8,500	8,250
propanil	4,480	4-lf				
Propanil fb	4,480	2-lf	6,700	6,050	8,050	7,450
propanil	4,480	6-lf				
Propanil fb	4,480	2-lf				
propanil +	4,480	6-lf	7,250	6,950	8,500	7,900
acifluorfen	224	6-lf				
Saflufenacil fb	25	2-lf	6,950	7,350	8,500	7,850
saflufenacil	25	6-lf				
Propanil +	4,480	2-lf	7,050	6,750	8,350	8,450
saflufenacil	25	2-lf				
Carfentrazone	560	2-lf	6,150	6,350	7,400	7,050
Propanil +	4,480	2-lf	6,550	6,100	6,950	7,350
carfentrazone	560	2-lf				
Nontreated			6,900	7,000	9,100	8,900
LSD(0.05)[c]			-----450-----		-----550-----	

[a] Treated seed received thiamethoxam
[b] Abbreviations: fb, followed by; lf, leaf
[c] Fisher's protected LSD is for comparing means with a shared LSD.

General Conclusion

Insecticide seed treatments have proven to be great insect management tools in rice production. Thiamethoxam, clothianidin, and chlorantraniliprole were all effective in controlling rice water weevils. In addition, the neonicotinoid seed treatments, thiamethoxam and clothianidin seemed to have some other benefits to rice crops. In the presence of low rates of imazethapyr or glyphosate, conventional rice treated with a neonicotinoid seed treatment had less injury and more groundcover compared to non-treated seed which in return led to greater yields. In other trials, thiamethoxam was tested to determine if similar results might be achieved with labeled rice herbicides that have a history of being injurious to rice plants. When averaged over cultivar and herbicide programs, Clearfield® seed treated with thiamethoxam had less injury and more groundcover after the ALS-inhibiting herbicide applications. Although there was no yield increase in this trial, less herbicide injury did lead to increased groundcover, which could ultimately lead to better weed control. Similar results were observed in the PRE and POST experiments, where reduced injury and increased groundcover were noticed when thiamethoxam treated seed was planted. Yields were also increased in the PRE experiment while some treatments in the POST experiment had increased yields when treated with thiamethoxam. It is speculated that a possible upregulation of stress genes by the neonicotinoid seed treatments could result in a quicker metabolism of herbicides and lead to quicker recovery time by the rice plants.