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Evaluation of Provisia Rice in Arkansas Rice Production Systems

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Evaluation of Provisia Rice in Arkansas Rice Production Systems

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Crop, Soil, and Environmental Science

by

Zachary Lancaster
Arkansas State University
Bachelor of Science in Agronomy, 2013

December 2017
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This thesis is approved for recommendation to the Graduate Council.

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ABSTRACT

With the continued evolution of herbicide resistance, it is becoming more difficult to achieve adequate weed control in Arkansas rice production systems. Thus, new technologies are needed to combat these troublesome weeds. A new non-GMO, herbicide-resistant rice type is under development that is resistant to quizalofop, an acetyl coenzyme A carboxylase (ACCase)-inhibiting herbicide that will allow for selective grass weed control in rice. With the commercialization of this technology by 2018, research was conducted to determine the best fit for quizalofop-resistant rice in current production systems. Experiments included evaluation of off-target movement of quizalofop, determination of plant-back risk from quizalofop application, best rate structure of quizalofop, general efficacy on common grass weeds, and tank-mix interactions of quizalofop with common herbicides used in rice. Overall, the risk for off-target movement of quizalofop on Midsouth grass crops is minimal, with injury only observed under conditions that would be rare in the field. Plant-back risk after quizalofop or other ACCase-inhibiting herbicide applications is relatively low, with only grain sorghum and corn showing potential for injury if planted in quick succession after herbicide application. Quizalofop applications in quizalofop-resistant rice are effective for controlling barnyardgrass, broadleaf signalgrass, and red rice, with the best results from sequential applications of quizalofop at 120 g ai ha^{-1}. A screening of barnyardgrass accessions from across the state of Arkansas proved quizalofop to be an effective graminicides, controlling all accessions evaluated. Tank-mix research for quizalofop and common rice herbicides prove that caution needs to be taken when tank-mixing quizalofop, especially with acetolactate synthase-inhibiting herbicides and auxinic herbicides due to the risk of antagonism. Overall, this research supports that quizalofop-resistant rice can be an effective tool for Arkansas rice producers.

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Chapter 1 - General Introduction

Rice Overview:

Rice is one of the most important crops grown in Arkansas. There were 639,000 ha of rice planted in Arkansas in 2016, making it the largest rice producing state in the US with more than twice the acreage in California the second-place state (NASS 2016). Arkansas has held the title of largest rice producing state for many years. Rice production increased dramatically after 1967, when planting area restrictions were eliminated and new, higher yielding varieties were released (Talbert and Burgos 2007). Arkansas rice is predominantly grown in the eastern, delta area of the state. Rice is also grown to a less extent in the Ouachita and Red River valleys in southwest Arkansas, and the Arkansas River valley that runs through central Arkansas (Hardke 2012).

Most of the rice produced in Arkansas is planted using conventional tillage methods, which involve fall tillage and subsequent spring tillage for seed bed preparation. Rice planting dates range from late March to early June and harvest is from late August to early November (Hardke and Wilson 2012). Approximately 53% of Arkansas rice is produced on silt-loam soils, with 43% on clay soils, and 4% on sandy loam soils (Hardke 2012). Most of Arkansas rice is drill seeded and grown in a delayed-flood system, while about 5% is grown using a water-seeded system (Hardke and Wilson 2012). Rice is grown in a flooded system because it thrives in the conditions, but it is primarily for the suppression of weeds (Smith and Fox 1973)

Rice Weed Control:

A major obstacle to Arkansas rice production is weed control. Weeds compete with rice for sunlight, water, nutrients, and other growth requirements (Smith 1988). Weeds can also cause economic losses such as yield loss, quality reduction, and grade reductions (Hardke 2012).

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A heavy infestation of weeds can also interfere with harvest operations, and increase harvest and drying costs. Like many other crops, an effective weed control program is essential. A successful weed control program in rice must include seed quality, knowledge of climatic conditions, seedbed and field preparation, stand establishment, and water management (Odero and Rainbolt 2005).

The first step in a weed control program is to get an adequate, weed-free stand of rice. Farmers should use only high quality, certified rice seed, which have regulations that restrict the amount of weed seed that can be found in the seed. Rice should be planted into a well prepared seed bed that has either been cultivated recently or a burn-down application is applied for preemergence (PRE) weed control (Odero and Rainbolt 2005). From 4 to 6 weeks after rice emergence is one the most important times for managing weeds in the field, and it is the period of time when weed control efforts should be most concentrated. This is the time between emergence and establishment of the permanent flood. Rice offers unusual methods of weed control because it is generally grown in a flooded system. Water management is important because the flood can control many species of weeds. This is also the time when many grass weed species can establish themselves, and if they are still present after the flood they become more difficult to control (Smith and Fox 1973).

There are many types of weeds found in rice, of which semi-aquatic and aquatic weeds are most common. Historically, the most troublesome weeds of Arkansas rice included barnyardgrass (*Echinochloa crus-galli* (L.) Beauv.), red rice (*Oryza sativa* L.), broadleaf signalgrass (*Urochloa platyphylla* (Nash) R.D. Webster), ducksalad (*Heteranthera limosa* (Sw.) Willd), hemp sesbania (*Sesbania herbacea* (P. Mill.) McVaugh), sprangletops (*Leptochloa* ssp.), and sedges (*Cyperus* ssp.) (Smith 1988). In a 2011 survey of Arkansas crop consultants, 63% of

the consultants listed barnyardgrass as the most problematic weed (Norsworthy et al. 2013). Red

rice and barnyardgrass can potentially cause yield losses as high as 82% and 70%, respectively

(Smith 1988). Many of Arkansas rice weeds are efficient C_4 plants, while rice is an inefficient C_3

plant; hence, many C_4 weeds outgrow rice, and are a serious problem in a rice production system

(Smith 1988).

Barnyardgrass (*Echinochloa crus-galli*):

The principle weed of rice globally is barnyardgrass or closely related *Echinochloa*

species. Barnyardgrass grows best in the rich, wet soils similar to those in which rice is grown

(Mitich 1990). Barnyardgrass can continue growth when under partially submerged conditions,

and hence thrives in a flooded rice field (Holm et al. 1977). Optimum moisture for germination

of barnyardgrass varies with soil type, but is usually 70% to 90% of maximum soil water-holding

capacity (Holm et al. 1977). Barnyardgrass is grass-like in nature, and has sessile leaf blades

that attach to a smooth stem without a ligule. The sheath is flat, and is pale green in color. The

collar is glabrous with no auricles present (Rahn et al. 1968). The leaf blade is narrow with

numerous parallel veins. The leaf blade is normally 10 to 30 cm long and 5 to 20 mm wide with

a broad base and an acute tip. The mid-rib is usually very prominent (Rahn et al. 1968). The

color of inflorescence is green to purple and has compound racemes that are 10 to 25 cm long.

The spikelets are oval, pointed, hairy, and normally have green to purple awns that are 2 to 5 mm

long (Holm et al. 1977). The seeds have a curve on one side and flat on the other. They are a

light orange to yellow color and 2.5 to 3.5 mm long (Rahn et al. 1968).

In Arkansas, one barnyardgrass plant can produce up to 39,000 seeds in the absence of

competition, whereas a plant that emerged 5 weeks after the rice crop only produced 14,750

seeds. In Arkansas cropping systems, the soil seedbank can contain as many as 194 million

seeds ha^{-1} with an average of 8.9 million seeds ha^{-1} (Bagavathiannan et al. 2010). The primary root system of a mature barnyardgrass plant is made up of fibrous or adventitious roots (Mitich 1990). This fibrous root system can cause fertilizer applications to be taken up more by the barnyardgrass plant than the rice. The fibrous root system overlays the rice roots and uses up the nutrients that the rice need (Holm et al. 1977). Barnyardgrass can also successfully grow in a range of photoperiods, from 8 to 16 hours, but prefers the later (Mitich 1990).

There are many characteristics that make barnyardgrass the most problematic weed in Arkansas rice systems. Barnyardgrass has evolved to closely mimic rice at the vegetative stages of growth. Barnyardgrass has developed an upright growth habit, giving it a striking similarity to rice and making it more efficient in capturing light in a crop canopy. The main distinguishing factor between rice and barnyardgrass is the absence of a ligule on barnyardgrass while rice has a large membranous, acute ligule with auricles around the sheath. Barnyardgrass has many morphological and physiological variations. Some closely resemble rice while others not so much (Barrett 1983).

Red Rice (*Oryza sativa*)

Arguably as problematic as barnyardgrass, red rice has long been a primary weed species in rice production systems. Red rice can out grow and compete with cultivated rice for sunlight, nutrients and water (Estorninos et al. 2005). Not only can red rice reduce rice yield, but can also reduce rice milling quality, resulting in dockage if samples are above the threshold of 2.5% (Ottis et al. 2005). The name "red rice" comes from the red-pigmented pericarp on the grain of most plants, which is caused by the presence of anthocyanins (Smith 1981).

Control of red rice in cultivated rice is very difficult due to both belonging to the same species and thus sharing the same physiological characteristics (Pantone and Baker 1991). This

makes postemergence chemical control impossible without a herbicide-resistant rice variety (Eleftherohorinos and Dhima 2002).

Herbicides Commonly Used in Arkansas Rice:

Propanil

Barnyardgrass has evolved resistance to multiple herbicides used in Arkansas rice, the first of which was propanil in the early 1990's (Carey et al. 1995). Propanil was commercialized for use in the early 1960's and was found to be effective at controlling barnyardgrass and many other agronomic weeds (Smith 1965). By the 1990's up to 98% of all the rice grown in Arkansas was treated with propanil at least once in the season (Carey et al. 1995). Propanil was most effective when applied to barnyardgrass plants at the 1- to 4-leaf stage. Repeated use of propanil on rice fields with no other modes of action used led to selection for resistance in barnyardgrass (Carey et al. 1995). In 1989, on a farm near Harrisburg, AR, a barnyardgrass population was found to survive propanil at 5607 g ai ha^{-1}. Field experiments further confirmed propanil at 11,214 g ai ha^{-1} (2.5X rate) was not effective on barnyardgrass (Baltazar and Smith 1994). From additional greenhouse experiments, it was concluded that some barnyardgrass populations had evolved resistance to propanil up to 20X the normal use rate (Carey et al. 1995).

Quinclorac

Following the evolution of propanil resistance in barnyardgrass, herbicide mixtures with propanil became a common tactic for controlling resistant populations. Quinclorac alone or in mixtures was found to be effective at controlling propanil-resistant barnyardgrass (Baltazar and Smith 1994). Quinclorac was heavily utilized to control barnyardgrass, and its overuse alone eventually led to a barnyardgrass population that was not controlled by a 16X rate of the herbicide (Lovelace 2003). Multiple resistance in barnyardgrass to propanil and quinclorac

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eliminates the use of two major modes of action as a control option, and recent survey evidence indicates that most quinclorac-resistant populations are likewise resistant to propanil (Norsworthy et al. 2012).

Clomazone

The current standard for barnyardgrass control is clomazone (Talbert and Burgos 2007). Clomazone was widely adopted for barnyardgrass control after registration of the herbicide for use in rice in the late 1990's (Norsworthy et al. 2007). Weed control with clomazone was promising, but concerns arose because of the occurrence of a bleached appearance in rice soon after emergence. This was a result of the clomazone uptake by rice (Talbert and Burgos 2007). Recent studies show that the bleaching effect is generally not problematic to the crop and caused no yield loss. Bleaching is greater on the sandy and silt loam soils, and lower on clays soils (Hardke 2012). The bleaching effect can be more apparent after a rainfall occurs soon after application, in turn activating the herbicide (Norsworthy et al. 2008). In the early stages of rice use, clomazone was most commonly pre-plant incorporated because the original formulation was easily volatilized on the surface. A new formulation of clomazone was released in 1995 that had a reduced risk of volatility. This was beneficial because it could be applied to the soil surface as a preemergence application. Clomazone is generally recommended for application at 14 days before seeding to 7 days after seeding (Hardke 2012). Applications rates of clomazone depend on soil texture. Clay based soils require 527 to 628 g ha^{-1} of clomazone, while silt and sandy loam soils require only 314 to 426 g ha^{-1} (Anonymous 2015). Clomazone is able to provide a broad-spectrum of control to annual grasses, but the low rates resulted in weak control of broadleaf weeds and sedges. Without the implementation of other herbicides, clomazone allows weeds such as rice flatsedge (*Cyperus iria* L.) and hemp sesbania to become serious problems

(Talbert and Burgos 2007). In the winter of 2006, a sample of barnyardgrass seed was received from Cord, AR that was resistant to clomazone. The resistant sample was 2.37 times less sensitive to clomazone than the susceptible biotype (Norsworthy et al. 2007). The ramifications of the spread of clomazone-resistant barnyardgrass is great. Clomazone should be applied with additional herbicides to reduce the chance of further resistance to evolve (Norsworthy et al. 2008).

Imidazolinone Herbicides

The next major development in rice weed control was the commercialization of ALS (acetolactate synthase) resistant rice in the form of imidazolinone-resistant (Clearfield™) rice in 2002 (Zhang 2006). Clearfield™ varieties may often yield less than conventional cultivars. This may limit the cultivars to areas with red rice infestations or certain weed control issues (Hardke 2012). Clearfield™ rice was developed with non-transgenic means to be resistant to imidazolinone herbicides. The herbicide-resistant gene was developed by the induced mutation of the seeds (Croughan 1994). The main objective for developing imidazolinone-resistant rice was to control red rice (*Oryza sativa*), which is a major weed in the rice production system (Burgos et al. 2008). The imidazolinone herbicides used in Clearfield™ rice were also effective at controlling barnyardgrass and many other grass and broadleaf weeds in rice (Hardke 2012). Imidazolinone-resistant rice was very effective at controlling red rice in the field and gave a new mode of action to control barnyardgrass (Burgos et al. 2008). The effectiveness of this technology resulted in many Mid-south farmers adopting Clearfield™ rice. A survey of crop consultants conducted in the fall of 2011 found that 64% of the planted rice acres in Arkansas and Mississippi were planted in imidazolinone-resistant rice (Norsworthy et al. 2014), however the share of imidazolinone-resistant rice in Arkansas has declined consecutively over the years to

44% in 2015 (Hardke 2016). This decline can be primarily attributed to the development of herbicide resistance in barnyardgrass and red rice, which leads farmers back to conventional rice production.

Stewardship guidelines were developed to reduce the chance of resistance in weeds to imidazolinone, although the implementation of these guidelines were unsuccessful. The main objectives of the stewardship program was to use different herbicide modes of action on imidazolinone-resistant rice fields, and to rotate imidazolinone-resistant rice with a different crop each year (Norsworthy et al. 2013). Crop safety concerns dictate that imidazolinone-resistant rice not be grown back to back in cropping systems without rotation with conventional crops. From 2006 to 2011, imidazolinone had been grown without rotation each year in 11% of the rice acres reported. Of the imidazolinone-resistant rice hectares, 42% were sprayed with ALS-inhibiting herbicides. The failure to follow these stewardship guidelines put into place has resulted in the development of ALS resistant weeds (Norsworthy et al. 2013). With the extensive use of ALS herbicides, barnyardgrass was at a high risk of developing resistance. In 2009, barnyardgrass samples were taken in northeast Arkansas, and were later confirmed to be resistant to imazethapyr, an ALS herbicide. The resistant varieties needed more than 32 times the field application rate of imazomox to kill 90% of the treated plants (Dilpreet et al. 2012). At this point, combination of different modes of action, and ALS herbicides is effective at controlling ALS-resistant barnyard grass in a Clearfield™ production system. When two applications of imazethapyr were applied to a field in combination with quinclorac, clomazone, pendimethalin, thiobencarb, or fenaxaprop effective season-long control was obtained (88%-100%) (Wilson et al. 2009).

Red rice was also able to evolve resistance to ALS herbicides. Red rice and cultivated rice can hybridize, albeit at low levels of <1% (Shivrain et al. 2009). With several imidozolinone-resistant rice fields not reaching 100% control, outcrossing between red rice and imidozolinone-resistant cultivars was expected. Red rice plants that escape herbicide applications are then exposed to pollen from surrounding cultivated rice. Risk is greatest in fields where red rice biotypes flower simultaneously with rice cultivars (Gealy et al. 2015). These red rice plants can then outcross with imidozolinone-resistant rice, and the herbicide resistance gene can be transferred to red rice. Most of these hybrids have longer panicles than both of the parental cultivars, resulting in more seeds produced (Shivrain et al. 2009). Additionally, these new hybrids can carry the herbicide-resistant gene and require an integrated approach for control (Burgos et al. 2008). It is imperative that famers must use multiple modes of action when using ALS-resistant rice to control troublesome weed species and to conserve the ALS herbicide mode of action for future use (Norsworthy et al. 2012).

New Herbicide Technology

With the evolution of weeds that have resistance to multiple herbicide modes of action, a new technology is needed to control many of these troublesome weeds. The development of new herbicides has diminished since the launch of glyphosate-resistant crops in the mid- to late 1990s. Before the 1990s, herbicides with new modes of action were introduced on average every 3 years. However, currently it is less enticing to develop a new herbicide due to the increasing cost of discovery, development, and regulation. With the confirmation of glyphosate-resistant weeds, the agricultural industry began to increase investment in herbicide discovery (Duke 2011).

BASF is currently developing a new herbicide-resistant rice technology that will be resistant to quizalofop, an acetyl coenzyme A carboxylase (ACCase)-inhibiting herbicide. ACCase-inhibiting herbicides are commonly used for grass control in many crops such as soybean, sunflower, cotton, and canola (Abit 2010). Quizalofop will be primarily used in the to control barnyardgrass and red rice. Herbicide resistance modeling predicted that ACCase rice herbicides such as cyhalofop and fenoxaprop have a lower risk for evolving resistance when compared to ALS-inhibiting herbicides, such as those used in imidazolinone-resistant rice (Bagavathiannan et al. 2014). Hence, quizalofop could be a suitable selective herbicide in rice if a trait were developed. Quizalofop at 168 g ai ha^{-1} applied in soybean provided 84% red rice control at 2 weeks after application, and 91% late-season control (Noldin et al. 1998). In the same field experiment, late-season barnyardgrass control in soybean was 71% (Noldin et al. 1998). With the anticipated launch of quizalofop-resistant rice in 2018, research was conducted to understand the best for this technology in rice production systems.

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Chapter 2 - Sensitivity of Grass Crops to Low Rates of Quizalofop

Abstract

With the spread of herbicide-resistant weeds across the Midsouth, new technologies are needed to achieve adequate weed control in many areas. A new non-genetically modified rice trait is under development that will be resistant to quizalofop, an acetyl coenzyme A carboxylase (ACCase)-inhibiting herbicide. The addition of the quizalofop-resistant rice system to Midsouth production systems will increase the use of quizalofop, possibly increasing the risk for injury to other grass crops. Experiments were conducted in the summer of 2014 and 2015 to determine the sensitivity of corn, grain sorghum, and conventional rice to low rates of quizalofop (1/10X to 1/200X of 160 g ai ha^{-1}). Conventional rice was not affected by quizalofop rate or application timing. Corn displayed the greatest response to the 1/10X quizalofop rate at the 2- to 3-leaf growth stage, with 50 to 65% injury and 35 to 37% relative yield compared to the non-treated check. Grain sorghum was injured 31 to 34% by the 1/10X quizalofop rate applied at the 2- to 3-leaf stage, and there was 20% to 26% injury at the panicle exertion growth stage. The highest rate of quizalofop reduced yields at the panicle exertion growth stage 28 to 46%. Overall, risk for injury to any of the three evaluated crops from quizalofop appears low, with greatest injury observed at the highest quizalofop drift rate, with minimal injury at lower rates.

