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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

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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).

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 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.

## Literature Cited


Abit MJ (1994) Grain sorghum response to postemergence applications of mesotrione and quizalofop. Ph. D dissertation. Manhattan, KS: Kansas State University Manhattan. 62-68 p

Anonymous (2017) Command® herbicide product label. FMC Corporation Publication No. 07-25-15. Philadelphia, PA. FMC Corporation. 19 p

Bagavathiannan MV, Norsworthy JK, Smith KL, Scott RC, Burgos NR (2010) Seedbank, germination, and reproductive ecology of barnyardgrass in rice production systems. *in*: RJ Norman and KAK Moldenhauer (eds). B.R. Wells Arkansas Rice Research Studies 2009. University of Arkansas Agricultural Experiment Station Research Series. Fayetteville, AR. 591:117-127

Bagavathiannan MV, Norsworthy JK, Smith KL, Neve P (2014) Modeling the simultaneous evolution of resistance to ALS- and ACCase-inhibiting herbicides in barnyardgrass (*Echinochloa crus-galli*) in Clearfield® rice. Weed Technol 28:89-103

Baltazar AM, Smith KL (1994) Propanil-resistant barnyardgrass (*Echinochloa crus-galli*) control in rice. Weed Technol 8:576-581

Barrett SC (1983) Crop mimicry in weeds. Economic Botany 37:255-282

Burgos NR, Norsworthy JK, Scott RC, Smith KL (2008) Red rice (*Oryza sativa*) status after 5 years of imidazolinone-resistant rice technology in Arkansas. Weed Technol 22:200-208

Carey VF, Hoagland RE, Talbert RE (1995) Verification and distribution of propanil-resistant barnyardgrass (Echinochloa crus-galli) in Arkansas. Weed Technol 9:366-372

Croughan TP (1994) Application of tissue culture techniques to the development of herbicide resistant rice. Lousiana Agriculture 3:25-26

Dilpreet SR, Norsworthy JK, Bond JA, Bararpour MT, Wilson MJ, Scott RC (2012) Resistance of *Echinochloa crus-galli* populations to acetolactate synthase-inhibiting herbicides. Int J Agron 10.1155/2012/893953

Duke SO (2011) Why have no new herbicide modes of action appeared in recent years? Pest Manag Sci 68:505-512

Eleftherohorinos IG, Dhima KV (2002) Red rice (*Oryza sativa*) control in rice (*O. sativa*) with preemergence and postemergence herbicides. Weed Technol 16:537-540

Estorninos LE, Gealy DR, Gbur EE, Talbert RE, McClelland MR (2005) Rice and red rice interference. II. Rice response to population densities of three red rice (*Oryza sativa*) ecotypes. Weed Sci 53:683-689

Gealy DR, Burgos NR, Yeater KM, Jackson AK (2015) Outcrossing potential between U.S. blackhull red rice and *indica* rice cultivars. Weed Sci 63:647-657

Hardke JT (2012) Arkansas Rice Production Handbook. Arkansas Cooperative Extension Service Miscellaneous Publications 192. Little Rock, AR: University of Arkansas

Hardke JT, Wilson CE (2012) Trends in Arkansas rice production. *in*: RJ Norman and KAK Moldenhauer (eds). B.R. Wells Arkansas Rice Research Studies 2011. University of Arkansas Agricultural Experiment Station Research Series. Fayetteville, AR 591:38-47

Holm LG, Pancho JV, Herberger JP, Plucknett DL (1977). The World's Worst Weeds. Honolulu, HI: University Press of Hawaii

Lovelace M (2003) Implications of quinclorac use in Arkansas: Impacts of quinclorac drift on tomato physiology and development of quinclorac resistance in barnyardgrass. Ph.D dissertation. Fayetteville, AR: Univerisity of Arkansas. p 23

Mitich LW (1990) Barnyardgrass. Weed Technol 4:918-923

[NASS] National Agricultural Statistics Service (2016) Arkansas acreage report 2016. https://www.nass.usda.gov/Statistics_by_State/Arkansas/Publications/Crop_Releases/Acreage/2016/aracreage16.pdf. Accessed: January 14, 2017

Noldin JA, Chandler JM, McCauley GN, Sij JW (1998) Red rice (*Oryza sativa*) and *Echinochloa spp*. Control in Texas gulf coast soybean (*Glycine max*). Weed Technol 12:677-683