Nomenclature: Quizalofop; corn, *Zea mays* L.; grain sorghum, *Sorghum bicolor* L.; rice, *Oryza sativa* L.

Key words: Drift, off-target, acetyl coenzyme A carboxylase, ACCase, simulated drift

Rice is one of the most important crops grown in Arkansas, with a major obstacle to rice production being weed control. In a 2011 survey, 63% of Arkansas crop consultants listed barnyardgrass (*Echninochloa crus-galli* (L.) Beauv.) as the most problematic weed of rice, with red rice (*Oryza sativa* L.) ranking second (Norsworthy et al. 2013). Red rice and barnyardgrass can potentially cause yield losses as high as 82% and 70%, respectively (Smith 1988).

Barnyardgrass has evolved resistance to multiple herbicides used in Arkansas rice, the first of which was propanil in the early 1990's (Carey et al. 1995). Poor stewardship of alternative herbicides led to continued evolution of-resistance by barnyardgrass to quinclorac, clomazone, and several acteolactate synthase (ALS)-inhibiting herbicides (Talbert and Burgos 2007; Norsworthy et al. 2013). With the evolution of weeds that have resistance to multiple herbicide mechanisms of action, weed control has increasingly become more challenging in Arkansas rice production systems. A new technology is needed to control many of these troublesome weeds. A new herbicide-resistant rice technology that will allow for topical applications of quizalofop, an acetyl coenzyme A carboxylase (ACCase)-inhibiting herbicide, will soon be commercialized (Guice et al. 2015).

Quizalofop is a systemic herbicide currently used to control annual and perennial grass weeds in soybean (*Glycine max* (L.) Merr.), potato (*Solanum tubersom* L.), cotton (*Gossypium hirsutum L.*), vegetables, and in non-crop areas. Growth soon ceases after application of quizalofop, with young and actively growing tissues being first effected. Chlorosis and eventual necrosis develop 1 to 3 weeks after application (Ahrens 1994). Research has shown that quizalofop is effective in controlling both barnyardgrass (Noldin et al. 1998) and red rice (Salzman et al. 1988). In soybean, quizalofop is applied from 35 to 84 g ai ha^{-1} (Shaner 2014), but usage rates in quizalofop-resistant rice could be as high as 138 g ha^{-1} for single application

(Anonymous 2017). This higher application rate of quizalofop could lead to greater risk for injury to neighboring crops, especially crops such as corn, grain sorghum, or conventional rice.

Off-target movement of herbicides can be problematic, especially when environmental conditions favor re-deposition combined with improper application (Wall 1994; Wauchope et al. 1982). Many factors influence the severity of herbicide drift. Primary contributors to physical drift are wind speed, application height, and nozzle selection (Hanks 1995). Physical drift in close proximity to the actual application often occurs at herbicide use rates ranging from 1/10 to 1/100X (Al-Khatib et al. 2003). Even at lower rates, drift events can still result in significant injury to susceptible plants, depending upon the herbicide and sensitivity of the plants evaluated (Al-Khatib et al. 2003).

While ACCase-inhibiting herbicides have no activity on broadleaf plant species (Konishi and Sasaki 1994), there is risk for damage of monocot plant species due to off-target movement. Sethoxydim, an ACCase-inhibiting herbicide, was found to reduce grain sorghum yield at rates of 1/3 and 1/10X a recommended rate of 168 g ai ha^{-1} (Al-Khatib et al. 2003). Likewise, drift rates of multiple ACCase-inhibiting herbicides were determined to affect vegetative buffer strips by producing chlorosis and reducing biomass production (Rankins et al. 2005). With the addition of quizalofop-resistant rice to current production systems, it is expected that quizalofop use in the Midsouth will increase in the coming years. This increase in quizalofop use could lead to a higher risk for off-target movement onto other monocot crops. Little research has been published on the risk for quizalofop to injure corn, grain sorghum, or non-quizalofop-resistant rice, and with the anticipated launch of quizalofop-resistant rice in 2018, research is needed to evaluate such risk in the aforementioned crops. The objective of this research was to evaluate the sensitivity of corn, grain sorghum, or conventional rice to low rates of quizalofop.

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Materials and Methods

Experiments were conducted in 2014 and 2015 to evaluate simulated drift rates of quizalofop to corn, grain sorghum, and conventional rice. For all experiments, the experimental design was a 2-factor factorial, randomized complete block with four replications. Factors consisted of simulated drift rate of quizalofop and growth stage at time of application. Simulated drift rates of quizalofop were 1/10X, 1/25X, 1/50X, 1/75X, 1/100X, and 1/200X of 160 g ai ha^{-1} (anticipated maximum use rate of quizalofop in quizalofop-resistant rice at the time of experiment initiation). Growth stage at time of application varied by crop. A non-treated control plot was included for comparison. Herbicide treatments were applied with a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} at 276 kPa. Visual estimates of percent injury and plant heights were taken at 14 and 28 days after each application (DAA). Visual injury rating were based on a scale of 0 to 100%, with 0 representing no injury and 100 representing complete plant death. Height of five plants per plot were measured approximately 2 weeks before harvest from the soil surface to the top of the plant. There was no intent to compare quizalofop sensitivity across crops, thus crops were grown in separate trails.

Corn Field Experiment

Experiments were conducted on a Sharkey clay loam (Very-fine, smectitic, thermic Chromic Epiaquerts) at the Northeast Research and Extension Center in Keiser, AR in 2014 and 2015. A Smartstax™ (glyphosate/glufosinate-resistant) corn variety 'Croplan 6274SS' was planted on May 22, 2014 and on April 30, 2015 at a seeding rate of 74,000 seed ha^{-1}. In both years, the fields were tilled and beds were formed on 96 cm centers before planting.

Experimental plots were maintained weed-free by a preemergence application of a premix of thiencarbazone methyl plus tembotrione (Capreno™ herbicide, Bayer CropScience, Research Triangle Park, NC) at 15 + 75 g ai ha^{-1} in 2014 and a tank-mix of *S*-metalachlor (Dual II Magnum™ herbicide, Syngenta Crop Protection, Greensboro, NC) at 1,068 g ai ha^{-1} plus atrazine (Aatrex 4L™ herbicide, Syngenta Crop Protection, Greensboro, NC) at 1,680 g ai ha^{-1} in 2015 and a postemergence application of glufosinate (Liberty™ herbicide, Bayer CropScience, Research Triangle Park, NC) at 450 g ai ha^{-1} at the V4 growth stage for both years. Corn experiments were fertilized according to University of Arkansas Extension recommendations.

Plots consisted of four rows, 7.6 m long. Growth stages evaluated for corn were 2- to 3-leaf, tassel, and silk stages. The applications were made on the following dates: 2- to 3-leaf stage applied June 6, 2014 and May 21, 2015; tassel stage applied July 21, 2014 and July 1, 2015; and silk stage applied July 31, 2014 and July 15, 2015. Corn was harvested from the center two rows of each plot September 17, 2014, and September 21, 2015 using a small-plot combine. Yields were adjusted to 15.5% moisture.

Grain Sorghum Experiment

Grain sorghum experiments were conducted at the same location as the corn experiments. A DeKalb™ conventional variety (DKS53-67) was planted on May 20, 2014, and the variety DK554-00 was planted on June 11, 2015 at a seeding rate of 200,000 seed ha^{-1}. In both years, fields were tilled and beds were formed on 96 cm centers before planting. Plots were maintained weed-free by a preemergence application of *S*-metalachlor (Dual II Magnum™ herbicide, Syngenta Crop Protection) at 1,068 g ha^{-1} and atrazine (Aatrex 4L™ herbicide, Syngenta Crop Protection) at 1,680 g ha^{-1} and a postemergence application of quinclorac (Facet L™ herbicide,

BASF corporation, Florham Park, NJ) at 421 g ha^{-1} at the V3 growth stage for both years. Experiments were fertilized according to Univerisity of Arkansas Extension recommendations.

Plots consisted of four rows, 7.6 m long. Growth stages evaluated for grain sorghum were 2- to 3- leaf, boot, and panicle exertion stages. Quizalofop applications were made the following dates: 2- to 3-leaf stage applied May 20, 2014 and June 25, 2015; boot stage applied July 8, 2014 and July 30, 2015; and panicle exertion stage applied July 12, 2014 and August 5, 2015. Grain sorghum was harvested on August 10, 2014 and August 20, 2015. Yields were adjusted to 13% moisture.

Rice Experiment

A rice experiment was conducted in 2014 on a Sharkey clay loam (Very-fine, smectitic, thermic Chromic Epiaquerts) at the Northeast Research and Extension Center in Keiser, AR (NEREC). Environmental and soil conditions hindered harvest of rice in 2014, resulting in no yield data; therefore, two alternate locations were chosen for the conventional rice experiment in 2015. The experiment in 2015 was conducted on a Calloway silt loam (Fine-silty, mixed, active, thermic Aquic Fraglossudalfs) at the Pine Tree Research Station near Colt, AR (PTRS) and on a Immanuel silt loam (Fine-silty, mixed, active, thermic Oxyaquic Glossudalfs) at the University of Arkansas at Pine Bluff Farm near Lonoke, AR (UAPB). The imidazolinone-resistant variety 'CL152' was planted at the NEREC on May 7, 2014, with the imidazolinone-resistant variety 'CL111' planted at the PTRS on April 31, 2015 and at the UAPB on June 8, 2015. An imidazolinone-resistant variety was chosen in both years to aid in keeping the plots weed-free. All locations were planted at a seeding rate of 65 seeds m^{-1} row. Plots were maintained weed-free with preemergence applications of clomazone (Command™ herbicide, FMC corporation, Philadelphia, PA) at 547 g ai ha^{-1} and quinclorac (Facet L™ herbicide, BASF corporation,

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Florham Park, NJ) at 280 g ai ha^{-1}, with a postemergence application of imazethapyr (Newpath™ herbicide, BASF corporation) at 105 g ai ha^{-1} for all locations. Experiments were fertilized according to University of Arkansas Extension recommendations.

Plots consisted of 9 drill seeded rows on 18 cm centers, 7.6 m long. Growth stages evaluated for rice were 2- to 3- leaf stage and 1.3 cm internode elongation stage. Herbicide applications were made on the following dates: 2- to 3-leaf growth stage on May 20, 2014 at the NEREC, on May 12, 2015 at the PTRS, and on June 22, 2015 at the UAPB; 1.3 cm internode elongation stage on June 8, 2014 at the NEREC, on June 7, 2015 at the PTRS, and on July 14, 2015 at the UAPB. Rice was harvested at the PTRS on September 4, 2015 and at the UAPB on October 3, 2015.

Statistical Analysis

All data for corn, grain sorghum, and conventional rice experiments were analyzed using JMP Pro 12.1 (SAS Institute Inc., Cary, NC) using the Fit Model function. Year and replication nested within years were considered random effects. For data that met the assumptions for ANOVA, means were separated using Fisher's protected LSD test ($\alpha = 0.05$). If assumptions for ANOVA were not met, then treatments means alone are presented.

<div align="center">

Results and Discussion

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Corn Experiment

In general, injury from simulated drift rates of quizalofop on corn was most severe with the 1/10x rate (Table 1), which was the highest rate of quizalofop applied. Injury from the 1/10x rate was greatest at the 2- to 3-leaf growth stage (58%) compared to both tassel (6%) and silk growth stages (4%). The only other quizalofop rate that caused significantly greater injury was the 1/25x rate at the 2- to 3-leaf growth stage (12%) compared to the two later timings. The

increased injury at the 2- to 3-leaf growth stage can be attributed to the inability of the corn to recover from the quizalofop application, which resulted in complete plant death of several plants within the plot, and an overall stand reduction. Injury at later growth stages mainly consisted of leaf chlorosis, but also resulted a dark ring in the center of stalk, especially at the two highest rates evaluated.

Likewise, the greatest reduction of plant height resulted from the 1/10x rate at the 2- to 3-leaf growth stage (P=0.0004). At the 2- to 3-leaf growth stage the 1/10x rate resulted in 86% relative height compared to non-treated control at 2 weeks before harvest (Table 1). The height for the non-treated control was 241 cm averaged over both years. The 1/10x treatment resulted in greater height reduction, compared to the same quizalofop rate at the tassel and silk growth stages.

Corn grain yield followed the same trends as injury and plant height. The treatment with the greatest reduction in yield was the 1/10x quizalofop rate applied at the 2- to 3-leaf growth stage (P=<0.0001) with 57% yield loss compared to the non-treated check (Table 1). However, the 1/25x rate at the 2- to 3-leaf stage and the 1/10x rate at the tassel stage resulted in significantly lower relative grain yields at 89 and 90% compared to the non-treated control, respectively. The yield of the non-treated check was 11,000 kg ha^{-1} averaged over both years. The 1/10x quizalofop rate resulted in greater yield reduction at the 2- to 3-leaf growth stage compared to the tassel and silk growth stages.

Grain Sorghum Experiment

Grain sorghum injury varied with growth stage at the time of herbicide application, but was generally the greatest from the 1/10x quizalofop rate (Table 2). The 1/10x rate applied at the 2- to 3-leaf growth stage resulted in the greatest injury of 31% (P=<0.0001). The same rate

applied at the panicle exertion stage resulted in 23% injury. These results were similar to Al-Khatib (2003) who reported an average of 20% injury on grain sorghum from the 1/10x rate of sethoxydim applied at the 2- to 4-leaf growth stage. The boot growth stage was more tolerant to quizalofop application, with the 1/10x rate resulting in only 2% injury. Generally, grain sorghum injury symptoms consisted of leaf chlorosis and some necrosis at the 2- to 3-leaf stage; however, at the panicle exertion stage, head and grain malformation was seen at the 1/10x quizalofop rate.

The greatest grain sorghum height reduction was from the 1/10x quizalofop rate at the panicle exertion stage (86% relative height) (Table 2.). The 1/10x rate at the 2- to 3-leaf growth stage resulted in lower heights (92% relative height) than the non-treated control plot. The height of the non-treated control was 141 cm averaged over both years.

Grain sorghum relative yield followed similar trends as injury and relative height. The greatest reduction in yield resulted from the 1/10x quizalofop rate applied at the panicle exertion growth stage (P=0.0152) with 29% relative yield, with the non-treated control yielding 5,080 kg ha^{-1} (Table 2). However, the 1/10x rate at the 2- to 3-leaf growth stage (55%) and the 1/25x rate at the panicle exertion stage (70%) had lower relative yield than the highest yielding treatments. The greater yield loss at the panicle exertion growth stage can be attributed to the malformed grain heads, which reduced overall grain production.

Rice Experiment

Rice showed no significant interaction or main effects of quizalofop rate or growth stage for any parameter evaluated. Overall, rice displayed no biologically significant injury from any rate of quizalofop applied (Table 3). Because of the high degree of rice tolerance to drift rates of quizalofop, growth stage during a drift event will not likely impact the sensitivity of the crop to

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this herbicide. Similarly, no differences were observed among treatments for plant height prior to harvest, and rice yields across experimental treatments did not differ.

Practical Implications

Overall, the risk for damage from off-target movement of quizalofop onto corn, grain sorghum, and rice is low. Conventional rice (non-quizalofop resistant) shows no effects from low rates of quizalofop. Corn displays a higher degree of sensitivity to quizalofop; but even then, almost all the negative effects of quizalofop drift occurred from the high drift rate, which would be rare in actual field conditions. However, the most sensitive growth stage for corn is the 2- to 3-leaf growth stage, and with overlapping planting timing in Arkansas for both corn (April 1-26) and rice (April 14-May 19), the risk of an off-target application of quizalofop from quizalofop-resistant rice is great (USDA 2010). Likewise, grain sorghum displays the greatest risk for injury and yield reduction from off-target movement of quizalofop at the 2- to 3-leaf stage due to typical applications of quizalofop in quizalofop-resistant rice coinciding with 2- to 3-leaf grain sorghum.

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Table 1. Injury (2 weeks after herbicide application), height (2 weeks before harvest), and grain yield of corn following low rates of quizalofop at three different application timings averaged over years in Keiser, AR.[a]

Growth stage	Rate	Injury[c]		Height[df]		Grain yield[ef]	
	(Fraction of use rate)[b]	------------------------------%------------------------------					

2- to 3-Leaf	1/10X	58	a	86	d	43	d
	1/25X	12	b	96	bc	89	bc
	1/50X	4	c	100	ab	105	a
	1/75X	4	c	97	bc	96	abc
	1/100X	0		100	ab	96	abc
	1/200X	0		100	ab	98	abc
Tassel	1/10X	5	c	98	ab	90	bc
	1/25X	3	c	101	ab	96	abc
	1/50X	2	c	103	a	96	abc
	1/75X	2	c	100	ab	97	abc
	1/100X	0		100	ab	95	abc
	1/200X	0		101	ab	95	abc
Silk	1/10X	4	c	101	ab	100	abc
	1/25X	3	c	99	abc	96	abc
	1/50X	1	c	100	ab	100	abc
	1/75X	1	c	100	ab	96	abc
	1/100X	0		101	ab	96	abc
	1/200X	0		99	abc	101	ab

[a] Means within a column followed by the same lowercase letter are not different based on Fisher's protected LSD (0.05).
[b] Quizalofop rate with 1X equal to 160 g ai ha^{-1}.
[c] Treatments 1/100X and 1/200X quizalofop rate were removed from analysis for corn injury due to violating the assumptions of ANOVA (homogeneity of variance).
[d] Data expressed as percent relative height compared with non-treated control. Height for non-treated control was 241 cm averaged over site years.
[e] Data expressed as percent relative grain yield compared with non-treated control. Grain yield for non-treated control was 11,000 kg ha^{-1} averaged over site years.
[f] LSD (0.05) is 6 for percent relative height and 12 for grain yield to compare to the non-treated control (100%).

Table 2. Injury (2 weeks after herbicide application), height (2 weeks before harvest), and grain yield of grain sorghum following sublethal rates of quizalofop at three different application timings averaged over years in Keiser, AR.[a]

Growth stage	Rate	Injury[b]		Height[dg]		Grain yield[fg]	
	(Fraction of use rate)[b]	-----------------------------------%-----------------------------------					
2- to 3-Leaf	1/10X	31	a	92	b	55	cd
	1/25X	6	c	101	a	91	ab
	1/50X	5	cd	99	a	87	ab
	1/75X	3	de	100	a	102	a
	1/100X	0		99	a	104	a
	1/200X	0		100	a	107	a
Boot	1/10X	2	de	98	a	92	ab
	1/25X	1	e	100	a	98	a
	1/50X	1	e	101	a	102	a
	1/75X	2	de	101	a	86	ab
	1/100X	0		99	a	95	ab
	1/200X	0		98	a	96	ab
Pan. Exert.[e]	1/10X	23	b	86	c	29	d
	1/25X	3	de	96	ab	70	bc
	1/50X	1	e	99	a	81	abc
	1/75X	1	e	99	a	98	a
	1/100X	0		100	a	93	ab
	1/200X	0		99	a	87	ab

[a] Means within a column followed by the same uppercase letter are not different based on Fisher's protected LSD (0.05).

[b] Quizalofop rate with 1X equal to 160 g ai ha^{-1}.

[c] Treatments 1/100X and 1/200X quizalofop rate were removed from analysis for corn injury due to violating the assumptions of ANOVA (homogeneity of variance). In particular there was no variability among the reps for these rates.

[d] Data expressed as percent relative height compared with non-treated control. Height for non-treated control was 141 cm averaged over site years.

[e] Data expressed as percent relative grain yield compared with non-treated control. Grain yield for non-treated control was 5,080 kg ha^{-1} averaged over site years.

[f] Pan. Exert = panicle exertion

[g] LSD (0.05) is 6 and 27 for percent relative height and grain yield, respectively, to compare to the non-treated control (100%).

Table 3. Injury (2 weeks after treatment), height (2 weeks before harvest), and yield of rice following simulated drift of quizalofop at two different application timings averaged over site years in Keiser, Colt, and Lonoke, AR.[a]

Growth stage	Rate	Injury[b]	Height[e]	Yield[f]
	(Fraction of use rate)[c]	-----------------------------%-----------------------------		
2- to 3-leaf	1/10X	1	97	93
	1/25X	1	102	98
	1/50X	0	98	95
	1/75X	1	95	98
	1/100X	0	102	105
	1/200X	0	100	105
Int. Elong.[d]	1/10X	0	98	99
	1/25X	2	95	91
	1/50X	0	103	93
	1/75X	1	102	100
	1/100X	1	102	93
	1/200X	0	103	99

[a] All parameters evaluated for rice resulted in no significant interaction or main effects.

[b] Due to low overall injury observed and no variance between reps for multiple treatments, no official analysis were conducted for injury.

[c] Quizalofop rate with the 1X rate equal to 160 g ai ha^{-1}.

[d] Abbreviations: Int. Elong, internode elongation.

[e] Data expressed as percent relative height compared with non-treated control. Height for non-treated control was 81 cm.

[f] Data expressed as percent relative yield compared with non-treated control. Yield for non-treated control was 11,048 kg ha^{-1}.

Chapter 3 - Residual Activity of ACCase-inhibiting Herbicides on Monocot Crops and Weeds

Abstract

With the evolution of weeds having resistance to multiple herbicide mechanisms of action, a new technology is needed for improved control. A new rice that will be resistant to quizalofop, an acetyl coenzyme A carboxylase (ACCase)-inhibiting herbicide, will be commercialized in 2018. A field experiment was conducted in 2014 and 2015 to evaluate the residual activity of ACCase-inhibiting herbicides for monocot crop injury and weed control. This experiment evaluated four different crops (conventional rice, quizalofop-resistant rice, grain sorghum, and corn). Herbicide treatments were quizalofop at 80 and 160 g ai ha^{-1}, fenoxaprop at 122 g ai ha^{-1}, cyhalofop at 131 g ai ha^{-1}, fluazifop at 210 and 420 g ai ha^{-1}, clethodim at 68 and 136 g ai ha^{-1}, and sethoxydim at 140 and 280 g ai ha^{-1}. Overhead sprinkler irrigation in the amount of 1.3 cm was applied immediately after treatment to one-half of the plots, and the crops planted into the treated plots at 0, 7, and 14 days after herbicide treatment. In 2014, injury from herbicide treatments increased with activation via irrigation over relying solely on rainfall for activation for all crops evaluated, except for quizalofop-resistant rice. At 14 days after treatment, corn and grain sorghum were injured 19% and 20%, respectively, from the high rate of sethoxydim with irrigation activation. Conventional rice was injured 13% by the high rate of fluazifop. Quizalofop-resistant rice was injured no more than 4% by any of the graminicides evaluated in either year. In 2015, a large rainfall event occurred within 24 hours of initiating the experiment; thus, there were no differences between activation via irrigation or by rainfall. However, like 2014, grain sorghum and corn were injured 16% and 13%, respectively, by the high rate of sethoxydim. All herbicides provided little residual control of grass weeds, mainly broadleaf signalgrass and barnyardgrass. Based on these findings, there should continue to be a plantback interval to rice following a

graminicide application, unless quizalofop-resistant rice is to be planted. The plantback interval

will vary by graminicide and the amount of moisture received following the application.

Nomenclature: Clethodim; cyhalofop; fenoxaprop; fluazifop; quizalofop; sethoxydim;

barnyardgrass, *Echinochloa crus-galli* (L.) Beauv.; broadleaf signalgrass, *Urochloa platyphylla*

(Nash) R.D. Webster; corn, *Zea mays* L.; grain sorghum, *Sorghum bicolor* (L.) Moench.; rice,

Oryza sativa L.

Key words: Residual herbicide, carryover, plant-back interval, graminicide, crop tolerance.

Rice is one of the most important crops grown in Arkansas with over 639,000 ha planted in 2016. Arkansas is the largest rice producing state in the U.S. with more than twice the acreage in California, the second place state (NASS 2016). One of the major obstacles for rice production is weed control, with the major weeds of Arkansas rice being barnyardgrass, sprangletops (*Leptochloa* spp.), red rice (*Oryza sativa* L.), northern jointvetch (*Aeschynomene virginica* L.), Palmer amaranth (*Amaranthus palmeri* (S.) Wats.), and broadleaf signalgrass (Norsworthy et al. 2013). Achieving adequate control of banyardgrass and red rice is particularly difficult due to the presence of herbicide resistance. In Arkansas, barnyardgrass has evolved resistance to propanil, quinclorac, clomazone, and acetoacetate synthase (ALS)-inhibiting herbicides (Talbert and Burgos 2007; Norsworthy et al. 2013).

To combat the pressure herbicide-resistant weeds place on current production systems, new technologies are needed. Rice with resistance to quizalofop, an acetyl coenzyme A carboxylase (ACCase)-inhibiting herbicide, is expected to be commercialized in the United States in 2018. This technology will be called Provisia™, with the Provisia name being associated with both the herbicide-resistant rice trait and the commercial quizalofop product labeled for use. The use rate for quizalofop in quizalofop-resistant rice will range from 100 to 138 g ai ha^{-1} for single applications and 240 g ai ha^{-1} for maximum yearly application (Anonymous 2017). Quizalofop, a systemic herbicide, is most notably used in soybean (*Glycine max* (L.) Merr.) for postemergence control of annual and perennial grasses; albeit, it can provide moderate residual grass control (Shaner 2014). It is anticipated that quizalofop will be restricted solely to postemergence applications in quizalofop-resistant rice (Youman et al. 2016).

ACCase-inhibiting herbicides are commonly used in multiple crops to selectively control annual and perennial grass species. These graminicides inhibit the enzyme acetyl-CoA-

carboxylase, which is an integral step in fatty acid synthesis. Eventually this inhibition blocks the production of phospholipids needed for cell growth (Shaner 2014). Sethoxydim, clethodim, fluazifop, and quizalofop are commonly used in broadleaf crops (Anonymous 2003; Anonymous 2009; Anonymous 2015a; Anonymous 2015b), mainly because broadleaf plants are naturally tolerant to ACCase-inhibiting herbicides (Konishi and Sasaki 1994). This tolerance is due to broadleaf species having the herbicide-tolerant prokaryote form of ACCase from the accD gene, while grass species lack this gene and are sensitive to ACCase-inhibiting herbicides (Konishi and Sasaki 1994). Although high levels of efficacy have been observed with ACCase-inhibiting herbicides on grasses, differing levels of tolerance across species have been observed. This has led to cyhalofop and fenoxaprop being labeled for postemergence use in rice (Anonymous 2003B; Anonymous 2016). The tolerance in rice to cyhalofop and fenoxaprop is due to reduced absorption through the cuticle and enhanced metabolism of the herbicide compared to other susceptible grass species (Ruiz-Santaella et al. 2005).

While generally not applied preemergence (PRE) or for residual weed control, it is known that graminicides do have limited residual activity (Barber et al. 2015). Persistence and efficacy of a herbicide in soil largely dictates the length of a plantback interval following application. Herbicide persistence in soil can have an effect on prolonged weed suppression, or can cause carry-over effects to a subsequent crop (Ogle and Warren 1954). The activity and length of residual of herbicides may depend on both soil moisture and soil texture, among other soil chemical properties. Generally, soil-applied herbicides need 1.3 to 1.9 cm of precipitation for optimum activation (Riar et al. 2012). Activation is the movement of a herbicide into the soil profile, where it can come into contact with the germinating seed (Knake et al. 1967). Smith et al. (2016) determined that efficacy of *S*-metolachlor on Palmer amaranth was greatest when 0.6

and 1.3 cm of irrigation were applied compared to a non-irrigated check. Specific herbicides

with high water solubility have the capability to move with water through the soil in the presence

of rainfall or irrigation. Hence, it is possible to lose a herbicide via runoff or leaching if too much

water is present (Friesen 1965). However, this movement is also impacted by a herbicide's K_d

(soil sorption) and K_{oc} (soil organic carbon sorption), which can bind a herbicide to soil particles

and organic matter (Wauchope et al. 2002).

Generally, plantback intervals to monocot (grass) crops range from 30 to 120 days

following most ACCase-inhibiting herbicide applications (Barber et al. 2015; Anonymous

2003a; Anonymous 2003b; Anonymous 2009; Anonymous 2015a; Anonymous 2015b;

Anonymous 2016). However, previous research on ACCase-inhibiting herbicides support no

significant residual herbicidal activity onto subsequent grass crop plantings (Mahoney et al.

2016; Spader et al. 2012). Planting within graminicide plantback intervals would be unlikely in

the Midsouth; however, crop failure after a graminicide application could limit subsequent

planting options. Likewise, the occurrence of glyphosate-resistant grass weeds in the Midsouth

could also cause a decreased time between ACCase-inhibiting herbicide application and the

planting of a sensitive crop. Glyphosate-resistant ryegrass (*Lolium perenne* ssp. *multiflorum* (L.)

was confirmed in Arkansas in 1995 (Heap 2017), glyphosate-resistant goosegrass (*Eleusine*

indica L.) (Mueller et al. 2011) confirmed in Tennessee in 2011, and glyphosate-resistance in

barnyardgrass was recently documented in Tennessee and Mississippi (Steckel et al. 2017). Due

to glyphosate resistance and the subsequent reduced efficacy, many producers have begun to add

graminicides to glyphosate applied prior to planting, causing reduced time between application

and grass crop planting (Steckel et al. 2017). Furthermore, there has been little research to

document how precipitation or irrigation could influence the residual activity of ACCase-

inhibiting herbicides. Thus, research was conducted to determine the residual activity of ACCase-inhibiting herbicides on grass weeds and crops, with and without use of irrigation for activation. It was hypothesized that all graminicides would have some residual activity and thus cause injury to corn, grain sorghum, and non-quizalofop-resistant rice planted soon after application.

Materials and Methods

Experiments were conducted in 2014 and 2015 to determine the length of residual activity that could be expected on grass crops and grass weeds following ACCase-inhibiting herbicide application. The field experiment was conducted at the Agricultural Research and Extension Center in Fayetteville, Arkansas on a Leaf silt-loam soil (Fine, mixed, active, thermic Typic Albaquults) with a pH of 5.2 and organic matter content of 1.8%. Experiments were initiated June 13, 2014 and June 18, 2015. The experiment was set up as a split-split plot design, with the whole plot factor being means of activation (irrigation immediately after application versus rainfall), split plot factor being plantback interval (0, 7, and 14 days after application), and the split-split plot factor being herbicide treatment (six graminicides evaluated at multiple rates). Plots had either a 1.3 cm overhead irrigation applied with a traveling gun sprinkler system (Water Reel™, Smith Irrigation Equipment, Kensington, KS) or no irrigation. Irrigation equipment was pre-calibrated with multiple rainfall gauges to insure accurate irrigation amounts were achieved.

Conventional rice, quizalofop-resistant rice, grain sorghum, and corn were planted in single rows perpendicular to the treated plots across each of the four replications of the experiment at the abovementioned three intervals. The conventional rice cultivar 'Roy J' and an

experimental quizalofop-resistant variety (Provisia™ rice, BASF Corp., Research Triangle Park, NC) was planted at a seeding rate of 68 seeds m^{-1} row. For grain sorghum, DeKalb™ hybrid DKS53-67 was planted at a seeding rate of 20 seeds m^{-1} row, and a Smartstax™ (glyphosate/glufosinate-resistant) corn hybrid 'Croplan 6274SS' was planted at a seeding rate of 13 seeds m^{-1} row. Herbicides were applied to a tilled, bare soil prior to planting crops using a CO_2-pressurized backpack sprayer calibrated to deliver 143 L ha^{-1} at 276 kPa. Herbicide treatments evaluated are listed in Table 1, with some being applied at two rates. The split-split plot to which herbicides were applied was 1.8 by 7.6 m. The plots were over-sprayed with 2,4-D at 533 g ae ha^{-1} (Weedar™ herbicide, Nufarm Americas INC, Alsip, IL) at 2 and 4 weeks after initiating the experiment to control broadleaf weeds.

Stand counts from 1 m of row for each crop were recorded 14 days after planting. Visual observations were collected for crop injury and weed control on a scale of 0 to 100, with 0 being no injury or weed control and 100 being complete crop death or weed control. Biomass from 1 m of row for all crops and a random 1 m^2 for a natural population of broadleaf signalgrass and barnyardgrass were collected at 35 days after each separate planting. Biomass samples were oven-dried at 65 C for 14 days.

All data were analyzed with JMP Pro 12.1 (SAS Institute Inc, Cary, NC) using the Fit Model procedure. For data that met the assumptions for ANOVA, means were separated using Fisher's protected LSD ($\alpha = 0.05$). Due to differing environmental conditions years were analyzed seperately. Unlike crop response, banyardgrass and broadleaf signalgrass measurements were analyzed as a split-plot design because the weed species evaluated were a natural population; thus, there were no multiple plantback intervals.

Results and Discussion

Overall, significant interactions and main effects occurred with year; thus, 2014 and 2015 data were analyzed and are presented separately. This significance can be attributed to the differing rainfall patterns between years. For 2014, ideal conditions for this experiment were achieved with minimal rainfall after initiation of the experiment (Figure 1), with the first appreciable rainfall of 1.2 cm 10 days after treatment (DAT). This rain-free period allowed for differentiation between activation treatments through use of irrigation. Thus, the main effect and interactions with activation were generally significant for the parameters evaluated (Tables 2-6). However, in 2015, a total of 10.4 cm of rainfall occurred within 36 hours of initiating the experiment (Figure 1), resulting in minimal difference between activation treatments (Tables 2-6).

Crop densities at 14 days after planting resulted in no significant herbicide interactions or main effects for either year (data not shown). Although a significant main effect was observed for plantback interval for multiple crop stand counts both years, within a plantback interval no differences between treated and non-treated plots were observed either year, thus differences may be due to conditions that effected germination at planting (Tables 2-6). Graminicides did not appear to have an effect on stand establishment of any crop evaluated.

All crops exhibited a negative response from residual activity of the evaluated herbicides, except for quizalofop-resistant rice. Quizalofop-resistant rice showed no significant effect from any of the applied herbicides, with no more than 4% injury observed in 2014 and 3% injury in 2015 (data not shown).

Grain Sorghum

In 2014, a significant herbicide treatment by activation interaction occurred for visible injury and biomass production of grain sorghum (Table 2). The greatest injury resulted from the high rate of sethoxydim with irrigation activation (20% injury), which was significantly greater than all other herbicide treatments but the high rate of fluazifop with irrigation (15%) (Table 7). Greater injury from sethoxydim can most likely be attributed to having lower K_d and K_{oc} compared to other herbicides evaluated (Table 9), which leads to greater availabity of the herbicide in the soil. Likewise, although fluazifop is tightly bound to the soil it rapidly degrades to fluazifop-p-acid, which is highly mobile in the soil and likely led to greater injury to grain sorghum (Martens 2014). Quizalofop (low and high), clethodim (low), fenoxaprop, fluazifop (high), and sethoxydim (high) all resulted in greater injury when activated by sprinkler irrigation compared to the same herbicide without irrigation activation, averaged across plantback intervals. Without irrigation for activation, injury was much lower, with the highest injury being only 7% from multiple treatments, with few differences between treatments. Likewise, biomass for grain sorghum followed a similar trend as injury (Table 2), with the lowest biomass resulting when sethoxydim was applied at a high rate with irrigation activation (85%) (Table 7); however, the sethoxydim (high) treatment with activation was only different than sethoxydim (low) with activation for relative biomass. Relative biomass was significantly reduced for quizalofop (low and high), fluazifop (high), and sethoxydim (high) with herbicide activation compared to non-activated treatments (Table 7). Plantback timing did not have a significant effect on either injury or relative biomass.

In 2015, with the increased rainfall soon after test initiation, grain sorghum injury did not respond to activation treatment (Table 2). Like 2014, sethoxydim (high) resulted in the greatest

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injury of 16% (Table 7). Similarly, sethoxydim (high) produced the lowest relative biomass of 92%. Unlike 2014, a significant main effect for plantback timing occured in 2015 for relative grain sorghum biomass. At the plantback timings of 0 and 7 days after treatment, relative biomass was 96% of the nontreated control averaged across herbicides and activation. However, at 14 days after treatment relative biomass increased to 98%, thus showing an overall decrease in residual activity of the herbicides by that timing (Table 8).

The differences between years can again be contributed to the greater rainfall in 2015. Research has shown that even though rainfall or irrigation is sometimes required to activate a herbicide in the soil, excessive rainfall can accelerate degradation of a herbicide, or cause a loss from runoff or leaching. This can reduce the length of residual activity of a herbicide (Heatherly and Hodges 1998; Splittsoesser and Derscheid 1962).

Corn

Like grain sorghum, a significant herbicide treatment by activation interaction occurred for visible injury and reduced corn biomass in 2014 (Table 3). Greatest injury resulted from sethoxydim (high) with activation of 19% (Table 7), which was higher than any other treatment. Herbicide treatments without activation resulted in much lower injury, with the highest injury of any treatment being only 6% (Table 8). Injury from quizalofop (high), fluazifop (high), and sethoxydim (high) increased when irrigation was applied, over no activation treatments. Corn biomass showed similar results, with sethoxydim (high) with activation having the lowest relative biomass of 86%, which was lower than other treatments (Table 7). Similarly, relative biomass decreased with herbicide activation for quizalofop (high) and sethoxydim (high) compared to treatments without activation.

In 2015, only main effects of herbicide and plantback timing were significant for corn injury or relative biomass (Table 3). Similar to 2014, the herbicide sethoxydim (high) produced the greatest visual injury of 13% in 2015, which was greater than any other treatment (Table 9). Sethoxydim (high) also resulted in the lowest relative biomass (93%) of any herbicide. Plantback timing had a significant effect on corn injury, with the 0 and 7 days after treatment timings resulting in 7% injury averaged across herbicides and activation, while the 14 days after treatment timing resulted in lower injury at 5% (Table 8).

Conventional Rice

Conventional rice showed similar results as grain sorghum and corn, but with generally lower levels of injury. In 2014, conventional rice injury was 11% following fluazifop (high) and sethoxydim (high) with activation (Table 7). Activation treatment only increased the injury of sethoxydim (high) from 0 without to 11% with activation. Little difference was observed between activation treatments for fluazifop (high), with visual injury being 8% even without activation (Table 7). Biomass of conventional rice did not show any significant interactions or main effects (Table 4). Main effect of herbicide for crop injury was the only significant parameter for conventional rice in 2015. Overall, injury observed in 2015 was very similar to 2014 for those treatments with activation due to the rainfall events in 2015. Fluazifop (high) and sethoxydim (high) resulted in the greatest injury to conventional rice of 12 and 11%, respectively (Table 8).