Norsworthy JK, Scott RC, Smith KL (2007) Confirmation and management of clomozone-resistant barnyardgrass. *In*: RJ Norman and KAK Moldenhauer (eds). *in*: RJ Norman and KAK Moldenhauer (eds). B.R. Wells Arkansas Rice Research Studies 2015. University of Arkansas Agricultural Experiment Station Research Series. Fayetteville, AR 560:113-116

Norsworthy JK, Scott RC, Bangarwa S, Griffith G, Wilson MJ, Still J (2008) Control of clomozone-resistant barnyardgrass in rice with preemergence herbicides. *in*: RJ Norman and KAK Moldenhauer (eds). B.R. Wells Arkansas Rice Research Studies 2015. University of Arkansas Agricultural Experiment Station Research Series. Fayetteville, AR 571:190-193

Norsworthy JK, Scott RC, Johnson DB (2012) A six-year summary of the herbicide-resistance weed screening program in rice at the University of Arkansas: 2006-2012. *in*: RJ Norman and KAK Moldenhauer (eds). B.R. Wells Arkansas Rice Research Studies 2015. University of Arkansas Agricultural Experiment Station Research Series. Fayetteville, AR 609:153-158

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the risks of herbicides resistance: best management practices and recommendations. Weed Sci 60 (Sp Issue I):31-62

Norsworthy JK, Bond J, Scott RC (2013) Weed management practices and needs in Arkansas and Mississippi rice. Weed Technol 27:623-630

Odero DC, Rainbolt C (2005) Weed management in rice. Florida Cooperative Extension Service SS-AGR-10. Gainesville, FL: University of Florida

Ottis BV, Smith KL, Scott RC, Talbert RE (2005) Rice (*Oryza sativa* L.) yield and quality as affected by cultivar and red rice (*Oryza sativa* L.) density. Weed Sci. 53:499–504

Pantone DJ, Baker JB (1991) Reciprocal yield analysis of red rice (Oryza sativa) competition in cultivated rice. Weed Sci. 39:42–47.

Rahn EM, Sweet RD, Vengris J, Dunn S (1968) Life history studies as related to weed control in the northeast – barnyardgrass. Northeast Regional Weed Control Technical Committee. Bulletin 368

Shivrain VK, Burgos NR, Gealy DR, Sales MA, Smith KL (2009) Gene flow from weed red rice (*Oryza sativa* L.) to cultivated rice and fitness of hybrids. Pest Manag Sci 65:1124-1129

Smith RJ, Fox WT (1973) Soil water and growth of rice and weeds. Weed Sci 21:61-63

Smith RJ (1965) Propanil and mixtures with propanil for weed control in rice. Weed Sci 13:236-238

Smith RJ (1981) Control of red rice (*Oryza sativa*) in water-seeded rice (*O. sativa*). Weed Sci. 29:663–666

Smith RJ (1988) Weed thresholds in southern U.S. rice, *Oryza sativa*. Weed Technol 2:232-241

Talbert RE, Burgos NR (2007) History and management of herbicide-resistant barnyardgrass (*Echinochloa crus-galli*) in Arkansas rice. Weed Technol 21:324-331

Wilson MJ, Norsworthy JK, Johnson DB, McCallister EK, Devore JD, Griffith GM, Bangarwa SK, Scott RC, Smith KL (2009) Herbicide programs for controlling ALS-resistant barnyardgass in Arkansas rice. *in*: RJ Norman and KAK Moldenhauer (eds). B.R. Wells Arkansas Rice Research Studies 2007. University of Arkansas Agricultural Experiment Station Research Series. Fayetteville, AR 581:153-155

# 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.

## 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, 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.

## Results and Discussion

### 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 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.

## Literature Cited


Anonymous (2017) Provisia™ herbicide product label. BASF Corporation Publication No. NVA 2017-04-522-0004. Research Triangle Park, NC. BASF Corporation. 12 p

Ahrens WH, ed (1994) Herbicide Handbook. 7th edition. Champaign, IL: Weed Science Society of America. Pp 260-262

Al-Khatib K, Claassen MM, Stahlman PW, Geier PW, Regehr DL, Duncan SR, Heer WF (2003) Grain sorghum response to simulated drift from glufosinate, glyphosate, imazethapry, and sethoxydim. Weed Sci 17:261-265

Carey VF, Hoagland RE, Talbert RE (1995) Verification and distribution of propanil-resistant barnyardgrass (*Echinochloa crus-ga*lli) in Arkansas. Weed Technol 9:366-372

Guice J, Youman C, Rhodes A, Schultz J, Bowe S, Armel A, Harden J (2015) Provisia™ rice system; weed management strategies for rice. Page 197 *in* Proceedings of Souther Weed Science Society the annual meeting. Savanna, GA: Southern Weed Science Society

Hanks JE (1995) Effect of drift retardant adjuvants on spray droplet size of water and paraffinic oil applied at ultralow volume. Weed Technol 9:380–384

Konishi T, Sasaki Y (1994) Compartmentalization of two forms of acetyl-CoA carboxylase in plants and the origin of their tolerance toward herbicides. Proc Natl Acad Sci 91:3598-3601

Noldin JA, Chandler JM, McCauley GN, Sij JW (1998) Red rice (*Oryza sativa*) and *Echinochloa spp*. control in Texas gulf coast soybean (*Glycine max*). Weed Technol 12:677-683

Norswothy JK, Bond J, Scott RC (2013) Weed management practices and needs in Arkansas and Mississippi rice. Weed Technol 27:623-630

Rankins A, Shaw DR, Douglas J (2005) Response of perennial grasses potentially used as filter strips to selective postemergence herbicides. Weed Technol 19:73-77

Salzman FP, Smith RJ, Talbert RE (1988) Suppression of red rice (*Oryza sativa*) seed production with fluazifop and quizalofop. Weed Sci 36:800-803

Smith RJ (1988) Weed thresholds in southern U.S. rice, *Oryza sativa*. Weed Technol 2:232-241

Talbert RE, Burgos NR (2007) History and management of herbicide-resistant barnyardgrass (*Echinochloa crus-galli*) in Arkansas rice. Weed Technol 21:324-331

Wall, DA (1994) Potato (*Solanum tuberosum*) response to simulated drift of dicamba, clopyralid, and tribenuron. Weed Sci 42:110–114

[USDA-NASS] United States Department of Agriculture-National Agricultural Statistics Service (2010) Field Crops – Usual Planting and Harvest Dates. Agricultural Handbook Number 628

Wauchope RD, Richard EP, Hurst HR (1982) Effects of simulated MSMA drift on rice (*Oryza sativa*). II. Arsenic residues in foliage and grain and relationships between arsenic residues, rice toxicity symptoms, and yields. Weed Sci 30:405-410

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 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 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 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.

## Literature Cited

Anonymous (2003A) Targa® herbicide product label. Gowan Company Publication No. 03-R0415. Yuma, AZ. Gowan Company. 16 p

Anonymous (2003B) Ricestar® HT herbicide product label. Bayer CropScience Publication No. 264-682. Research Triangle Park, NC. Bayer CropScience. 5 p

Anonymous (2009) Poast Plus® herbicide product label. BASF Corporation Publication No. NVA 2008-04-026-0356. Research Triangle Park, NC. BASF Corporation. 15 p

Anonymous (2015A) Select Max® herbicide product label. Valent U.S.A. Corporation Publication No. 2015-SMAX-0001. Walnut Creek, CA. Valent U.S.A. Corporation. 45 p

Anonymous (2015B) Fusilade® DX herbicide product label. Syngenta Crop Protection Publication No. SCP 1070A-L1G 0815. Greensboro, NC. Syngenta Crop Protection, LLC. 39 p

Anonymous (2015C) Ricestar® HT safety data sheet. SDS No. 102000008377. Research Triangle Park, NC. Bayer CropScience. 13 p

Anonymous (2016) Clincher® herbicide product label. Dow AgroSciences Publication No. D02-161-008. Indianapolis, IN. Dow AgroSciences LLC. 5 p

Anonymous (2017) Provisia™ herbicide product label. BASF Corporation Publication No. NVA 2017-04-522-0004. Research Triangle Park, NC. BASF Corporation. 12 p

Barber LT, Norsworthy JK, Scott RC (2015) Row crop plant-back intervals for common herbicides. University of Arkansas Division of Agriculture. MP519

[EPA] United States Environmental Protection Agency (1996) Time-limited extensions on tolerance for residues of sethoxydim in/on asparagus, cranberries, endive, carrots, and mint. Washington, DC. EPA series 361. 26 p