Grass Weed Control

Control of grass weeds was evaluated both years, with broadleaf signalgrass (15 plants m^{-2}) and barnyardgrass (3 plants m^{-2}) being the predominant grasses both years. Overall, little residual weed control was observed from any ACCase-inhibiting herbicide evaluated, with only

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the main effect of herbicide being significant for the 14 DAT rating of broadleaf signalgrass (Table 6). Subsequent control rating and relative biomass at 35 DAT did not result in any significant interactions or mains effects for broadleaf signalgrass (Table 6) or barnyardgrass (data not shown) Due to the low level of residual injury to grass crops evaluated, little residual control of grass weeds was expected from ACCase-inhibiting herbicides.

Practical Implications

The results from this research primarily help determine plantback intervals for ACCase-inhibiting herbicides to grass crops. The results from this experiment demonstrate that quizalofop-resistant rice is tolerant to preplant applications of ACCase-inhibiting herbicides, both the cyclohexanediones and aryloxyphenoxy propionic acids, with the greatest injury only being 4%. Thus, quizalofop-resistant rice can be planted immediately following a graminicide application without risk of injury. Injury to conventional rice can occur if planted in close proximity to an ACCase-inhibiting herbicide application, but was generally less sensitive than grain sorghum or corn. Caution needs to be taken with subsequent planting of grain sorghum or corn after an ACCase-inhibiting herbicide application, especially with sethoxydim. No strong impact of plantback interval (0 to 14 DAT) on grass crop response was apparent for either year, supporting that although the residual activity was relatively low, many of the herbicides persisted in the soil past 14 days. Timing and amount of rainfall following application of an ACCase herbicide will impact the risk for injury to a subsequent crop or the length of time between application and planting of a grass crop. Receiving a rainfall event after herbicide application can increase the residual activity of ACCase herbicides; however, large rainfall events can decrease the persistence of the herbicide in the soil. This is likely because of particle runoff (Wauchope 1978) due to the generally high adsorption to soil particles (K_d), high adsorption to

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soil organic carbon (K_{oc}), and the low water solubility of most ACCase-inhibiting herbicides (Table 9). Likewise, increased microbial degradation from greater soil water availability (Parker and Doxtader 1983) could reduce residual activity of ACCase-inhibiting herbicides, which are in large part degraded by soil microbes (Shaner et al. 2014). Overall, the evaluated ACCase-inhibiting herbicides produced little residual grass weed control and hence, should only be relied on for postemergence control.

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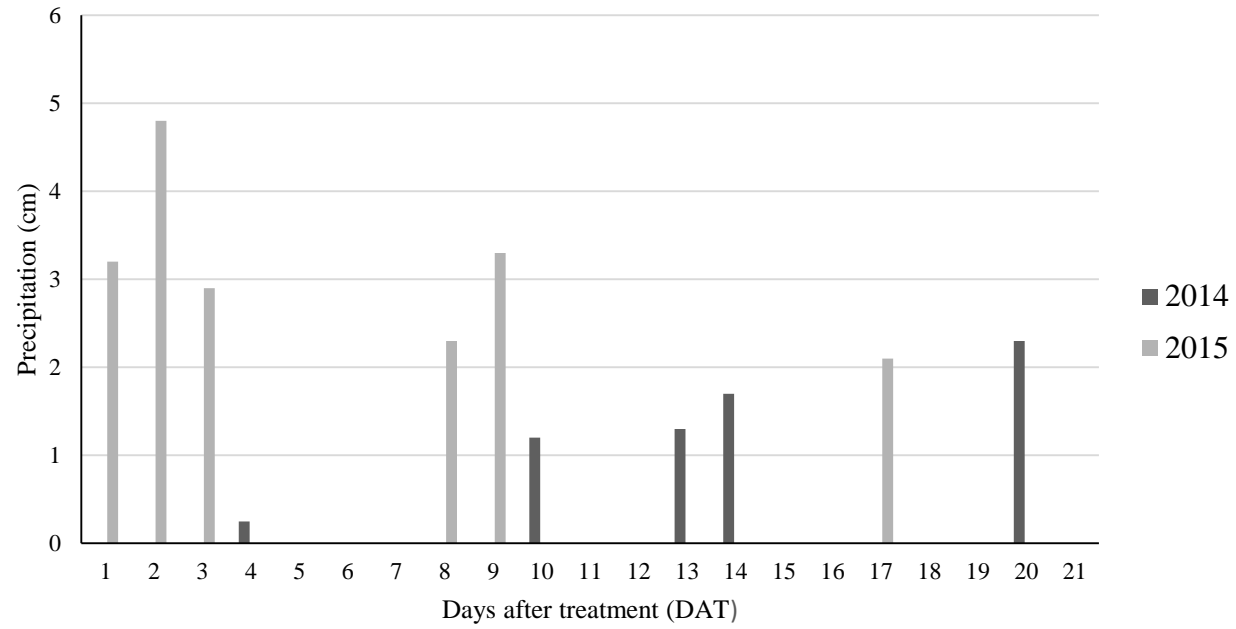
Figure 1. Precipitation history for 21 days after herbicide treatment for Fayetteville, Arkansas in 2014 and 2015. Experiment was initiated on June 13, 2014 and June 18, 2015.

Table 1. Herbicide treatments applied before first planting at Fayetteville, Arkansas.

Herbicide treatments[a]	Rate	Trade name	Manufacturer	Address
	(g ai ha-1)			
Quizalofop	80	Targa	Gowan Company	Yuma, AZ
Quizalofop	160			
Clethodim	68	SelectMax	Valent USA Corporation	Longwood, FL
Clethodim	136			
Fenoxaprop	122	Ricestar HT	Bayer CropScience LP	Research Triangle Park, NC
Cyhalofop	313	Clincher	Dow AgroSciences LLC	Indianapolis, IN
Fluazifop	210	Fusilade DX	Syngenta Crop Ptotection LLC	Greensboro, NC
Fluazifop	410			
Sethoxydim	140	Poast	BASF Corporation	Research Triangle Park, NC
Sethoxydim	280			

Table 2. Analysis of variance for grain sorghum response in 2014 and 2015 .

| | P-value | | | | | |
| Response variable | Plant density 14 DAP[a] | | Injury 14 DAP | | Biomass 35 DAP | |
	2014	2015	2014	2015	2014	2015
Activation	0.8919	0.4216	0.0009	0.3719	0.0003	0.4156
Plantback timing	0.0023	<0.0001	0.3054	0.0456	0.2362	0.0361
Herbicide	0.7123	0.4781	<0.0001	<0.0001	<0.0001	0.0012
Activation x herbicide	0.8642	0.3287	0.0076	0.1935	0.0253	0.5326
Activation x plantback timing	0.4231	0.6932	0.8557	0.9688	0.6750	0.4265
Herbicide x plantback timing	0.5632	0.3749	0.2845	0.8659	0.1360	0.1923

[a] DAP = days after planting

Table 3. Analysis of variance for corn response in 2014 and 2015.

| | P-value | | | | | |
| Response variable | Plant density 14 DAP[a] | | Injury 14 DAP | | Biomass 35 DAP | |
	2014	2015	2014	2015	2014	2015
Activation	0.4536	0.7561	0.0061	0.6542	0.0018	0.5236
Plantback timing	0.0023	0.0128	0.1654	0.0456	0.8351	0.5641
Herbicide	0.2165	0.3325	<0.0001	<0.0001	0.0125	0.0021
Activation x herbicide	0.2694	0.4622	<0.0001	0.2136	0.0326	0.3216
Activation x plantback timing	0.4569	0.6623	0.1986	0.5823	0.4149	0.6256
Herbicide x plantback timing	0.8564	0.3549	0.1356	0.3971	0.8941	0.6513
Activation x plantback timing x herbicide	0.8521	0.8996	0.2316	0.5010	0.6658	0.8651

[a] DAP = days after planting

Table 4. Analysis of variance for conventional rice response in 2014 and 2015.

| Response variable | P-value | | | | | |
| | Plant density 14 DAP[a] | | Injury 14 DAP | | Biomass 35 DAP | |
	2014	2015	2014	2015	2014	2015
Activation	0.4532	0.6221	0.0026	0.6654	0.8864	0.7453
Plantback timing	<0.0001	<0.0001	0.4216	0.7519	0.6415	0.4216
Herbicide	0.2354	0.6549	<0.0001	<0.0001	0.2133	0.1932
Activation x herbicide	0.7513	0.8731	0.0351	0.2331	0.6621	0.6546
Activation x plantback timing	0.8964	0.7541	0.5312	0.3002	0.4816	0.8745
Herbicide x plantback timing	0.7896	0.6879	0.6564	0.8851	0.8764	0.7569
Activation x plantback timing x herbicide	0.8996	0.9125	0.7164	0.9995	0.9132	0.8996

[a] DAP = days after planting

Table 5. Analysis of variance for quizalofop-resistant rice response in 2014 and 2015.

| | P-value | | | | | |
| Response variable | Plant density 14 DAP[a] | | Injury 14 DAP | | Biomass 35 DAP | |
	2014	2015	2014	2015	2014	2015
Activation	0.8795	0.7456	0.4251	0.7243	0.5512	0.8330
Plantback timing	<0.0001	0.0032	0.6938	0.8410	0.8765	0.5402
Herbicide	0.4598	0.6535	0.3564	0.5613	0.2136	0.5316
Activation x herbicide	0.9876	0.6632	0.4457	0.7801	0.5691	0.8664
Activation x plantback timing	0.8456	0.7998	0.4754	0.8602	0.8430	0.3640
Herbicide x plantback timing	0.7654	0.9211	0.8763	0.7124	0.6897	0.8763
Activation x plantback timing x herbicide	0.8733	0.9376	0.9155	0.8630	0.8761	0.8861

[a] DAP = days after planting

Table 6. Analysis of variance for broadleaf signalgrass control in 2014 and 2015.

Response variable	Control 14 DAT[b]		Control 35 DAT		Biomass 35 DAT	
	2014	2015	2014	2015	2014	2015
Activation	0.8454	0.7861	0.8964	0.7561	0.8763	0.7612
Herbicide	0.0469	0.0389	0.2169	0.8700	0.4369	0.5132
Activation x herbicide	0.9031	0.7560	0.8761	0.8697	0.8633	0.7761

[a] DAT = days after treatment

Table 7. Injury (14 days after planting) and biomass (35 days after planting) of grain sorghum, corn, and conventional rice as influenced by the residual activity of ACCase-inhibiting herbicides with and without irrigation activation in 2014 at Fayetteville, AR.[a]

Activation	Herbicide	Rate	Grain sorghum Injury[bcd]	Grain sorghum Biomass[e]	Corn Injury	Corn Biomass	Conventional rice Injury[e]	Conventional rice Biomass[f]
		(g ai ha^{-1})	--% of nontreated--					
Yes	Quizalofop	80	13 bc *	89 b *	9 bc	97 ab	6 bc	98
	Quizalofop	160	14 b *	86 b *	11 bc *	96 ab	5 bc	99
	Clethodim	68	13 bc *	90 ab	6 cd	97 ab	3 c	100
	Clethodim	136	14 b	88 b	5 cd	96 ab	3 c	100
	Fenoxaprop	122	13 bc *	92 ab	7 c	95 ab	3 c	99
	Cyhalofop	313	7 c	93 ab	4 cd	98 a	0	101
	Fluazifop	210	13 bc	90 ab	12 bc	95 ab	3 c	98
	Fluazifop	420	15 ab *	87 b *	13 bc *	95 ab	11 a	97
	Sethoxydim	140	9 c	94 a	5 cd	96 ab	1 cd	101
	Sethoxydim	280	20 a *	85 b *	19 a *	86 c	11 a *	98
No	Quizalofop	80	1 b *	103 a *	2 b	101 a	0	101
	Quizalofop	160	3 ab *	101 ab *	1 b *	101 a	0	100
	Clethodim	68	4 ab	100 ab	3 ab	101 a	3 b	99
	Clethodim	136	7 a	99 ab	4 ab	98 b	4 ab	102
	Fenoxaprop	122	3 ab *	102 ab	1 b	100 ab	0	101
	Cyhalofop	313	5 ab	100 ab	3 ab	101 a	0	99
	Fluazifop	210	5 ab	102 ab	6 a	97 b	5 ab	98
	Fluazifop	420	7 a *	99 ab *	6 a *	97 b	8 a	101
	Sethoxydim	140	3 ab	99 ab	1 b	98 b	0	100
	Sethoxydim	280	7 a *	95 b *	2 b *	98 b	0 *	98

[a] Means within a column and activation level followed by the same lowercase letter are not different.
[b] Injury data expressed as percent relative to the non-treated control.
[c] Asterisk denotes increased injury with activation compared to no activation within a herbicide treatment.
[d] Biomass data expressed as percent relative to a non-treated control. Non-treated control resulted in 285, 296, and 38 g m^{-1} of row oven-dried biomass for grain sorghum, corn, and conventional rice respectively.
[e] Treatments averaging 0 were removed from analysis for conventional rice injury due to violating the assumptions of ANOVA (homogeneity of variance).
[f] Conventional rice biomass resulted in no significant difference between treatments (0.05).

Table 8. Main effect of herbicide and plantback interval on injury (14 days after planting) and biomass (35 days after planting) of grain sorghum, corn, and conventional rice in 2015 at Fayetteville, AR.

Herbicide[a]	Rate	Grain sorghum Injury[bc]		Biomass[bd]		Corn Injury[bc]		Biomass[bd]		Conventional rice Injury[bc]		Biomass[de]
	(g ai ha^{-1})	------------------------------------% of nontreated----------------------------										
Quizalofop	80	5	de	98	bc	5	bc	98	bcd	4	cd	102
Quizalofop	160	8	bc	96	de	6	b	96	d	5	bc	100
Clethodim	68	6	cde	98	bc	3	c	100	a	2	de	98
Clethodim	136	6	cde	97	cd	3	c	99	b	3	de	103
Fenoxaprop	122	4	e	100	a	3	c	100	a	2	e	102
Cyhalofop	313	6	cde	99	ab	6	b	99	b	1	e	97
Fluazifop	210	6	cde	97	cd	6	b	98	bc	6	b	102
Fluazifop	420	9	b	95	e	7	b	97	cd	12	a	101
Sethoxydim	140	6	cde	97	cd	6	b	98	bc	4	cd	98
Sethoxydim	280	16	a	92	f	13	a	93	e	11	a	98
Plantback interval												
0 DAT[f]				96	b	7	a					
7 DAT				96	b	7	a					
14 DAT				98	a	5	b					

[b] Means within a column followed by the same lowercase letter are not different according to Fisher's protected LSD (α=0.05)

[c] Injury data expressed as percent relative to the non-treated control.

[d] Biomass data expressed as percent relative to non-treated control. Non-treated control resulted in 276, 291, and 42 g m^{-1} of row oven-dried biomass for grain sorghum, corn, and conventional rice respectively.

[e] Conventional rice biomass resulted in no interactions or main effects.

[f] DAT = days after treatment.

Table 9. Adsorption to soil particles (K_d), adsorption to soil organic carbon (K_{oc}), and solubility in water of ACCase-inhibiting herbicides.

Herbicide	K_d ml g^{-1}	K_{oc} ml g^{-1}	Solubility in water ml L^{-1}	Source
Clethodim	0.08-1.6	8,000	0.5-0.23	FAO 1999; Shaner et al. 2014
Cyhalofop	265.38	2,092	0.46	Sondhia and Khare. 2014
Fenoxaprop	0.187	11,354	0.78	Anonymous 2015C; Shaner et al. 2014
Fluazifop	0.79	5,700	1.1	Shaner et al. 2014
Fluazifop-p-acid	n/a[a]	50	780	Martens 2014
Sethoxydim	0.09-0.68	100	257	EPA 1996; Shaner et al. 2014
Quizalofop	8.61	510	0.3	Kamrin and Montgomery 1999; Shaner et al. 2014

[a] n/a, not available.

Chapter 4 - Evaluation of Quizalofop-Resistant Rice for Arkansas Rice Production Systems

Abstract

Due to the ongoing evolution of herbicide-resistant weeds, new technologies are needed to maintain effective levels of control. A new rice that will be resistant to quizalofop, an acetyl coenzyme A carboxylase (ACCase)-inhibiting herbicide, is currently under development. With the anticipated launch of this technology in 2018, multiple experiments were conducted to determine effectiveness of the quizalofop-resistant rice system for common grass weed species found in Arkansas rice production. One hundred and twenty-six barnyardgrass accessions were collected across Arkansas and treated with quizalofop at 80 g ai ha^{-1} to determine a baseline of response. All accessions evaluated were effectively controlled ($\geq$ 92%) by quizalofop, with only 13 accessions resulting in lower than 98% control. A greenhouse and field trial was conducted to compare efficacy of quizalofop to currently labeled rice graminicides for control of common rice grass weeds. Results from the greenhouse experiment showed that quizalofop treatments resulted in greater efficacy of common grass weeds compared to cyhalofop or fenoxaprop. This was especially apparent at the larger grass growth stages. A field experiment conducted compared season-long weed control programs of quizalofop to fenoxaprop and cyhalofop. The quizalofop-containing treatments were no better than fenoxaprop and cyhalofop for barnyardgrass and broadleaf signalgrass control. Barnyardgrass and broadleaf signalgrass control were greater than 96% for all herbicide treatments. An additional field experiment was conducted to determine the best rate structure for sequential applications of quizalofop in rice. Sequential applications of quizalofop at 120 g ha^{-1} followed by 120 g ha^{-1} two weeks later resulted in the highest barnyardgrass and broadleaf signalgrass control. Likewise, applying the

full seasonal use rate of 240 g ha^{-1} of quizalofop resulted in greater control compared to 200 and 160 g ha^{-1}. Results from this research indicate a strong benefit for quizalofop use in rice.

Nomenclature: Quizalofop; cyhalofop; fenoxaprop; barnyardgrass, *Echinochloa crus-galli* (L.) Beauv.; broadleaf signalgrass, *Urochloa platyphylla* (Nash) R.D. Webster; rice, *Oryza sativa* L.

Key words: ACCase, acetyl coenzyme A carboxylase, gramminicide, provisia

Arkansas is the top rice producing state, contributing over half of the United States rice acreage and production, more than doubling the contribution from California, the next most productive state (NASS 2015). Rice production in Arkansas is generally located in the eastern half of the state, in the Mississippi River Delta region (Hardke 2016). Weed control is a major obstacle for Arkansas rice production. Most of the rice grown is produced in a drill seeded, delayed flooding system, with only around 5% annually produced using a water-seeded system (Hardke and Wilson 2012). Hence, an effective weed control program in Arkansas begins with a preemergence residual herbicide followed by postemergence herbicide applications (Norsworthy et al. 2013). One of the main challenges to rice production is the ever increasing herbicide resistance found in multiple common rice weeds.

Two of the most problematic weeds to Arkansas rice production are barnyardgrass and red rice (*Oryza sativa* L.). While already difficult to control in rice, both of these species have evolved resistance to commonly used rice herbicides, making effective control even more difficult. Barnyardgrass is a principle rice weed globally, along with other closely related *Echinochloa* species, and thrives in the flooded rice production system (Holm et al. 1977). Barnyardgrass has evolved resistance to many common rice herbicides, including propanil (Carey et al. 1995), quinclorac (Lovelace et al. 2000), and clomazone (Norsworthy et al. 2007). Red rice has long been difficult to control in rice due to physiological similarities between itself and commercial rice varieties (Baldwin et al. 1977). Thus, to selectively control red rice as well as other common rice weeds, imidazolinone-resistant (Clearfield™) rice was commercially released in 2002 (Burgos et al. 2008a). At its height of acceptance (2011), 64% of planted rice in Arkansas and Mississippi were an imidazolinone-resistant variety (Norsworthy et al 2014); however, the share of imidazolinone-resistant rice in Arkansas has declined in recent years to

44% in 2015 (Hardke 2016). The reduction in usage can partially be attributed to imidazolinone resistance in red rice (Burgos et al. 2008) and barnyardgrass (Riar et al. 2012).