[FAO] Food and Agriculture Organization of the United Nations (1999) Pesticide residues in food – 1999. Rome, Italy. World Health Organization, p 126

Friesen HA (1965) The movement and persistence of dicamba in the soil. Weeds 13:30-33

Heap, I. The International Survey of Herbicide Resistant Weeds. Available www.weedscience.org. Accessed February 26, 2017

Heatherly LG, Hodges HF (1998) Soybean production in the Midsouth. 1st edition. Boca Raton, Florida. CRC Press. 180 p

Kamrin AK, Montgomery JH (2000) Agrochemical and Pesticide Desk Reference. Boca Raton, FL. CRC Press. 349 p

Knake EL, Appleby AP, Furtick WR (1967) Soil incorporation and site of uptake of preemergence herbicides. Weeds 15:228-232

Konishi T, Sasaki Y (1994) Compartmentalization of two forms of acetyl-CoA carboxylase in plants and the origin of their tolerance toward herbicides. Proc Natl Acad Sci 91:3598-3601

Mahoney KJ, Shropshire C, Sikkema PH (2016) Examining the plant-back interval for glyphosate/glufosinate-resistant corn after the application of ACCase inhibitors. Can J Plant Sci 96:6-10

Martens J (2014) Registration of the major change in labeling for the product Fusilade DX herbicide (EPA Reg. No. 100-1070) containing the active ingredient fluazifop-p-butyl (chemical code 122809). New York State Department of Environmental Conservation. Albany, New York. 25 p

Mueller TC, Barnett KA, Brosnan JT, Steckel LE (2011) Glyphosate-resistant goosegrass (*Eleusine indica*) confirmed in Tennessee. Weed Sci 59:562-566

[NASS] National Agricultural Statistics Service (2016) Arkansas acreage report 2016. https://www.nass.usda.gov/Statistics_by_State/Arkansas/Publications/Crop_Releases/Acreage/2016/aracreage16.pdf. Accessed: January 14, 2017

Norsworthy JK, Bond J, Scott RC (2013) Weed management practices and needs in Arkansas and Mississippi rice. Weed Technol 27:623-630

Ogle RE, Warren GF (1954) Fate and activity of herbicides in the soil. Weeds 3:255-258

Parker LW, Doxtader KG (1983) Kinetics of the microbial degradation of 2,4-D in soil: Effects of temperature and moisture. J Environ Qual 12:553-558

Riar DS, Norsworthy JK, Bararpour MT, Bell HD, Schrage BW (2012) Activation and length of residual herbicides under furrow and sprinkler irrigation. Pages 108-113 *in* DM Oosterhuis, ed. Summaries of Arkansas Cotton Research 2011. Arkansas Agricultural Experiment Station Research Series 602:108-113

Ruiz-Santaella JP, Heredia A, Prado RD (2006) Basis of selectivity of cyhalofop-butyl in *Oryza sative L.* Planta 223:191-199

Shaner DL, ed (2014) Herbicide Handbook. 10th Edition. Lawrence, KS: Weed Science Society of America. Pp 11, 401-402

Sondhia S, Khare RR (2014) Soil adsorption studies of a rice herbicide, cyhalofop-butyl, in two texturally different soils of India. Environ Monit Assess 186:5969-5976

Spader V, Lopes EC, dos Santos EG, Mendonca CG, Pelissari A (2012) Residual activity of ACCase inhibitor herbicides applied at pre-sowing of corn crop. Rev Bras Herb 11:42-48

Splittsoesser WE, Derscheid LA (1962) Effect of environment upon herbicides applied preemergence. Weeds 10:304-307

Smith HC, Ferrel JA, Webster TM, Fernandez JV, Dittmar PJ, Munoz PR, MacDonald GE (2016) Impact of irrigation volume of PRE herbicide activity. Weed Technol 30:793-800

Steckel LE, Bond JA, Montgomery GB, Phillips TL, Nandula V (2017) Glyphosate-resistant barnyardgrass in Tennessee and Mississippi. In press *in* Proceedings of the Southern Weed Science Society annual conference. Birmingham, AL: Southern Weed Science Society

Talbert RE, Burgos NR (2007) History and management of herbicide-resistant barnyardgrass (*Echinochloa crus-galli*) in Arkansas rice. Weed Technol 21:324-331

Wauchope RD, Yeh S, Linders J, Kloskowski R, Tanaka K, Rubin K, Katayama A, Kordel W, Gerstl Z, Lane M, Unsworth JB (2002) Pesticide soil sorption parameters: theory, measurement, uses, limitations, and reliability. Pest Manag Sci 58:419-445

Youman C, Guice J, Rhodes A, Schultz A, Harden J (2016) Provisia™ rice production system efficacy and stewardship. Page 278 *in* Proceedings of the Southern Weed Science Society annual conference. San Juan, PR: Southern Weed Science Society

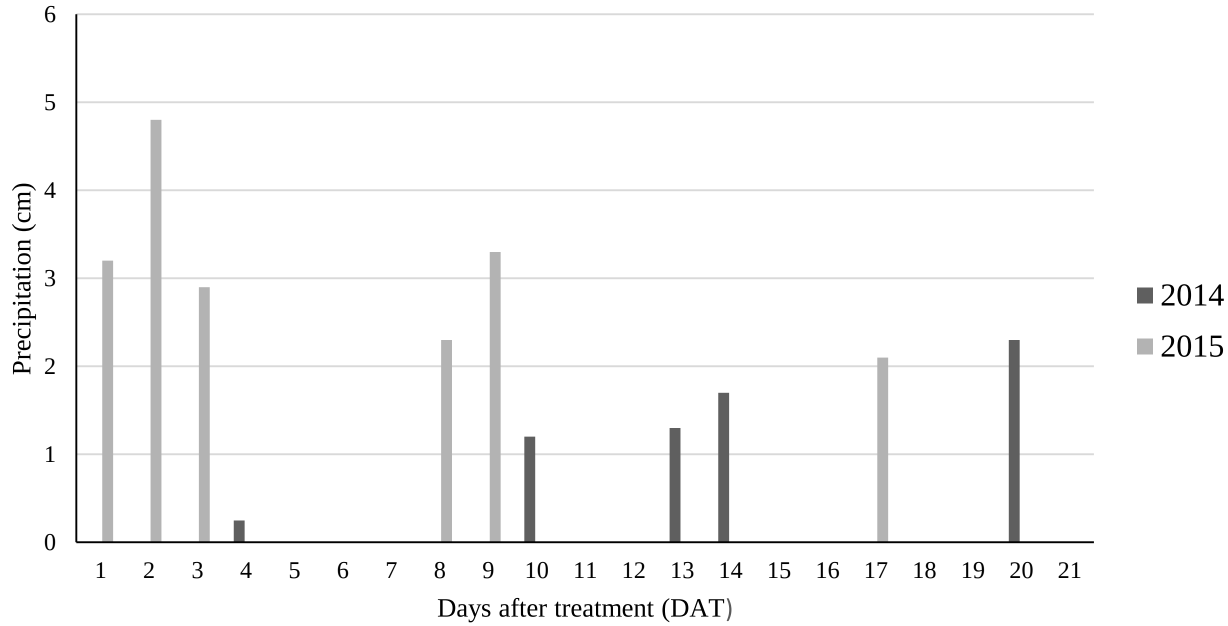


Figure 1. Precipitation history for 21 days after herbicide treatment for Fayetteville, Arkansas in 2014 and 2015. Experiment was initiated on June 13, 2014 and June 18, 2015.

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 | | | | | |
|---|---|---|---|---|---|---|
| | Plant density 14 DAP[a] | | Injury 14 DAP | | Biomass 35 DAP | |
| Response variable | 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 | | | | | |
|---|---|---|---|---|---|---|
| | Plant density 14 DAP[a] | | Injury 14 DAP | | Biomass 35 DAP | |
| Response variable | 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.

| | P-value | | | | | |
|---|---|---|---|---|---|---|
| | Plant density 14 DAP[a] | | Injury 14 DAP | | Biomass 35 DAP | |
| Response variable | 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 | | | | | |
|---|---|---|---|---|---|---|
| | Plant density 14 DAP[a] | | Injury 14 DAP | | Biomass 35 DAP | |
| Response variable | 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.

| | P-value | | | | | |
|---|---|---|---|---|---|---|
| | Control 14 DAT[b] | | Control 35 DAT | | Biomass 35 DAT | |
| Response variable | 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]

| | | | Grain sorghum | | Corn | | Conventional rice | |
|---|---|---|---|---|---|---|---|---|
| Activation | Herbicide | Rate | Injury[bcd] | Biomass[e] | Injury | Biomass | Injury[e] | 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.

| | | Grain sorghum | | | | Corn | | | | Conventional rice | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Herbicide[a] | Rate | Injury[bc] | | Biomass[bd] | | Injury[bc] | | Biomass[bd] | | 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 (≥ 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.