With the increased pressure herbicide-resistant weeds place on current rice production systems, a new technology is needed to achieve effective control of these weeds. The development of new herbicides quickly diminished with the launch of glyphosate-resistant crops in the 1990's. Although glyphosate-resistant weeds pushed the agri-chemical industry to re-invest in herbicide discovery (Duke 2011), no new herbicide mechanisms of action have been commercialized in recent years, leaving growers to work with a suite of herbicides that are less effective today because of widespread resistance (Talbert and Burgos 2007). To help combat herbicide-resistant rice weeds, a new herbicide-resistant rice technology (Provisia™ rice) is being developed. Provisia rice is resistant to quizalofop, an acetyl coenzyme A carboxylase (ACCase)-inhibiting herbicide (Guice et al. 2015). Quizalofop-resistant rice is a non-GMO crop and was developed using traditional plant breeding techniques to isolate the G2096S gene, which makes the acetyl-coenzyme A carboxylase enzyme resistant to ACCase-inhibiting herbicides (Hinga et al. 2013).

Quizalofop is a member of the aryloxyphenoxy propionate family and commonly used for effective control of annual weedy grasses and most perennial grass weeds (Shaner 2014). Quizalofop, like other ACCase-inhibiting herbicides, only has activity on grass species, with broadleaf species having a natural tolerance (Konishi and Sasaki 1994). Quizalofop is currently labeled for use in multiple broadleaf crops and non-crop areas, where 35 to 84 g ai ha^{-1} can be applied postemergence in soybean (*Glycine max* (L.) Merr.) and up to 112 g ai ha^{-1} in non-crop areas (Shaner 2014).   The use rate for quizalofop in quizalofop-resistant rice will range from 100 to 138 g ai ha^{-1} for a single application and 240 g ai ha^{-1} as a maximum yearly application

(Anonymous 2017). Although quizalofop can provide moderate residual grass control (Shaner 2014), quizalofop will be restricted to only postemergence applications in quizalofop-resistant rice (Youman et al. 2016).

Herbicide resistance modeling has been used to predict that ACCase-inhibiting rice herbicides such as cyhalofop and fenoxaprop have a lower risk for resistance when compared to acetolactate synthase (ALS)-inhibiting herbicides, such as those used in imidazolinone-resistant rice (Bagavathiannan et al. 2014). These findings support the hypothesis that quizalofop could be a successful selective herbicide in quizalofop-resistant rice if properly integrated with strategies to mitigate resistance. However, there are cases of grass weed species that have already evolved resistance to ACCase-inhibiting herbicides, including barnyardgrass in the Arkansas (Heap 2017). While no resistance to quizalofop has been confirmed in Arkansas, common rice weeds such as barnyardgrass (Mississippi), Amazon sprangletop (*Leptochloa panicoides* (J. Presl) A.S. Hitchc.; Louisiana), and junglerice (*Echinochloa colona* (L.) Link; Arkansas) have been confirmed resistant to ACCase-inhibiting herbicides (Heap 2017; Rouse et al. 2016). Likewise, gene flow between a quizalofop-resistant rice variety and red rice could transfer herbicide resistance to red rice (Burgos et al. 2008). Although outcrossing percentage is low (0.109-0.434%), this could result in several hundred resistant plants per hectare (Burgos et al. 2008). Hence, proper stewardship of this technology is imperative for prolonged effectiveness.

Stewardship of this technology can be accomplished through yearly crop rotation. Crop rotation restriction will be unlikely with applications of quizalofop; however, quizalofop-resistant rice cannot be planted after imidazolinone-resistant rice due to a lack of stacking of resistance traits to confer resistance to the imidazolinone herbicides (Guice et al. 2015). With

the commercialization of quizalofop-resistant rice in 2018, multiple experiments were conducted to determine the baseline response of Arkansas barnyardgrass accessions to quizalofop as well as the efficacy of the quizalofop-resistant rice system compared to current grass weed control standards used in Arkansas rice production.

Materials and Methods

Barnyardgrass Accession Screening

Barnyardgrass panicles were collected from 126 agricultural fields across the Mississippi delta region of Arkansas in the fall of 2014 (Table 1). Accessions were designated as B (barnyardgrass) and given a number value (1 to 126). Samples B1-B74 were personally collected with samples B75-B126 being sent in by University of Arkansas county extension agents. Number of panicles collected per accession was dependent on barnyardgrass density within a field. On average, 30 to 40 panicles were collected per accession. An Iphone navigation application (Where am I at?, Wharton Apps Inc. 2014) was used to record GPS coordinates for each accession location for B1-B74, with GPS coordinates for the remaining accessions taken by multiple means. Crop in the field at time of sampling was recorded. Accessions were dried in the greenhouse (32/22C) for 7 days, then seed were threshed from panicles and combined into single composite samples for each accession.

Approximately 50 seeds were sown into 8 by 14 by 5 cm trays containing a commercial potting mix (Professional Growing Mix, LC1 mix, Sun Gro Horticultural Distribution Inc., Bellevue, WA 98008). Trays were then placed in the greenhouse under conditions of 32/22 C day/night temperatures with a 16-h photoperiod. Trays were irrigated on a daily basis. The experiment was conducted as a randomized complete block design with four replications.

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Quizalofop (Targa[TM] herbicide, Gowan Company, Yuma, AZ) was applied at the 3- to 4-leaf growth stage at 80 g ai ha^{-1} with 1% v/v crop oil concentrate (COC) (Agri-Dex, Helena Chemical Company, West Helena, AR 72390). Applications were made inside a stationary spray chamber calibrated to deliver 187 L ha^{-1} at 276 kPA with 800067 nozzles. After quizalofop application, trays were returned to the greenhouse.

Visual barnyardgrass control estimates were taken at 14 and 21 days after treatment (DAT). Control was assessed on a scale of 0 to 100%, where 0% was equivalent to no response and 100% being complete plant death compared to a non-treated check of each accession. Total emerged plants were counted for each tray. Mortality (%) was calculated at 21 DAT. Alive plants were any plant with living tissue remaining after treatment. Due to collection method and greenhouse space constraints only 45 accessions were evaluated within one run. Within a run, 4 replications were included with non-treated checks for each accession. No formal analyses were conducted on individual runs to compare accessions.

Efficacy of Quizalofop Compared to Currently Registered Rice Graminicides

A greenhouse and field experiment were conducted to compare the efficacy of quizalofop to currently registered rice graminicides. The greenhouse experiment was conducted in the fall of 2014 and spring of 2015 at the University of Arkansas Research and Extension Center in Fayetteville, AR to determine the effect of growth stage at application and choice of ACCase-inhibiting herbicide on control of common grass weeds found in Arkansas rice production systems. The experiment was conducted as a two-factor factorial, randomized complete block design (RCBD), with factor-A being growth stage of grass species at time of application and fayfactor-B being ACCase-inhibiting herbicide treatment with four replications. Growth stages evaluated were 2- to 3-leaf, 5- to 6-leaf, and 12- to 16-leaf grasses. ACCase-inhibiting

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herbicides evaluated were quizalofop at 80, 120, and 160 g ai ha^{-1}, fenoxaprop (Ricestar® HT herbicide, Bayer CropScience LP, Research Triangle Park, NC) at 122 g ai ha^{-1}, and cyhalofop (Clincher® SF herbicide, Dow AgroSciences LLC, Indianapolis, IN) at 313 g ai ha^{-1}. A COC at 1% v/v was added to quizalofop and cyhalofop treatments. Treatments were evaluated for barnyardgrass, broadleaf signalgrass, fall panicum (*Panicum dichotomiflorum* L.), and Amazon sprangletop. Approximately 20 seeds per 8 by 14 by 5 cm tray were sown into a commercial potting mix and watered daily under greenhouse conditions of 32/22C with a 16-h photoperiod. After emergence, plants were thinned to 5 plants tray^{-1}. Herbicide applications were made in a stationary spray chamber calibrated to deliver 187 L ha^{-1} at 276 kPA with 800067 nozzles. After herbicide application, trays were returned to the greenhouse.

Visual estimates of control were evaluated at 14 and 21 DAT on a scale of 0 to 100%, where 0% represents no plant response and 100% being complete plant death compared to a non-treated check. Biomass of plants were harvested immediately following the 21 DAT rating. Plants were clipped at the soil surface and biomass was weighed after being oven-dried at 65 C for 14 days. Biomass data were converted to a percent relative to the non-treated check. Visual estimate of control and percent relative biomass were analyzed using JMP Pro 12.1 using the Fit Model procedure. For data that met the assumptions for ANOVA, means were separated using Fisher's protected LSD (α=0.05). For data that did not meet the assumptions for ANOVA only treatment means are presented. Few differences were observed between 14 and 21 DAT control ratings, thus only the 21 DAT rating will be presented.

A field experiment was conducted in 2014 and 2015 to determine the efficacy of quizalofop compared to other ACCase-inhibiting rice herbicides with and without clomazone preemergence in quizalofop-resistant rice. The experiment was located at the Pine Tree

Research Station near Colt, AR on a Calloway silt loam soil (Fine-Silty, mixed, active, thermic Aquic Flaglossudalfs). An experimental quizalofop-resistant rice variety (Provisia™ rice, BASF Corp., Research Triangle Park, NC) was planted on May 2, 2014 and April 30, 2015 at a seeding rate of 67 seeds m^{-1} row. Plots consisted of 9 drill seeded rows on 18 cm centers, 7.6 m long.

The experimental design was a RCB factorial with four replications and three factors: presence or absence of clomazone preemergence, sequential application of quizalofop vs. fenoxaprop followed by cyhalofop, and timing of the sequential herbicide application. Plots either had clomazone (Command™ herbicide, FMC Corporation, Philadelphia, PA) applied at 336 g ai ha^{-1} preemergence or no preemergence herbicide. Herbicide regimes consisted of either sequential applications of quizalofop at 120 g ha^{-1} each or a sequential application of fenoxaprop at 122 g ha^{-1} followed by cyhalofop at 313 g ha^{-1}. The initial postemergence application was always made at the 3- to 4-leaf stage of rice, whereas the sequential application was either made pre-flood or 2 weeks post-flood. Herbicide treatments were applied using a CO_2-backpack sprayer calibrated to deliver 143 L ha^{-1} at 276 kPA with XR110015 nozzles. All quizalofop and cyhalofop treatments included a COC at 1% v/v. Broadleaf weeds and sedges were controlled by over-spraying the entire test with 2,4-D at 533 g ae ha^{-1} (Weedar™ herbicide, Nufarm Americas INC, Alsip, IL) and halosulfuron at 21 g ai ha^{-1} (Permit® herbicide, Gowan Company LLC, Yuma, AZ). Experiments were fertilized according to University of Arkansas Extension recommendations.

Visual weed control and crop injury were assessed as previously noted. Ratings for control of a natural population of barnyardgrass and broadleaf signalgrass were taken 14 and 21 days after each herbicide application in both 2014 and 2015. Stand counts of emerged rice seedlings per meter row were taken at 14 days after planting. The experiment was terminated

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before the rice reached panicle exertion because a non-resistered rice variety was planted.

Before termination weed biomass of barnyardgrass and broadleaf signalgrass per m^2 was taken.

Biomass samples were weighed after being oven-dried at 65 C for two weeks. Data for this

experiment were analyzed using the Fit Model procedure in JMP Pro 12.1. Year and replication

nested within years were considered random effects. No parameters for this experiment resulted

in significant interactions or main effects; hence, only treatment means are presented.

Best Rate Structure for Sequential Applications of Quizalofop in Quizalofop-Resistant Rice

An experiment was conducted to determine the best rate structure of sequential

applications of quizalofop to quizalofop-resistant rice, when applied initially to either 2- or 6-leaf

grasses. The field experiment was conducted in 2014 and 2015 on a Dewitt silt-loam soil (Fine,

smectitic, thermic Typic Albaqualfs) at the Rice Research and Extension Center near Stuttgart,

AR. The experiment was conducted as a two-factor RCBD with factor-A being growth stage of

grass weeds at time of first application and factor-B being quizalofop rate structure with four

replications. An experimental quizalofop-resistant rice variety was planted on 18-cm width

rows, in 1.8 by 6.1 m plots, at a rate of 67 seeds m^{-1} row. Planting occurred on April 26, 2014

and April 21, 2015. Quizalofop applications were applied to a natural population of grasses,

with no preemergence herbicide applied to insure a high weed density. Quizalofop was applied

using a CO$_2$-pressurized backpack sprayer calibrated to deliver 143 L ha^{-1} at 276 kPA using

XR110015 nozzles. Sequential applications of quizalofop were applied, with the second

application being made at 14 days after the first application. All applications included a COC at

1% v/v. This experiment was conducted to solely evaluate grass weed control; thus, broadleaf

weeds and sedges were controlled by over-spraying the entire test with 2,4-D at 533 g ha^{-1} and

halosulfuron at 21.3 g ha^{-1}. The quizalofop rate structure was 80, 120, or 160 g ha^{-1} followed by

a sequential application of 80, 120, 160 g ha^{-1}. All rate combinations evaluated did not exceed

the maximum yearly application rate of 240 g ha^{-1} to be applied over both combinations. For

instance, quizalofop at 160 g ha^{-1} followed by 120 g ha^{-1} was not evaluated because this

treatment would have exceeded the allowable yearly maximum (Anonymous 2017).

Visual estimates of weed control and crop injury were rated. Barnyardgrass and

broadleaf signalgrass control were evaluated in 2014 and 2015 along with red rice in 2015. Rice

plant heights were taken multiple times throughout the experiment for both 2014 and 2015. Due

to working with an experimental rice variety that was not registered at the time, the crop was

terminated before reproductive growth stage #3 (panicle exertion). Data for this experiment

were analyzed using the Fit Model procedure in JMP Pro 12.1. For data that met assumptions

for ANOVA, means were separated using Fisher's protected LSD (α=0.05) and preplanned

contrasts were conducted for select treatments to compare between total yearly amounts of

quizalofop applied (α=0.05). Years were analyzed and will be presented separately for 2014 and

2015.

Results and Discussion

Barnyardgrass Accession Screening

Overall, quizalofop at 80 g ai ha^{-1} was effective for controlling the accessions tested. At

21 DAT, barnyardgrass control across accessions was 99% (data not shown). Of the 126

accessions evaluated, 113 were completely controlled by quizalofop (100%), with no living

tissue remaining at 21 DAT. For the 13 accessions that were not completely controlled,

quizalofop achieved at least 92% control (Table 2). A significant difference (P=0.02086) for

mortality of the 13 accessions was observed; however, the lowest mortality was only 80% with

accession B91 (Table 2). Even with an 80% mortality rate, live plants only had a small portion

of living tissue, and most likely would not have been competitive in a field setting. Although

ACCase-resistant barnyardgrass has been confirmed in the Midsouth (Heap 2017), all accessions

evaluated were adequately controlled with quizalofop. With use rates to be 100 to 138 g ha^{-1} for

a single application (Anonymous 2017), quizalofop is expected to be an effective herbicide to

control barnyardgrass in rice.

Efficacy of Quizalofop Compared to Registered Rice Graminicides

Greenhouse Experiment: A significant growth stage by herbicide interaction was observed for

visual control and biomass for all grass species. ACCase-inhibiting herbicides were effective for

controlling all species evaluated at the 2- to 3-leaf growth stage (>96%) (Table 3), with no

significant difference between treatments. Likewise, no difference was observed between

herbicides for relative biomass at the 2- to 3-leaf timing of any grass species (Table 4). For

applications to larger grass, there did appear to be differences in efficacy among the herbicides

evaluated. At the 5- to 6-leaf and 12- to 16-leaf growth stages, quizalofop across rates

consistently provided greater control compared to fenoxaprop and cyhalofop (Table 3). Only the

lowest rate of quizalofop (91%) was similar to fenoxaprop (89%) for control of 5- to 6-leaf

barnyardgrass. Quizalofop, regardless of rate, provided a high level of control (>90%) for all

grass species at the 5- to 6-leaf growth stage. Similarly, broadleaf signalgrass, fall panicum, and

Amazon sprangletop treated at the 5- to 6-leaf stage usually had less biomass following

quizalofop treatments compared to fenoxaprop and cyhalofop (Table 4).

Control drastically decreased for all graminicides applied to 12- to 16-leaf grasses (Table

3). For barnyardgrass, control from the high rate of quizalofop was reduced from 99% at the 5-

to 6-leaf growth stage to only 53% at the 12- to 16-leaf stage (Table 3) while relative biomass

increased from 6 to 55% (Table 4).   Likewise, these herbicides were not effective for controlling

broadleaf signalgrass at the largest growth stage (33 to 64% control), except for the high rate of

quizalofop (86%). Fall panicum was still highly sucseptable to quizalofop at the 12- to 16-leaf

growth stage, with all quizalofop treatments producing >90% control (Table 3) with ≤20%

biomass relative to the nontreated (Table 4). Overall, at the rates tested, quizalofop appears to

have greater grass activity than either fenoxaprop or cyhalofop, which is similar to previous

experiments which have often shown quizalofop to outperform other ACCase-inhibiting

herbicides (Blackshaw et al. 2006; Deen et al. 2006; Minton et al. 1989). Moreover, quizalofop

remained more effective on the grass weeds evaluated at larger growth stages (5- to 6-leaf, 12- to

16-leaf), where as fenoxaprop and cyhalofop efficacy quickly diminished.

Field Experiment: Overall, no parameter evaluated for this experiment produced a significant

interaction or main effect for either 2014 or 2015. Grass weeds were effectively controlled by all

treatments, with all control ratings for both barnyardgrass and broadleaf signalgrass >96% (Table

5). At 21 days after the sequential application, barnyardgrass and broadleaf signalgrass control

ranged from 97 to 99% for all treatments.   Presence or absence of clomazone preemergence did

not affect the emergence of rice, with no significant difference between rice stand counts at 14

days after planting (data not shown). The experimental quizalofop-resistant rice variety showed

no symptoms of injury from any ACCase-inhibiting herbicide applied. Visual injury ratings

taken 14 and 21 days after graminicide application were never higher than 5% for any treatment,

with injury symptoms being small chlorotic spots consistent with injury caused from the

adjuvant. Only non-treated check plots had grass weeds present at the time of test termination,

thus they were the only plots in which weed biomass were harvested. Non-treated checks

averaged 43.2 and 28.7 g m^{-2} oven dried biomass averaged over both years for barnyardgrass and broadleaf signalgrass, respectively.

Averaged over both years, density of barnyardgrass and broadleaf signalgrass were only 4.2 and 3.6 plants m^{-2}, respectively at time of the initial postemergence application (3- to 4-leaf rice). Previous research has shown that as weed density decreases, efficacy of herbicides can increase. This is especially true with ACCase-inhibiting herbicides, where Ndou (2009) found that as large crabgrass (*Digitaria sanguinalis* (L.) Scop.) density decreased, percent mortality with clethodim increased.