Quizalofop (Targa™ 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 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 ($\alpha$=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 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 ($\alpha$=0.05) and preplanned contrasts were conducted for select treatments to compare between total yearly amounts of quizalofop applied ($\alpha$=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.

## Literature Cited

Anonymous (2017) Provisia™ herbicide product label. BASF Corporation Publication No. NVA 2017-04-522-0004. Research Triangle Park, NC. BASF Corporation. 12 p

Baldwin FL, Huey BA, Morris GL (1977) Distribution of three weed species in Arkansas rice fields. Proc South Weed Sci Soc 30:398

Blackshaw RE, Harker KN, Clayton GW, O'Donovan JT (2006) Broadleaf herbicide effects on clethodim and quizalofop-p efficacy on volunteer wheat (*Triticum aestivum*). Weed Technol 20:221-226

Burgos NR, Norsworthy JK, Scott RC, Smith KL (2008) Red rice (*Oryza sativa*) status after 5 years of imidazolinone-resistant rice technology in Arkansas. Weed Technol 22:200-208

Carey VF, Hoagland RE, Talbert RE (1995) Verification and distribution of propanil-resistant barnyardgrass (*Echinochloa crus-galli*) in Arkansas. Weed Technol 9:366-372

Deen W, Hamill A, Shropshire C, Soltani N, Sikkema PH (2006) Control of volunteer glyphosate-resistant corn (*Zea mays*) in glyphosate-resistant soybean (*Glycine max*). Weed Technol 20:261-266

Duke SO (2011) Why have no new herbicide modes of action appeared in recent years? Pest Manag Sci 68:505-512

Gealy DH, Agrama H, Jia MH (2012) Genetic analysis of atypical U.S. red rice phenotypes: indications of prior gene flow in rice fields? Weed Sci 60:451-461

Guice J, Youman C, Rhodes A, Schultz J, Bowe S, Armel A, Harden J (2015) Provisia™ rice system; weed management strategies for rice. Page 197 in Proceedings of Souther Weed Science Society the annual meeting. Savanna, GA: Southern Weed Science Society

Hardke JT (2012) Arkansas Rice Production Handbook. Arkansas Cooperative Extension Service Miscellaneous Publications 192. Little Rock, AR: University of Arkansas

Hardke JT (2016) Trends in Arkansas rice production, 2015. *In*: RJ Norman and KAK Moldenhauer (eds). B.R. Wells Arkansas Rice Research Studies 2015. University of Arkansas Agricultural Experiment Station Research Series 634:13-16. Fayetteville, AR

Heap, I. The International Survey of Herbicide Resistant Weeds. Available www.weedscience.org. Accessed February 26, 2017

Hinga M, Griffin S, Moon MS, Rasmussen RD, Cuevas F, inventor; RiceTec Inc, assignee (2013) January 24. Methods and compositions to produce rice resistant to ACCase inhibitors. US patent 20130023416 A1

Holm LG, Pancho JV, Herberger JP, Plucknett DL (1977). The World's Worst Weeds. Honolulu, HI: University Press of Hawaii

Konishi T, Sasaki Y (1994) Compartmentalization of two forms of acetyl-CoA carboxylase in plants and the origin of their tolerance toward herbicides. Proc Natl Acad Sci 91:3598-3601

Minton BW, Shaw DR, Kurtz ME (1989) Postemergence grass and broadleaf herbicide interactions for red rice (*Oryza sativa*) control is soybeans (*Glycine max*). Weed Technol 3:329-334

Ndou AM (2009) Interaction of weed emergence, weed density, and herbicide rate in soybean. Ph.D dissertation. Manhattan, KS: Kansas State University. 100 p

Norsworthy JK, Scott RC, Smith KL (2007) Confirmation and management of clomozone-resistant barnyardgrass. *In*: RJ Norman and KAK Moldenhauer (eds). B.R. Wells Arkansas Rice Research Studies 2006. University of Arkansas Agriculture Experiment Station Research Series 560:113-116. Fayetteville, AR

Norsworthy JK, Bond J, Scott RC (2013) Weed management practices and needs in Arkansas and Mississippi rice. Weed Technol 27:623-630

Riar DS, Norsworthy JK, Bond JA, Bararpour MT, Wilson MJ, Scott RC (2012) Resistance of *Echinochloa crus-galli* populations to acetolactate synthase-inhibiting herbicides. Int J Agron DOI:10.1155/2012/893953

Rouse CE, Burgos N, Lawton-Rauh A, Salas RA (2016) Herbicide resistance mechanisms of multiple resistant junglerice (*Echinochloa colona*) from Arkansas. Page 481 *in* Proceedings of the Southern Weed Science Society annual conference. San Juan, PR: Southern Weed Science Society

Shaner DL, ed (2014) Herbicide Handbook. 10$^{th}$ Edition. Lawrence, KS: Weed Science Society of America. Pp 401-402

Talbert RE, Burgos NR (2007) History and management of herbicide-resistant barnyardgrass (*Echinochloa crus-galli*) in Arkansas rice. Weed Technol 21:324-331

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]

| | | | Control[b] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Growth stage | Herbicide | Rate | 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]

| | | | Biomass[bc] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Grass size | Herbicide | Rate | 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 ($\alpha$=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 ($\alpha$=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 +

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 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).

## Literature Cited


Abit M, Al-Khatib K, Olson BL, Stahlman PW, Geier PW, Thompson CR, Currie RS, Schlegel AJ, Holman JD, Hudson KA, Schoup DE, Moechnig MJ, Grichar WJ, Bean BW (2011) Efficacy of postemergence herbicides tankmixes in aryloxyphenoxypropionate-resistant grain sorghum. Crop Prot 30:1623-1628

Anonymous (2003) Targa® herbicide product label. Gowan Company Publication No. 03-R0415. Yuma, AZ. Gowan Company. 16 p

Anonymous (2017) Provisia™ herbicide product label. BASF Corporation Publication No. NVA 2017-04-522-0004. Research Triangle Park, NC. BASF Corporation. 12 p

Blackshaw RE, Harker KN, Clayton GW, O'Donovan JT (2006) Broadleaf herbicide effects on clethodim and quizalofop-p efficacy on volunteer wheat (*Triticum aestivum*). Weed Technol 20:221-226

Bourgeois L, Kenkel NC, Morrison IN (1997) Characterization of cross-resistance patterns in acetyl-Coa carboxylase inhibitor resistant wild oat (*Avena fatua*). Weed Sci 45:750-755

Brommer CL, Shaw DR, Duke SO, Reddy KN, Willeford KO (2000) Antagonism of BAS 625 by selected broadleaf herbicides and the role of ethanol. Weed Sci 48:181-187

Buehring NW, Talbert RE, Baldwin FL (2006) Interactions of graminicides with other herbicides applied to rice (*Oryza sativa*). Weed Technol 20:215-220

Burgos NR, Norsworthy JK, Scott RC, Smith KL (2008) Red rice (Oryza sativa) status after 5 years of imidazolinone-resistant rice technology in Arkansas. Weed Technol 22:200-208

Colby SR (1967) Calculating synergistic and antagonistic responses of herbicide combinations. Weeds 15:20-22

Culpepper AS, York AC, Jordon DL, Corbin FT, Sheldon YS (1999) Basis for antagonism in mixtures of bromoxynil plus quizalofop-p applied to yellow foxtail (*Setaria glauca*). Weed Technol 13:515-519

Damalas CA (2004) Herbicide tank mixtures: common interactions. Int J Agri Biol 6:209-2012

Hale RR, Norsworthy JK, Godwin JA, Steppig NR, Meyer CJ, Scott RC, Barber LT, Schultz J (2016) Sharpen tank-mixtures with rice herbicides for barnyardgrass control in Provisia™ rice. *In*: RJ Norman and KAK Moldenhauer (eds). B.R. Wells Arkansas Rice Research Studies 2015. University of Arkansas Agricultural Experiment Station Research Series 634:167-173. Fayetteville, AR

Hatzios KK, Penner D (1985) Interactions of herbicides with other agrochemicals in higher plants. Rev Weed Sci 1:1-63

Hydrick HT, Lawrence B, Edwards HM, Phillips TL, Bond JA, Peeples JD (2016) Grass control with mixtures of quizalofop and broadleaf herbicides in Provisia™ rice. Page 126 *in* Proceedings of the Southern Weed Science Society annual conference. San Juan, PR: Southern Weed Science Society