Best Rate Structure for Sequential Applications of Quizalofop in Quizalofop-Resistant Rice

In 2014, there was not a significant interaction of quizalofop rate structure by growth stage; however, there were significant main effects of rate structure and growth stage for both barnyardgrass (P=<0.0001, 0.0165, respectively) and broadleaf signalgrass control (P=<0.0001, 0.0010, respectively). At 21 days after the sequential application, the 120 fb 120 g ha^{-1} rate structure controlled banyardgrass 98%, but was only significantly different from the 80 fb 80 g ha^{-1} structure which produced 89% control (Table 6). Similarly, the highest control of broadleaf signalgrass was produced with the 120 fb 120 g ha^{-1} rate structure, but again was only significantly different from the 80 fb 80 g ha^{-1} rate structure which resulted in 91% control. Based on an orthogonal contrast, using the full seasonal quizalofop use rate of 240 g ha^{-1} significantly increased both barnyardgrass and broadleaf signalgrass control compared to seasonal use rates of 200 and 160 g ha^{-1}. When the initial application of quizalofop was made at the 2-leaf growth stage it resulted in 98% control of barnyardgrass, averaged over rates; however, when the application occurred at the 6-leaf growth stage control declined to 87% (Table 7). The same trend was apparent for broadleaf signalgrass as well, where when initially

applied at the 2-leaf growth stage control averaged 98% over rate structure, but when initiated at the 6-leaf growth stage control declined to 95%.

In 2015, the experiment contained red rice in addition to barnyardgrass and broadleaf signalgrass. The overall weed density was less in 2015, which may have contributed to differing results between years. No significant difference was observed between quizalofop rate structure for either barnyardgrass, broadleaf signalgrass, or red rice. Control of barnyardgrass, broadleaf signalgrass, and red rice ranged from 94 to 98%, 97 to 100%, and 95 to 99%, respectively at 21 days after sequential application (Table 6). Based on an orthogonal contrast, there was a difference in full seasonal quizalofop use rate (240 g ha^{-1}) compared to the low seasonal use rate (160 g ha^{-1}) for barnyardgrass and red rice control. Likewise, there was a main effect of growth stage of initial application for barnyardgrass (P=0.0040) and red rice control (P=0.0403). When the initial application of quizalofop was made at the 2-leaf growth stage barnyardgrass grass control was 98%; however, when initiated at the 6-leaf growth stage control decreased to 93% (Table 7). Similarly, red rice control was 99% when applied at the 2-leaf growth stage, but was reduced to 97% when the first application was to 6-leaf plants. Although this seems like a small difference, due the potential for gene flow from quizalofop-resistant rice to red rice, even a few escapes of red rice within a field can lead to the rapid evolution of resistance (Gealy et al. 2012).

Results from this experiment support applications of quizalofop in quizalofop-resistant rice as an effective option for controlling annual grass weed species. Moreover, the results support the current labeled single application rates of quizalofop at 100 to 138 g ha^{-1} as well as the total seasonal use rate of 240 g ha^{-1} (Anonymous 2017).

Practical Implications

Findings from this research lead to the conclusion that quizalofop-resistant rice is an effective weed control technology for annual grass control in Arkansas rice production systems. Quizalofop alone effectively controlled all 126 barnyardgrass accessions from across the state of Arkansas, even at a lower than labeled rate (80 g ha^{-1}) for quizalofop-resistant rice. Quizalofop also generally outperformed other currently labeled rice graminicides, especially on larger grasses. Over multiple years and locations, quizalofop-resistant rice exhibited high levels of tolerance to quizalofop (<5% injury), meaning the likelihood for injury to commercial cultivars from the herbicide should be low. For optimum efficacy, it is best that sequential applications be employed, where the first application targets two-leaf or smaller grasses using the full seasonal rate of 240 g ha^{-1}. Delaying applications or reducing the use rate would likely increase the risk for resistance in barnyardgrass and gene flow from red rice. Within the full seasonal quizalofop use rate, sequential applications of 120 g ha^{-1} followed by 120 g ha^{-1} performed best for the grass weeds evaluated.

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Table 1. Barnyardgrass accessions listed by county, crop, and GPS coordinates from which they were collected.

Accession	County	Crop	Latitude	Longitude
			°N	°W
B1	Arkansas	Rice	34.446	91.415
B2	Arkansas	Rice	34.327	91.337
B3	Arkansas	Rice	34.298	91.449
B4	Arkansas	Rice	34.391	91.537
B5	Arkansas	Rice	34.552	91.555
B6	Prairie	Rice	34.685	91.559
B7	Prairie	Rice	34.833	91.566
B8	Prairie	Rice	34.985	91.578
B9	Prairie	Rice	34.870	91.415
B10	Prairie	Rice	34.773	91.496
B11	Monroe	Rice	34.654	91.448
B12	Monroe	Rice	34.693	91.221
B13	Desha	Rice	33.573	91.384
B14	Chicot	Rice	33.573	91.372
B15	Desha	Rice	33.673	91.423
B16	Chicot	Rice	33.341	91.289
B17	Chicot	Rice	33.195	91.263
B18	Chicot	Soybean	33.068	91.225
B19	Arkansas	Rice	33.889	91.429
B20	Arkansas	Rice	34.034	91.375
B21	Arkansas	Rice	34.152	91.346
B22	Arkansas	Rice	34.330	91.270
B23	Monroe	Soybean	34.418	91.073
B24	Phillips	Rice	34.526	90.961
B25	Phillips	Rice	34.555	90.799
B26	Lee	Rice	34.655	90.768
B27	Lee	Soybean	34.775	90.793
B28	Lee	Rice	34.775	90.971
B29	Monroe	Rice	34.776	90.971
B30	St. Francis	Rice	35.137	90.901
B31	Prairie	Rice	34.803	91.651
B32	Lonoke	Rice	34.780	91.794
B33	Lonoke	Rice	34.764	92.029
B34	Lonoke	Rice	34.777	91.914
B35	Lonoke	Rice	34.582	91.883
B36	Lonoke	Rice	34.559	91.718
B37	Lonoke	Rice	34.868	91.876
B38	Mississippi	Rice	35.607	90.107
B39	Mississippi	Rice	35.549	90.249
B40	Mississippi	Rice	35.750	90.181
B41	Craighead	Rice	35.907	90.483
B42	Craighead	Rice	35.720	90.570

Table 1. (Cont.) Barnyardgrass accessions listed by county, crop, and GPS coordinates from which they were collected.

B43	Poinsett	Rice	35.529	90.446
B44	Poinsett	Rice	35.548	90.591
B45	Poinsett	Rice	35.678	90.615
B46	Craighead	Rice	35.777	90.625
B47	Craighead	Rice	35.720	90.769
B48	Craighead	Rice	35.764	90.925
B49	Poinsett	Rice	35.550	90.731
B50	Poinsett	Rice	35.612	90.885
B51	Jackson	Rice	35.651	90.998
B52	Jackson	Rice	35.654	91.202
B53	Jackson	Rice	35.725	91.126
B54	Jackson	Rice	35.549	91.230
B55	Jackson	Rice	35.381	91.231
B56	Woodruff	Rice	35.288	91.347
B57	Woodruff	Rice	35.139	91.240
B58	Woodruff	Rice	35.060	91.122
B59	Woodruff	Rice	35.259	91.074
B60	Cross	Rice	35.394	90.985
B61	Cross	Rice	35.449	90.774
B62	Cross	Rice	35.248	90.872
B63	Crittenden	Rice	35.261	90.661
B64	Crittenden	Rice	35.263	90.657
B65	Crittenden	Rice	35.384	90.339
B66	Crittenden	Rice	35.240	90.339
B67	St. Francis	Rice	34.949	90.528
B68	St. Francis	Rice	35.037	90.688
B69	St. Francis	Rice	35.156	90.857
B70	St. Francis	Rice	35.104	90.986
B71	St. Francis	Rice	35.005	91.241
B72	Crittenden	Rice	35.055	90.406
B73	Crittenden	Rice	35.228	90.336
B74	Poinsett	Rice	35.626	91.159
B75	Arkansas	Rice	34.169	91.782
B76	Arkansas	Rice	34.412	91.725
B77	Arkansas	Rice	34.423	91.782
B78	Arkansas	Rice	34.399	91.781
B79	Arkansas	Rice	34.555	91.721
B80	Arkansas	Rice	34.122	91.255
B81	Arkansas	Rice	34.412	91.631
B82	Arkansas	Rice	34.861	98.716
B83	Arkansas	Rice	34.423	91.726
B84	Arkansas	Rice	34.456	91.712
B85	Jefferson	Rice	34.319	92.091
B86	Jefferson	Rice	34.394	91.895

Table 1. (Cont.) Barnyardgrass accessions listed by county, crop, and GPS coordinates from which they were collected.

B87	Jefferson	Rice	34.381	91.782
B88	Lonoke	Rice	34.008	91.762
B89	Jefferson	Rice	34.386	91.725
B90	Lonoke	n/a	34.123	91.712
B91	Arkansas	n/a	34.432	91.125
B92	Cross	n/a	35.201	90.925
B93	Cross	n/a	35.404	90.993
B94	Woodruff	n/a	35.258	91.296
B95	Woodruff	n/a	35.287	91.411
B96	Clay	Rice	36.408	90.735
B97	Clay	Rice	36.594	90.488
B98	Lonoke	n/a	34.881	91.706
B99	Greene	Rice	36.229	90.717
B100	Greene	Rice	35.993	90.761
B101	Greene	Rice	36.039	90.776
B102	Greene	Rice	36.042	90.724
B103	Greene	Rice	36.185	90.673
B104	Greene	Rice	36.157	90.692
B105	Greene	Rice	36.047	90.701
B106	Greene	Rice	35.994	90.468
B107	Greene	Rice	36.159	90.650
B108	Greene	Rice	36.172	90.698
B109	Greene	Rice	35.997	90.781
B110	Greene	Rice	36.132	90.726
B111	Poinsett	Rice	35.476	90.619
B112	Phillips	n/a	34.301	90.893
B113	Greene	n/a	36.054	90.727
B114	Greene	n/a	36.061	90.619
B115	Greene	n/a	36.114	90.473
B116	Greene	n/a	36.066	90.799
B117	Greene	n/a	35.988	90.843
B118	Greene	n/a	36.046	90.802
B119	Lawrence	n/a	36.018	90.904
B120	Lawrence	n/a	36.415	90.658
B121	Lawrence	n/a	35.969	91.103
B122	Lawrence	n/a	35.895	90.412
B123	Lawrence	n/a	35.991	90.862
B124	Poinsett	Rice	35.686	90.854
B125	Poinsett	Rice	35.535	90.833
B126	Poinsett	Rice	35.662	90.892

[a] n/a, none available.

Table 2. Control and percent mortality of 13 barnyardgrass accessions 21 days following a postemergence application of quizalofop at 80 g ha^{-1}.[a]

Accession[b]	Control[c]	Mortality[d]
	----------------------------------%----------------------------------	
B17	98	92
B30	95	86
B31	96	84
B40	97	89
B41	95	83
B58	95	85
B78	96	89
B91	92	80
B96	95	83
B103	94	85
B118	98	92
B119	96	90
B125	95	90

[a] Quizalofop applied to 3- to 4-leaf barnyardgrass

[b] A total of 126 accessions were evaluated. Accessions that were completely controlled are not presented and were excluded from analysis.

[c] Percent control of barnyardgrass accessions did not differ among accessions (α=0.05)

[d] Means within a column followed by the same letter are not different according to Fisher's LSD (α=0.05).

Table 3. Effect of ACCase-inhibiting herbicide and growth stage at time of application for control of barnyardgrass, broadleaf signalgrass, fall panicum, and Amazon sprangletop at 21 DAT.[a]

Growth stage	Herbicide	Rate	Control[b] ECHCG		BRAPP		PANDI		LEFPA	
		g ai ha^{-1}	\-%\-							
2- to 3-leaf	Quizalofop	80	100		99	a	100		100	
	Quizalofop	120	100		100		100		100	
	Quizalofop	160	100		100		100		100	
	Fenoxaprop	122	96	ab	99	a	100		99	a
	Cyhalofop	313	96	ab	98	a	100		98	ab
5- to 6-leaf	Quizalofop	80	91	bc	100		99	a	96	b
	Quizalofop	120	97	a	100		100		100	
	Quizalofop	160	99	a	100		100		100	
	Fenoxaprop	122	89	c	85	b	76	c	85	c
	Cyhalofop	313	48	d	56	d	39	d	44	g
12- to 16-leaf	Quizalofop	80	36	e	54	d	92	b	70	e
	Quizalofop	120	40	e	64	c	90	b	73	e
	Quizalofop	160	53	d	86	b	95	ab	80	d
	Fenoxaprop	122	27	f	33	f	75	c	61	f
	Cyhalofop	313	19	g	47	e	29	e	38	h

[a] DAT = days after treatment, ECHCG = barnyardgrass, BRAPP = broadleaf signalgrass, PANDI = fall panicum, LEFPA = Amazon sprangletop.
[b] Means within a column followed by the same letter are not different according to Fisher's LSD (α=0.05).
[c] Treatments resulting in 100% control were excluded from analysis due to having no variance between reps, thus not meeting the assumptions of ANOVA.

Table 4. Effect of ACCase-inhibiting herbicide and growth stage at time of application on relative biomass of barnyardgrass, broadleaf signalgrass, fall panicum, and Amazon sprangletop at 21 DAT.[a]

Grass size	Herbicide	Rate	Biomass[bc]							
			ECHCG		BRAPP		PANDI		LEFPA	
		g ai ha^{-1}	------------------ % of nontreated -----------------------							
2- to 3-leaf	Quizalofop	80	5	e	7	e	4	d	4	f
	Quizalofop	120	7	e	6	e	3	d	3	f
	Quizalofop	160	5	e	4	e	3	d	3	f
	Fenoxaprop	122	8	e	6	e	4	d	5	f
	Cyhalofop	313	8	e	7	e	6	d	4	f
5- to 6-leaf	Quizalofop	80	7	e	8	e	4	d	7	ef
	Quizalofop	120	8	e	7	e	5	d	5	f
	Quizalofop	160	6	e	7	e	4	d	4	f
	Fenoxaprop	122	9	e	20	d	20	c	16	de
	Cyhalofop	313	43	d	41	c	63	a	60	a
12- to 16-leaf	Quizalofop	80	61	bc	57	ab	20	c	27	c
	Quizalofop	120	58	c	51	bc	19	c	27	c
	Quizalofop	160	55	c	22	d	18	c	22	cd
	Fenoxaprop	122	67	b	65	a	39	b	44	b
	Cyhalofop	313	84	a	62	ab	69	a	67	a

[a] DAT = days after treatment, ECHCG = barnyardgrass, BRAPP = broadleaf signalgrass, PANDI = fall panicum, LEFPA = Amazon sprangletop

[b] Means within a column followed by the same letter are not different according to Fisher's protected LSD (α=0.05)

[c] Data expressed as percent relative biomass compared with non-treated control for each grass species and growth stage. Non-treated check was harvested on the same day as treated plots.

Table 5. Effect of clomazone preemergence, graminicides regime, and timing of sequential application on barnyardgrass and broadleaf signal grass control at 21 days after sequential application in Colt, AR.[a]

Clomazone preemergence	Graminicide regime	Timing of sequential application[c]	Control[b] Barnyardgrass	Broadleaf Signalgrass
			---------------------------%---------------------------	
Clomazone	Quizalofop/Quizalofop	Pre-flood	99	99
	Quizalofop/Quizalofop	2 week post-flood	98	98
	Fenoxaprop/Cyhalafop	Pre-flood	98	98
	Fenoxaprop/Cyhalafop	2 week post-flood	98	98
None	Quizalofop/Quizalofop	Pre-flood	97	99
	Quizalofop/Quizalofop	2 week post-flood	98	98
	Fenoxaprop/Cyhalafop	Pre-flood	98	97
	Fenoxaprop/Cyhalafop	2 week post-flood	97	98

[a] Herbicides were applied at the following rates: clomazone at 336 g ai ha^{-1}, quizalofop at 120 g ai ha^{-1}, fenoxaprop at 122 g ai ha^{-1}, and cyhalofop at 313 g ai ha^{-1}.

[b] No significant interactions or main effects were observed for barnyardgrass or broadleaf signalgrass control.

[c] Initial application of the sequential treatments were applied at an early postemergence timing (3- to 4-leaf rice).

Table 6. Effect of quizalofop application structure on barnyardgrass, broadleaf signalgrass, and red rice control at Stuggart, AR in 2014 and 2015 averaged over time of first application followed by contrast between total quizalofop usage rates.

	Control[b]				
	2014[c]		2015[d]		
Application structure[a]	ECHCG	BRAPP	ECHCG	BRAPP	ORYSA
g ai ha^{-1}	--%--------------------------------------				
80/80	89 b	91 b	94	97	95
80/120	90 ab	95 ab	96	98	99
80/160	91 ab	98 a	97	100	98
120/80	91 ab	96 ab	94	99	98
120/120	98 a	99 a	98	100	99
160/80	95 a	98 a	98	100	98
Contrast[e]					
g ai ha^{-1}					
240 vs. 160	<0.0001	0.0032	0.0415	NS	0.0150
240 vs. 200	0.0049	0.0311	NS	NS	NS
200 vs. 160	0.0246	0.0099	NS	NS	NS

[a] First rate applied followed by (/) second rate applied 2 weeks later

[b] ECHCG = barnyardgrass, BRAPP = broadleaf signalgrass, ORYSA = red rice

[c] Means within a column followed by the same letter are not different according to Fisher's protected LSD (α=0.05).

[d] 2015 resulted in no significant difference between quizalofop application structure for any weed species.

[e] Represents total yearly amount of quizalofop applied.

Table 7. Effect of grass growth stage at time of first quizalofop application on barnyardgrass, broadleaf signalgrass, and red rice control in 2014 and 2015 at Stuttgart, AR.

	Control[a]				
	2014		2015		
Growth stage[b]	ECHCG	BRAPP	ECHCG	BRAPP	ORYSA
2 leaf	98 a	98 a	98 a	98	99 a
6 leaf	87 b	95 b	93 b	97	97 b

[a] ECHCG = barnyardgrass, BRAPP = broadleaf signalgrass, ORYSA = red rice
[b] Growth stage of grasses at the first application of quizalofop with a subsequent applications 14 days later.
[c] Means within a column followed by the same letter are not different according to Fisher's protected LSD (α=0.05).
[d] 2015 resulted in no significant difference between growth stage at initial application for broadleaf signalgrass (α=0.05).

Chapter 5 - Evaluation of Quizalofop Tank-Mixtures for Quizalofop-Resistant Rice

Abstract

Effective grass weed control in rice is becoming more difficult due to herbicide resistance. To combat weed resistance a new non-GMO resistant rice is under development. Quizalofop, an acetyl coenzyme A carboxylase (ACCase)-inhibiting herbicide, can be applied over-the-top of quizalofop-resistant rice for selective grass control. Due to the absence of broadleaf weed control from this herbicide, other herbicides will be needed to achieve control of a diverse weed spectrum. Antagonism often occurs when mixing ACCase-inhibiting herbicides with other herbicides; thus, two experiments were conducted to evaluate quizalofop in tank-mixes with common rice herbicides having either grass or broadleaf activity. Both greenhouse experiments were a two-factor factorial where factor-A was quizalofop rate and factor-B was tank-mix partner. The first experiment contained tank-mix partners for grass control with some treatments having activity on broadleaf species as well. The second experiment contained tank-mix partners that when applied alone are not effective in controlling grass weeds. The first experiment included labeled rates of clomazone, pendimethalin, thiobencarb, quinclorac, propanil, imazethapyr, bispyribac, penoxsulam, cyhalofop, and fenoxaprop in tank-mixes with quizalofop at 0 or 80 g ai ha^{-1} on common grass weeds found in rice production. The second experiment included labeled rates of triclopyr, acifluorefen, carfentrazone, salfufenacil, halosulfuron, halosulfuron + thifensulfuron, bentazon, or 2,4-D amine in tank-mixes with quizalofop at 0, 80, or 160 g ai ha^{-1}. Tank-mix interactions for percent control or biomass reduction were evaluated using Colby's method. Overall, quizalofop alone provided effective control of all grass species evaluated (>90%) in both experiments, except for ACCase-resistant Amazon sprangletop. When quizalofop was tank-mixed with other herbicides, antagonism was

observed for various combinations on multiple grass weeds. The acetolactate synthase (ALS)-inhibiting herbicides consistently antagonized quizalofop in terms of grass weed control and biomass reduction. Likewise, the addition of propanil to quizalofop antagonized the graminicide based on multiple grass species evaluated. Similarly, the auxinic herbicides antagonized quizalofop, with 2,4-D being the most consistently antagonistic tank-mix partner, resulting in reduced control of all grass weeds evaluated compared to quizalofop alone. Overall, the results indicate caution should be taken before tank-mixing quizalofop with other rice herbicides, and ultimately, separate applications may be needed when a diverse spectrum of grasses, broadleaves, and/or sedges are present in a rice field.

Nomenclature: Acifluorfen; bentazon; bispyribac; carfentrazone; clomazone, cyhalofop, fenoxaprop; halosulfuron; halosulfuron + thifensulfuron; imazethapyr; penoxsulam; propanil; quinclorac; quizalofop; salfufenacil; thiobencarb; triclopyr; 2,4-D; Amazon sprangletop, *Leptochloa panacoides (*J.Presl) A.S. Hitchc; rice, *Oryza sativa* L.

Key words: Tank-mix, antagonism, interaction, ACCase, acetyl coenzyme A carboxylase, graminicide, Provisia

The increase in occurance of herbicide resistant barnyardgrass, sprangletop, and weedy

rice has been well documented (Burgos et al. 2008; Norsworthy et al. 2013; Tehranchian et al.

2016). With this increase in herbicide-resistant weeds, achieving effective efficacy in rice

production systems is becoming more difficult. To help combat this issue, a new herbicide

resistant rice type is being developed to control troublesome grass weeds. Provisia™ rice (BASF

Corporation, Research Triangle Park, NC), which is resistant to quizalofop, is set to be

commercialized in 2018 (personal communication, John Schultz, BASF Corporation).

Quizalofop, an acetyl coenzyme A carboxylase (ACCase)-inhibiting herbicide, has been used for

control of annual and perennial grass weeds (Shaner 2014). Applications of quizalofop

effectively control barnyardgrass (*Echinochloa crus-galli* (L.) Beauv.) and red rice (*Oryza sativa*

L.) (Noldin et al. 1998), which are two of the most problematic weeds in Arkansas rice

production (Norsworthy et al. 2013).

Quizalofop is a member of the aryloxyphenoxy propionate family of ACCase-inhibiting

herbicides. Like other ACCase-inhibiting herbicides, quizalofop has no activity on broadleaf

weed species (Shaner 2014). This lack of activity in broadleaf species is due to having the accD

gene, which causes the presence of the herbicide-tolerant prokaryote form of ACCase, compared

to grass species which have the herbicide-sensitive eukaryote form of ACCase (Konishi and

Sasaki 1994). With no broadleaf control, producers growing quizalofop-resistant rice will need

to rely on other herbicides to control a diverse weed spectrum. Commonly, herbicides are tank-

mixed because applying two or more herbicides as a mixture often increases spectrum of control

as well as saves time and money over sequential applications (Hatzios and Penner 1985).

Although tank-mixing of herbicides is a common practice, efficacy of the herbicides

mixed together can often be affected. When this type of interaction occurs, the results may be

synergistic, additive, or antagonistic (Colby 1967). In respect for grass weed control, antagonism of efficacy is more common than synergism (Damalas 2004). Antagonism of grass weed control between many ACCase-inhibiting herbicides and broadleaf herbicides have been reported (Kammler et al. 2008; Scherder et al. 2005, Brommer et al. 2000). Overall, ACCase-inhibiting herbicides are antagonized by many different herbicides from multiple mechanisms of action. Zhang (2005) reported antagonism of the rice graminicide fenoxaprop on barnyardgrass control from tank-mixes with bensulfuron, carfentrazone, and halosulfuron, all being common herbicides used in rice production. Likewise, broadleaf signalgrass control from fenoxaprop was antagonized by tank-mixes with triclopyr and halosulfuron (Buehring et al. 2006). Antagonism between tank-mixes of halosulfuron, triclopyr, and propanil with the rice graminicide cyhalofop has also been reported (Scherder et al 2005).

Quizalofop has been antagonized by tank-mixes with many different herbicides. Minton et al. (1989a, 1989b) reported quizalofop to be antagonized in tank-mixes with chlorimuron, imazaquin, and lactofen for barnyardgrass control and imazaquin for red rice control. Similarly, tank-mixes with auxinic herbicides such as 2,4-D amine and dicamba can antagonize quizalofop (Blackshaw et al. 2006; Underwood et al. 2016). Interactions among tank-mixes often are rate specific, with the antagonistic effects overcome with increased graminicide rate (Hatzios and Penner 1985). Current label restrictions for quizalofop use in broadleaf crops limit single applications to 92.5 g ai ha^{-1} (Anonymous 2003), with most quizalofop antagonism research evaluating rates ranging from 9 to 70 g ai ha^{-1} (Culpepper et al. 1999; Blackshaw et al. 2006; Minton et al. 1989a, Minton et al. 1989b; Underwood et al. 2016). In quizalofop-resistant rice, the herbicide can be applied at 100 to 138 g ha^{-1}, a higher use rate than in broadleaf crops

(Anonymous 2017). Enabling these higher use rates in quizalofop-resistant rice may overcome the potential for antagonism that has been observed at lower use rates.

Early results have proven quizalofop to be highly efficacious for grass weeds when used in the quizalofop-resistant rice system (Hale et al. 2016; Lancaster et al. 2016). However, due to quizalofop historically only being labeled in broadleaf crops, there is no research on the potential interactions with common rice herbicides. Determining the compatibility of quizalofop with herbicides used in rice is important to developing appropriate application recommendations for quizalofop-resistant rice. Thus, multiple experiments were conducted to determine the tank-mix interactions between quizalofop and rice herbicides having either broadleaf or grass activity.

Materials and Methods

Two greenhouse experiments were conducted in the fall of 2015 and the spring of 2016 to determine the tank-mix interactions of quizalofop with rice herbicides on grass weeds found in rice production systems. One experiment evaluated tank-mix interactions of quizalofop with rice herbicides having grass activity, while the other experiment evaluated quizalofop with broadleaf rice herbicides that have little or no efficacy on grasses.

Quizalofop Tank-Mix Interactions with Herbicides Having Grass Activity

The experiment was conducted as a two-factor factorial, randomized complete block design (RCBD), with factor-A being rate of quizalofop and factor-B being tank-mix partner. Quizalofop (Targa™ herbicide, Gowan Company, Yuma, AZ) was applied at either 0 or 80 g ai ha^{-1} alone or in tank-mixture with herbicides listed in Table 1. All treatments containing quizalofop, imazethapyr, or penoxsulam contained crop oil concentrate (COC) (Agri-Dex, Helena Chemical Company, West Helena, AR) at 1% v/v. Any treatments containing bispyribac

contained 2.5% v/v adjuvant and deposition aid (Dyne-A-Pak®, Helena Chemical Company, West Helena, AR). Herbicide treatments were evaluated for control of many of the important weedy grasses of Midsouth rice (Norsworthy et al. 2013), including propanil/quinclorac-resistant barnyardgrass, ALS-resistant barnyardgrass, broadleaf signalgrass, Amazon sprangletop (*Leptochloa panicoides* (J. Presl) A.S. Hitchc), ACCase-resistant Amazon sprangletop (Tehranchian et al. 2016), and red rice. Approximately 30 seeds were sown into a 8 by 14 by 5 cm tray containing a commercial potting mix (Professional Growing Mix, LC1 mix, Sun Gro Horticultural Distribution Inc., Bellevue, WA). Plants were grown in the greenhouse under conditions of 32/22C day/night temperatures with a 16-h photoperiod. Once grass seedlings emerged, plants were thinned to 15 plants tray^{-1}. Herbicide treatments were applied to all weed species at the 3- to 4-leaf growth stage. Herbicide applications were made in a stationary spray chamber calibrated to deliver 187 L ha^{-1} at 276 kPA with 800067 nozzles. After herbicide application, plants were returned to the greenhouse.

Visual estimates of control were evaluated at 14 and 21 days after treatment (DAT) on a scale of 0 to 100%, with a 0% representing no plant response and 100% representing complete plant death compared to a non-treated check. Aboveground biomass of plants were harvested immediately following the 21 DAT rating. Biomass samples were weighed after being oven-dried at 65 C for 14 days. Visual estimates of control and biomass were analyzed using JMP Pro 12.1 (SAS Institute Inc., Cary, NC) using Proc Mixed procedure. For data that met the assumptions for ANOVA, means were separated using Fisher's protected LSD test (α=0.05). Colby's equation was used to determine if tank-mix interactions were synergistic, additive, or antagonistic (Colby 1967). Expected values were calculated using the equation, $E = (X + Y) - (XY)/100$, where E is the expected value for the tank-mix with X and Y representing the

observed value for each tank-mix partner separately. The values calculated for the expected response of the tank-mix were compared to the observed response using a two-sided *t* test (α=0.05). Tank-mixtures were deemed antagonistic if observed value was significantly less than the expected, additive if there was no significant difference between observed and expected, and synergistic if the observed value was significantly higher than the expected value. Both visual control ratings and biomass were subjected to Colby's equation to determine tank-mix interaction. Little difference was observed between 14 and 21 DAT control ratings; thus, only 21 DAT ratings are presented. The experiment consisted of 4 replications and was conducted twice, with experimental runs considered a random effect.

Quizalofop Tank-Mix Interactions with Herbicides Having Broadleaf Activity

The experiment was conducted similarly to the previous experiment, with only differences being applied herbicides and weed biotypes evaluated. Quizalofop was applied at either 0, 80, or 160 g ai ha^{-1} alone or in tank-mixtures with herbicides listed in Table 2. Any treatments containing quizalofop, carfentrazone, saflufenacil, halosulfuron, halosufuron + thifensulfuron, or bentazon received COC at 1% v/v. Any treatments that received acifluorfen contained 0.25% v/v nonionic surfactant (Induce®, Helena Chemical Company, West Helena, AR). Herbicide treatments were evaluated on propanil/quinclorac-resistant barnyardgrass, broadleaf signalgrass, Amazon sprangletop, and red rice at the 3- to 4-leaf growth stage. Data collection and statistical analysis were similar to the previous experiment. Only 21 DAT control ratings are presented. The experiment was conducted twice, with experimental runs considered a random effect.

Results and Discussion

Quizalofop Tank-Mix Interactions with Herbicides Having Grass Activity

Overall, at 21 DAT, quizalofop alone was effective in controlling all grass weeds evaluated (>94%), except for ACCase-resistant Amazon sprangletop (70% control) (Tables 3-5). Quizalofop also reduced biomass at least 91% for all grass species evaluated other than ACCase-resistant Amazon sprangletop. Likewise, except for ACCase-resistant sprangletop, quizalofop was generally more efficacious on grass weeds compared to ALS- or other ACCase-inhibiting herbicides evaluated (P<0.0001). Although not completely effective, quizalofop alone provided a higher level of control of ACCase-resistant Amazon sprangletop than did fenoxaprop (20%) or cyhalofop (11%) (Table 5). This response to ACCase-inhibiting herbicides can be attributed to differing levels of resistance to the graminicides evaluated. Burgeois et al. (1997) reported that differing levels of herbicide efficacy was apparent for multiple ACCase-resistant wild oat (*Avena fatua* L.) populations, with resistance both across and within ACCase-inhibiting herbicide families. For ALS-resistant red rice, quizalofop provided 95% control whereas control with all non-quizalofop-containing treatments was ≤25% (Table 5).

Although highly effective, tank-mixing quizalofop with most herbicides having grass activity resulted in antagonism. Tank-mixing with ALS-inhibiting herbicides proved to be particularly antagonistic for quizalofop. Based on the control data, quizalofop tank-mixes with bispyribac were antagonistic for all grass species, with control declining 8 to 13 percentage points below calculated expected values across species (Tables 3-5). It should also be noted that quizalofop alone was often more efficacious than the mixture of quizalofop plus an ALS-inhibiting herbicide. For example, penoxsulam, an ALS-inhibiting herbicide, was antagonistic when tank-mixed with quizalofop for control of propanil/quinclorac-resistant barnyardgrass,

ACCase-resistant Amazon sprangletop, and broadleaf signalgrass. Similarly, imazethapyr was antagonistic for propanil/quinclorac-resistant barnyardgrass and Amazon sprangletop. These results are similar to previous research where antagonism resulted when tank-mixing ACCase-inhibiting and ALS-inhibiting herbicides (Hydrick et al. 2016; Meyers and Coble 1992; Zhang et al. 2005). Tank-mixtures with propanil were antagonistic for control of both barnyardgrass and Amazon sprangletop biotypes, as well as red rice, with reduction in control ranging from 7 to 13 percentage points below calculated expected values (Tables 3-5). Likewise, quinclorac tank-mixed with quizalofop resulted in antagonism for both Amazon sprangletop biotypes and red rice, with 10 to 17 percentage point reduction in control compared to the expected values (Tables 4-5). Generally, the residual herbicides (clomazone, pendimethalin, thiobencarb) did not antagonize quizalofop; however, thiobencarb addition to quizalofop did reduce red rice control (Table 5). When antagonism occurred based on visual estimates of control, a similar response was often observed for biomass reduction, except in a few instances.

Quizalofop Tank-Mix Interactions with Herbicides Having Broadleaf Activity

Similar to the previous experiment, there was a significant quizalofop rate by tank-mix partner interaction (P=<0.0001), with quizalofop alone at 80 and 160 g ha^{-1} at 21 DAT controlling all grass species evaluated >90% and >95%, respectively (Tables 6 and 7). As expected, all tank-mix partners resulted in minimal control of all grass species when applied alone. Antagonism with multiple tank-mix combinations with broadleaf herbicides were apparent with quizalofop. Although quizalofop + halosulfuron tank-mixtures were not deem antagonistic, this was not the case for the lowest rate of quizalofop when tank-mixed with halosulfuron + thifensulfuron for all grass species (Tables 6 and 7). Increasing the rate of quizalofop to 160 g ha^{-1} sometimes helped to overcome the antagonism with halosulfuron +

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thifensulfuron. Likewise, based on orthogonal contrasts, there was a significant difference between 80 and 160 g ha^{-1} of quizalofop for control and biomass reduction of all grass species evaluated (Table 8).

Similar to previous findings regarding the mixtures of ACCase herbicides with auxin herbicides (Blackshaw et al. 2006; Minton et al. 1989b; Underwood et al. 2016), tank-mixes with 2,4-D amine were especially antagonistic to quizalofop (Table 6,7). Most grass species had lower control when 2,4-D was added to quizalofop compared to quizalofop alone. The largest reduction in control was observed on red rice when 2,4-D was added to the quizalofop at 80 g ha^{-1}, resulting in 73% control compared to the 91% control from quizalofop alone (Table 7). These results are similar to research conducted by Abit et al. (2011) where antagonism of quizalofop was apparent in tank-mixes with 2,4-D amine for control of large crabgrass, giant foxtail (*Setaria faberi* Herrm.), and green foxtail (*Setaria viridis* (L) Beauv.). Unlike for other tank-mixtures, antagonism from 2,4-D amine was not overcome by increasing quizalofop rate to 160 g ha^{-1}.

Practical Implications

Quizalofop can be used to achieve effective control of many common grass weeds found in rice production; however, tank-mixing quizalofop with other herbicides can result in antagonism or reduced control over quizalofop alone. Caution should be taken when tank-mixing quizalofop with ALS-inhibiting herbicides, including imazethapyr, bispyribac, penoxsulam, and halosulfuron + thifensulfuron. Auxin herbicides can also be antagonistic when tank-mixed with quizalofop, especially 2,4-D, and to a lesser extent quinclorac. Likewise, tank-mixtures of quizalofop with propanil can antagonize quizalofop. For most tank-mixtures, increasing the rate of quizalofop is an option to overcome antagonism; however, this tactic

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would further limit the amount of herbicide available for a subsequent application because no more than 240 g ha^{-1} can be applied in a single growing season (Anonymous 2017).

There is concern that antagonism caused by inappropriate mixtures with quizalofop could reduce control to the point of allowing survival and seed production of escaped plants, especially barnyardgrass, which would in turn increase the risk for resistance evolving to this herbicide mode of action. For this reason, antagonism should be considered when developing proper stewardship guidelines for quizalofop use in quizalofop-resistant rice. It must be recognized that most growers limit trips across a field to save time and money, and that use of this technology may require some additional steps beyond that typically practiced in current weed control programs. Broadleaf weeds commonly occur in Midsouth rice fields and herbicides in addition to quizalofop must be integrated into these systems to provide a high level of control of a diverse weed spectrum. This research only investigated the risk for antagonism from a single application and it should be realized that most applications in quizalofop-resistant rice will involve sequential treatments of quizalofop for season-long grass control (McCown et al. 2016).

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Table 1. Tank-mix partners with grass activity applied alone and with quizalofop at 80 g ai ha^{-1}.

Herbicide treatments[ab]	Rate	Trade name	Manufacturer	Address
	g ai ha^{-1}			
Clomazone	313	Command 3E	FMC Corporation	Philadelphia, PA
Pendimethalin	1,060	Prowl H$_2$O	BASF Corporation	Research Triangle Park, NC
Thiobencarb	3,360	Bolero	Valent USA Corporation	Longwood, FL
Quinclorac	283[b]	Facet L	BASF Corporation	Research Triangle Park, NC
Propanil	2,240	Riceshot	RiceCo	Memphis, TN
Imazethapyr	70	Newpath	BASF Corporation	Research Triangle Park, NC
Bispyribac	28	Regiment	Valent USA Corporation	Longwood, FL
Penoxsulam	35	Grasp SC	Dow AgroSciences	Indianapolis, IN
Cyhalofop	313	Clincher	Dow AgroSciences	Indianapolis, IN
Fenoxaprop	122	Ricestar HT	Bayer CropScience	Research Triangle Park, NC

[a] Any treatments containing quizalofop, imazethapyr, or penoxsulam contained crop oil concentrate at 1% v/v. Any treatments containing bispyribac contained 2.5% v/v nonionic surfactant

[b] Quinclorac expressed as g ae ha^{-1}

Table 2. Tank-mix partners with broadleaf activity applied alone and with quizalofop at 80 or 160 g ai ha^{-1}.