Kammler KJ, Walters SA, Young BG (2008) Halosulfuron tank mixtures and adjuvants for weed control in pumpkin production. HortScience 43:1823-1825

Konishi T, Sasaki Y (1994) Compartmentalization of two forms of acetyl-CoA carboxylase in plants and the origin of their tolerance toward herbicides. Proc Natl Acad Sci. 91:3598-3601

Lancaster ZD, Norsworthy JK, Martin SM, Young ML, Scott RC, Barber LT (2016) Optimizing quizalofop rate structure for sequential applications in Provisia™ rice. *In*: RJ Norman and KAK Moldenhauer (eds). B.R. Wells Arkansas Rice Research Studies 2015. University of Arkansas Agricultural Experiment Station Research Series 634:180-184. Fayetteville, AR

McCown MS, Barber LT, Norsworthy JK, Lancaster ZD, Green J, Miller MR (2016) Evaluation of Provisia™ herbicide tank mixtures. *In*: RJ Norman and KAK Moldenhauer (eds). B.R. Wells Arkansas Rice Research Studies 2015. University of Arkansas Agricultural Experiment Station Research Series 634:190-195. Fayetteville, AR

Meyers PF, Coble HD (1992) Antagonism of graminicides activity on annual grass species by imazethapyr. Weed Technol 6:333-338

Minton BR, Kurtz ME, Shaw DR (1989a) Barnyardgrass (*Echinochloa crus-galli*) control with grass and broadleaf weed herbicide combinations. Weed Sci 37:223-227

Minton BR, Shaw DR, Kurtz ME (1989b) Postemergence grass and broadleaf herbicide interactions for red rice (*Oryza sativa*) control in soybeans (*Glycine max*). Weed Technol 3:329-334

Noldin JA, Chandler JM, McCauley GN, Sij JW (1998) Red rice (*Oryza sativa*) and Echinochloa spp. Control in Texas gulf coast soybean (*Glycine max*). Weed Technol 12:677-683

Norsworthy JK, Bond J, Scott RC (2013) Weed management practices and needs in Arkansas and Mississippi rice. Weed Tech 27:623-630

Shaner DL, ed (2014) Herbicide Handbook. 10th Edition. Lawrence, KS: Weed Science Society of America. Pp 401-402

Scherder EF, Talbert RE, Lovelace ML (2005) Antagonism of cyhalofop grass activity by halosulfuron, triclopyr, and propanil. Weed Technol 19:934-941

Tehranchian P, Norsworthy JK, Korres NE, McElroy S, Chen S, Scott RC (2016) Resistance to aryloxyphenoxypropionate herbicides in Amazon sprangletop: Confirmation, control, and molecular basis of resistance. Pestic Biochem Physiol 133:79-84

Underwood MG, Soltani N, Hooker DC, Robinson DE, Vink JP, Swanton CJ, Sikkema PH (2016) The addition of dicamba to POST applications of quizalofop-p-ethyl or clethodim antagonizes volunteer glyphosate-resistant corn control in dicamba-resistant soybean. Weed Technol 30:639-647

Zhang W, Webster EP, Blouin DC, Leon CT (2005) Fenoxaprop interactions for barnyardgrass (*Echinochloa crus-galli*) control in rice. Weed Technol 19:293-297

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 $H_2O$ | 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[ab] | 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]

| | | Prop/Quin-resistant barnyardgrass[d] | | | | ALS-resistant barnyardgrass | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Control | | Biomass reduction | | Control | | Biomass reduction | |
| Treatment | Rate | 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]

| | | Broadleaf signalgrass | | | | Amazon sprangletop | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Control | | Biomass reduction | | Control | | Biomass reduction | |
| Treatment[d] | Rate | 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]

| | | ACCase-resistant Amazon sprangletop | | | | Red rice | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Control | | Biomass reduction | | Control | | Biomass reduction | |
| Treatment[d] | Rate | 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]

| | | Barnyardgrass | | | | Broadleaf signalgrass | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Control | | Biomass reduction | | Control | | Biomass reduction | |
| Treatment[d] | Rate | 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]

| | | Amazon sprangletop | | | | Red rice | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | % Control | | % Biomass reduction | | % Control | | % Biomass reduction | |
| Treatment[d] | Rate | 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.