Herbicide treatments[a,b]	Rate	Trade name	Manufacturer	Address
	g ai ha^{-1}			
Triclopyr	421	Grandstand R	Dow AgroSciences	Indianapolis, IN
Acifluorfen	561	Ultra Blazer	United Phosphorus Inc.	King of Prussia, PA
Carfentrazone	56	Aim EC	FMC Corporation	Philadelphia, PA
Carfentrazone	112	Aim EC	FMC Corporation	Philadelphia, PA
Saflufenacil	25	Sharpen	BASF Corporation	Research Triangle Park, NC
Halosulfuron	52.5	Permit	Gowan Company	Yuma, AZ
Halosulfuron+Thifensulfuron	35 + 3.15	Permit Plus	Gowan Company	Yuma, AZ
Bentazon	421	Basagran	Winfield Solutions LLC	St. Paul, MN
2,4-D Amine	1,590[b]	Weedar 64	Nufarm Inc.	Alsip, IL

[a] Any treatments containing quizalofop, carfentrazone, saflufenacil, halosulfuron, halosufuron + thifensulfuron, or bentazon contained crop oil concentrate at 1% v/v. Any treatments containing acifluorfen contained 0.25% v/v nonionic surfactant

[b] Triclopyr and 2,4-D expressed as g ae ha^{-1}

Table 3. Activity of quizalofop on propanil/quinclorac-resistant barnyardgrass and ALS-resistant banyardgrass control and relative biomass as affected by tank mixing with other herbicides having grass activity commonly used in rice at 21 days after treatment.[abc]

Treatment	Rate	Prop/Quin-resistant barnyardgrass[d]				ALS-resistant barnyardgrass			
		Control		Biomass reduction		Control		Biomass reduction	
		Observed	Expected	Observed	Expected	Observed	Expected	Observed	Expected
	g ai ha^{-1}	--%--							
Quizalofop	80	94 a		95 a		96 ab		92 a	
Clomazone	313	5 fg		2 f		9 i		3 fg	
Pendimethalin	1,060	3 gh		3 f		9 i		4 fg	
Thiobencarb	3,360	8 f		5 f		15 gh		6 ef	
Quinclorac	283^e	0 h		2 f		91 cde		93 a	
Propanil	2,240	0 h		2 f		0 j		0 g	
Imazethapyr	70	91 abc		94 ab		11 hi		9 e	
Bispyribac	28	90 bcd		93 ab		11 hi		8 e	
Penoxsulam	35	93 ab		92 abc		10 hi		13 d	
Cyhalofop	313	88 cde		84 de		88 ef		87 bc	
Fenoxaprop	122	90 bcd		91 abc		92 cd		91 ab	
Quizalofop + Clomazone	80 + 313	94 ab	95	92 abc	95	96 ab	96	93 a	93
Quizalofop + Pendimethalin	80 + 1,060	93 ab	94	93 abc	95	96 ab	96	93 a	93
Quizalofop + Thiobencarb	80 + 3,360	94 a	95	94 ab	95	**88 ef**	**96**	92 a	93
Quizalofop + Quinclorac	80 + 283^b	91 abc	94	90 abc	95	94 abc	100	93 a	100
Quizalofop + Propanil	80 + 2,240	**86 de**	**94**	**85 de**	**95**	**89 def**	**96**	87 c	93
Quizalofop + Imazethapyr	80 + 70	**88 cde**	**100**	**89 bc**	**100**	93 bcd	96	92 a	94
Quizalofop + Bispyribac	80 + 28	**84 e**	**100**	**82 e**	**100**	**85 f**	**96**	**84 c**	**94**
Quizalofop + Penoxsulam	80 + 35	**86 de**	**100**	**89 bc**	**100**	92 cd	96	92 a	94
Quizalofop + Cyhalofop	80 + 313	94 a	99	94 ab	100	98 a	100	92 a	99
Quizalofop + Fenoxaprop	80 + 122	94 a	99	95 a	100	98 a	100	94 a	100

[a] Means within a column followed by the same lowercase letter are not different.

[b] Values presented in bold represent an antagonistic interaction according to Colby's equation.

[c] Percent control and biomass reduction as compared to non-treated check.

[d] Prop = Propanil; Quin = Quinclorac

[e] Quinclorac expressed as g ae

Table 4. Activity of quizalofop on broadleaf signalgrass and Amazon sprangletop control and relative biomass as affected by tank mixing with other herbicides having grass activity commonly used in rice at 21 days after treatment.[abc]

Treatment[d]	Rate	Broadleaf signalgrass				Amazon sprangletop			
		Control		Biomass reduction		Control		Biomass reduction	
		Observed	Expected	Observed	Expected	Observed	Expected	Observed	Expected
	g ai ha⁻¹	--%--							
Quizalofop	80	97 a		94 ab		98 a		93 ab	
Clomazone	313	9 f		11 h		9 fg		8 d	
Pendimethalin	1,060	7 f		9 h		5 g		6 d	
Thiobencarb	3,360	10 f		11 h		11 f		9 d	
Quinclorac	283[b]	91 bcd		90 b-f		91 d		88 b	
Propanil	2,240	92 bcd		89 def		90 d		88 b	
Imazethapyr	70	82 abc		89 def		91 d		88 b	
Bispyribac	28	92 bcd		89 def		92 d		89 b	
Penoxsulam	35	80 e		79 g		78 e		76 c	
Cyhalofop	313	89 cd		86 f		93 bcd		91 ab	
Fenoxaprop	122	91 bcd		90 b-f		92 cd		90 ab	
Quizalofop + Clomazone	80 + 313	94 ab	97	92 a-d	94	94 a-d	96	91 ab	94
Quizalofop + Pendimethalin	80 + 1,060	96 a	97	94 ab	94	92 d	96	92 ab	94
Quizalofop + Thiobencarb	80 + 3,360	95 ab	97	93 a-d	94	89 d	96	91 ab	94
Quizalofop + Quinclorac	80 + 283[b]	94 ab	100	92 a-d	97	**89 d**	**100**	**89 b**	**98**
Quizalofop + Propanil	80 + 2,240	94 ab	100	91 a-e	97	**90 d**	**100**	**89 b**	**98**
Quizalofop + Imazethapyr	80 + 70	93 abc	100	91 a-e	97	**89 d**	**100**	**88 b**	**98**
Quizalofop + Bispyribac	80 + 28	**89 cd**	**100**	**89 c-f**	**97**	**90 d**	**100**	91 ab	98
Quizalofop + Penoxsulam	80 + 35	**88 d**	**99**	**87 g**	**97**	93 bcd	99	92 ab	98
Quizalofop + Cyhalofop	80 + 313	97 a	100	94 a-d	97	97 ab	100	94 a	98
Quizalofop + Fenoxaprop	80 + 122	98 a	100	95 a	97	98 a	100	92 ab	98

[a] Means within a column followed by the same lowercase letter are not different.
[b] Values presented in bold represent an antagonistic interaction according to Colby's equation.
[c] Percent control and biomass reduction as compared to non-treated check.
[d] Quinclorac expressed as g ae ha⁻¹

Table 5. Activity quizalofop on broadleaf signalgrass and Amazon sprangletop control and relative biomass as affected by tank mixing with other grass herbicides commonly used in rice at 21 days after treatment.[abc]

Treatment[d]	Rate	ACCase-resistant Amazon sprangletop				Red rice			
		Control		Biomass reduction		Control		Biomass reduction	
		Observed	Expected	Observed	Expected	Observed	Expected	Observed	Expected
	g ai ha^{-1}	--%--							
Quizalofop	80	70 fg		71 e		95 abc		93 a	
Clomazone	313	7 ij		6 g		7 i		9 d	
Pendimethalin	1,060	7 j		7 g		7 i		6 def	
Thiobencarb	3,360	11 ij		8 g		8 i		7 de	
Quinclorac	283[b]	90 ab		88 ab		5 i		5 ef	
Propanil	2,240	87 bc		86 abc		0 j		3 f	
Imazethapyr	70	93 a		91 a		25 g		19 c	
Bispyribac	2.8	93 a		90 a		8 i		10 d	
Penoxsulam	35	86 bcd		86 abc		12 h		8 de	
Cyhalofop	313	11 ij		11 fg		4 i		4 ef	
Fenoxaprop	122	20 h		18 f		6 i		4 ef	
Quizalofop + Clomazone	80 + 313	73 f	73	70 e	73	94 bc	95	91 a	94
Quizalofop + Pendimethalin	80 + 1,060	71 fg	73	74 de	73	92 cd	95	91 a	93
Quizalofop + Thiobencarb	80 + 3,360	69 g	74	72 de	73	90 de	95	92 a	94
Quizalofop + Quinclorac	80 + 283[b]	**80 e**	**97**	**79 cd**	**96**	**85 f**	**95**	**85 b**	**93**
Quizalofop + Propanil	80 + 2,240	**83 de**	**96**	**79 cd**	**96**	**87 ef**	**95**	**84 b**	**93**
Quizalofop + Imazethapyr	80 + 70	91 ab	98	91 a	97	92 cd	95	92 a	94
Quizalofop + Bispyribac	80 + 2.8	**83 de**	**98**	**82 bc**	**97**	**84 f**	**95**	**82 b**	**94**
Quizalofop + Penoxsulam	80 + 35	**83 de**	**96**	**82 bc**	**96**	92 cd	95	91 a	93
Quizalofop + Cyhalofop	80 + 313	69 g	74	71 e	74	97 a	95	92 a	93
Quizalofop + Fenoxaprop	80 + 122	74 f	77	70 e	76	97 a	95	93 a	93

[a] Means within a column followed by the same lowercase letter are not different.
[b] Values presented in bold represent an antagonistic interaction according to Colby's equation.
[c] Percent control and biomass reduction as compared to non-treated check.
[d] Quinclorac expressed as g ae ha^{-1}

Table 6. Activity of 80 or 160 g ai ha^{-1} of quizalofop on barnyardgrass and broadleaf signalgrass control and biomass reduction as affected by tank mixing with broadleaf grass herbicides commonly used in rice at 21 days after treatment.[abc]

Treatment[d]	Rate	Barnyardgrass				Broadleaf signalgrass			
		Control		Biomass reduction		Control		Biomass reduction	
		Observed	Expected	Observed	Expected	Observed	Expected	Observed	Expected
	g ai ha^{-1}	---%---							
Quizalofop	80	94 ab		91 ab		95 ab		91 ab	
Quizalofop	160	98 a		93 ab		99 a		94 a	
Triclopyr	420	0 f		0 g		0 g		2 h	
Acifluorfen	560	0 f		-1 g		0 g		1 h	
Carfentrazone	56	12 f		5 fg		14 ef		10 fg	
Carfentrazone	112	14 e		7 fg		16 e		12 f	
Salfufenacil	25	27 d		9 f		22 d		18 e	
Halosulfuron	52.5	0 f		1 g		0 g		0 h	
Halosulfuron + Thifensulfuron	35 + 3.15	0 f		0 g		0 g		2 gh	
Bentazon	420	0 f		1 g		0 g		0 h	
2,4-D Amine	1,590[d]	0 f		2 g		0 g		0 h	
Quizalofop + Triclopyr	80 + 420	93 ab	94	90 ab	91	94 ab	95	92 ab	91
Quizalofop + Triclopyr	160 + 420	96 ab	98	92 ab	93	98 a	99	95 a	94
Quizalofop + Acifluorfen	80 + 560	93 ab	94	92 ab	91	93 b	95	93 ab	91
Quizalofop + Acifluorfen	160 + 560	97 a	98	94 a	93	99 a	99	96 a	94
Quizalofop + Carfentrazone	80 + 56	94 ab	94	93 ab	92	95 ab	96	92 ab	92
Quizalofop + Carfentrazone	160 + 56	99 a	99	94 a	94	98 a	100	94 a	95
Quizalofop + Carfentrazone	80 + 112	92 ab	94	92 ab	92	95 ab	96	91 ab	92
Quizalofop + Carfentrazone	160 + 112	96 ab	99	96 a	94	99 a	100	95 a	95
Quizalofop + Salfufenacil	80 + 25	92 ab	94	91 ab	92	94 ab	96	92 ab	93
Quizalofop + Salfufenacil	160 + 25	97 a	99	95 a	94	98 a	100	96 a	96
Quizalofop + Halosulfuron	80 + 52.5	94 ab	94	93 ab	91	96 ab	96	91 ab	91
Quizalofop + Halosulfuron	160 + 52.5	99 a	98	96 a	93	99 a	100	96 ab	94
Quizalofop + Halosulfuron + Thifensulfuron	80 + 35 + 3.15	**87 b**	**94**	88 b	91	**88 bc**	**95**	87 bc	91
Quizalofop + Halosulfuron + Thifensulfuron	160 + 35 + 3.15	95 ab	98	95 a	93	96 ab	99	93 ab	94

Table 6. (Cont.) Activity of 80 or 160 g ai ha^{-1} of quizalofop on barnyardgrass and broadleaf signalgrass control and biomass reduction as affected by tank mixing with broadleaf grass herbicides commonly used in rice at 21 days after treatment.

Quizalofop + Bentazon	80 + 420	92 ab	94	93 ab	91	94 ab	95	92 ab	91
Quizalofop + Bentazon	160 + 420	97 a	98	97 a	93	97 a	99	95 a	94
Quizalofop + 2,4-D Amine	80 + 1,590	**82 c**	**94**	**78 e**	**91**	**87 c**	**95**	**81 cd**	**91**
Quizalofop + 2,4-D Amine	160 + 1,590	**88 bc**	**98**	**86 bc**	**93**	**90 bc**	**99**	**87 bc**	**94**

[a] Means within a column followed by the same lowercase letter are not different.

[b] Values presented in bold represent an antagonistic interaction according to Colby's equation.

[c] Percent control and biomass reduction as compared to non-treated check.

[d] Triclopyr and 2,4-D amine expressed as g ae ha^{-1}

Table 7. Activity of 80 of 160 g ai ha^{-1} of quizalofop on Amazon sprangletop and red rice control and biomass reduction as affected by tank mixing with other broadleaf herbicides commonly used in rice at 21 days after treatment.[abc]

Treatment[d]	Rate	Amazon sprangletop				Red rice			
		% Control		% Biomass reduction		% Control		% Biomass reduction	
		Observed	Expected	Observed	Expected	Observed	Expected	Observed	Expected
	g ai ha^{-1}	--%--							
Quizalofop	80	93 ab		90 ab		91 b		90 ab	
Quizalofop	160	97 a		94 a		96 a		93 a	
Triclopyr	420	0 f		1 f		0 h		3 f	
Acifluorfen	560	0 f		3 f		2 h		4 f	
Carfentrazone	56	7 e		6 ef		7 gh		5 f	
Carfentrazone	112	12 de		10 e		12 fg		5 f	
Salfufenacil	25	19 d		20 d		18 f		12 e	
Halosulfuron	52.5	0 f		0 f		0 h		1 fg	
Halosulfuron + Thifensulfuron	35 + 3.15	0 f		1 f		0 h		0 fg	
Bentazon	420	0 f		3 f		0 h		3 f	
2,4-D Amine	1,590	0 f		2 f		3 h		2 fg	
Quizalofop + Triclopyr	80 + 420	92 ab	93	89 ab	90	90 bc	91	89 ab	90
Quizalofop + Triclopyr	80 + 420	94 ab	97	93 a	94	94 ab	96	92 ab	93
Quizalofop + Acifluorfen	80 + 560	91 b	93	91 ab	90	91 ab	91	91 ab	90
Quizalofop + Acifluorfen	160 + 560	95 ab	97	93 a	94	95 a	96	94 a	93
Quizalofop + Carfentrazone	80 + 56	93 ab	93	90 ab	90	89 bc	91	90 ab	91
Quizalofop + Carfentrazone	160 + 56	96 a	97	95 a	94	96 a	96	92 ab	94
Quizalofop + Carfentrazone	80 + 112	94 ab	94	91 a	91	92 ab	92	88 b	91
Quizalofop + Carfentrazone	160 + 112	96 a	98	94 a	95	96 a	97	92 ab	94
Quizalofop + Salfufenacil	80 + 25	94 ab	94	89 ab	91	92 ab	92	89 ab	91
Quizalofop + Salfufenacil	160 + 25	97 a	98	93 a	95	95 a	97	93 a	94
Quizalofop + Halosulfuron	80 + 52.5	93 ab	93	88 b	90	90 bc	91	89 ab	90
Quizalofop + Halosulfuron	160 + 52.5	96 a	97	93 a	94	96 a	96	94 a	93
Quizalofop + Halosulfuron + Thifensulfuron	80 + 35 + 3.15	**87 bc**	**93**	**83 bc**	**90**	**86 c**	**91**	**84 bc**	**90**
Quizalofop + Halosulfuron + Thifensulfuron	160 + 35 + 3.15	95 ab	97	89 ab	94	91 b	96	**88 b**	**93**

Table 7. (Cont.) Activity of 80 of 160 g ai ha^{-1} of quizalofop on Amazon sprangletop and red rice control and biomass reduction as affected by tank mixing with other broadleaf herbicides commonly used in rice at 21 days after treatment.

Quizalofop + Bentazon	80 + 420	90 bc	93	88 b	90	89 bc	91	90 ab	90
Quizalofop + Bentazon	160 + 420	96 a	97	92 ab	94	94 a	96	93 a	93
Quizalofop + 2,4-D Amine	80 + 1,590	**84 c**	**93**	**79 c**	**90**	**73 de**	**91**	**75 d**	**90**
Quizalofop + 2,4-D Amine	160 + 1,590	**88 bc**	**97**	**83 bc**	**94**	**83 cd**	**96**	**81 cd**	**93**

[a] Means within a column followed by the same lowercase letter are not different.

[b] Values presented in bold represent an antagonistic interaction according to Colby's equation.

[c] Percent control and biomass reduction as compared to non-treated check.

[d] Triclopyr and 2,4-D amine expressed as g ae ha^{-1}

Table 8. Contrasts between 80 and 160 g ai ha^{-1} of quizalofop in tank-mixes with broadleaf herbicides on control and biomass reduction of barnyardgrass, broadleaf signalgrass, Amazon sprangletop, and red rice at 21 DAT.[a]

	80 versus 160 g ha^{-1}
Barnyardgrass control	<0.0001
Barnyardgrass biomass reduction	0.0023
Broadleaf signalgrass control	<0.0001
Broadleaf signalgrass biomass reduction	0.0013
Amazon sprangletop control	<0.0001
Amazon sprangletop biomass reduction	<0.0001
Red rice control	<0.0001
Red rice biomass reduction	0.0132

[a] DAT = days after treatment

General Conclusions

With proper utilization, quizalofop-resistant rice can be an effective tool to control problematic grass weeds in rice. As demonstrated, risk of off-target movement of quizalofop to sensitive grass crops is minimal, with low levels of injury occurring only at quizalofop rates not typical to drift events in field situations. Overall, residual activity of quizalofop and other ACCase-inhibiting herbicides is low, with no commercial residual activity for grass weed control. However, some carry-over injury can occur if subsequent sensitive crops are planted soon after application and environmental conditions are conducive for injury. In the field, quizalofop-resistant rice was effective for controlling barnyardgrass, broadleaf signalgrass, and red rice. Best results were achieved when the full seasonal quizalofop use rate of 240 g ai ha^{-1} was applied, especially when applied as sequential applications of 120 g ha^{-1}. Comparisons of quizalofop and other ACCase-inhibiting herbicides in the field were not definitive; however, a greenhouse study found that quizalofop was more efficacious on common grass weeds compared to cyhalofop or fenoxaprop, especially at larger grass growth stages. All barnyardgrass accessions treated with to 80 g ha^{-1} of quizalofop were effectively controlled. Tank-mixing quizalofop with other herbicides can result in antagonism for grass weed control. This is especially true with ALS-inhibiting herbicides and auxinic herbicides. However, the use of broadleaf herbicides will be essential in quizalofop-resistant rice due to quizalofop having no activity on broadleaf weeds.