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Interactions Observed with Clomazone plus Pendimethalin when Mixed with Postemergence Rice Herbicides

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INTERACTIONS OBSERVED WITH CLOMAZONE PLUS PENDIMETHALIN WHEN MIXED WITH POSTEMERGENCE RICE HERBICIDES

A Thesis

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Abstract

A study was conducted at the Louisiana State University Agricultural Center's H. Rouse Caffey Rice Research Station (RRS) in 2017 and 2018 to evaluate whether the pre-packaged mixture of clomazone plus pendimethalin should be applied delayed preemergence (DPRE) or postemergence (POST) within a herbicide residual overlay with saflufenacil, clomazone, or quinclorac. POST applications also included penoxsulam or halosulfuron in combination with the second residual application. No differences were observed with barnyardgrass control at 14 DAT across all treatments with 92 to 98% control. At 42 DAT, barnyardgrass treated with either clomazone plus pendimethalin applied at either timing in combination with either clomazone or quinclorac applied POST controlled barnyardgrass 95 to 96%. However, when saflufenacil was applied PRE regardless of the POST herbicide or when saflufenacil was applied POST with halosulfuron resulted in reduced barnyardgrass control, 78 to 81%, compared with control with all other residual combinations, 95 to 96%. Yellow nutsedge and rice flatsedge increased when treated with halosulfuron compared with penoxsulam across all evaluation dates.

A study was conducted at RRS in 2017 and 2018 to evaluate the interaction between various rates of clomazone plus pendimethalin mixed with various rates of propanil. A synergistic response occurred when barnyardgrass was treated with all herbicide mixtures at 56 DAT. Yellow nutsedge control when treated with all herbicide mixtures was neutral except when treated with 1145 g ha^{-1} of clomazone plus pendimethalin mixed with 4485 g ha^{-1} of propanil. Rice flatsedge control at 28 DAT produced neutral interactions for all herbicide mixtures.

A study was conducted in 2017 and 2018 at RRS to evaluate the activity of quizalofop applied independently or in a mixture with clomazone, pendimethalin, clomazone plus

pendimethalin, and a pre-packaged mixture of clomazone plus pendimethalin. Even though antagonism occurred at 7 DAT for all mixtures except when pendimethalin was mixed quizalofop, control of barnyardgrass was 94 to 98% at 14, 28, and 42 DAT with all herbicide mixtures. A neutral interaction occurred for CL-111, CLXL-745, and red rice control when treated with all herbicide mixtures and evaluation dates. Rice yield decreased when not treated with the initial quizalofop application.

Chapter 1

Introduction

Rice (*Orzya sativa* L.) is a highly valued grain crop in the United States with approximately 1 million hectares planted in 2017 (USDA 2018). Louisiana ranked third among the states in rice production with nearly 162,000 hectares planted worth an estimated 312 million dollars in 2017 (USDA 2017). One of the most important decisions a rice grower must make in order to produce a marketable rice crop is deciding on a weed management program. During a given year, approximately 9% of total inputs are spent on pesticides which include a grower's weed control program (Salassi et al 2015).

Weeds interfere with rice production by directly competing with rice for water, nutrients, and sunlight, and this competition can result in the direct reduction of total rough rice yield and quality (Smith 1968, 1983, 1984, 1988). Indirect impacts of weeds consist of reduced grain quality, reduced harvesting efficiency, increased insect and disease pressure, and an increase of weed seeds in the soil seedbank. Therefore, weed control practices should encompass a variety of different chemical, cultural, and mechanical means to limit the impact of weeds on Louisiana rice production.

There are more than 70 weed species that infest rice production in the United States (Smith 1988). Troublesome monocots species include barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv], junglerice (*Echinochloa colona* L.), broadleaf signalgrass [*Urochloa platyphylla* (Munro ex C. Wright) R.D. Webster], Amazon sprangletop [*Diplachne panicoides* (J. Presl) Hitchc.], spreading dayflower (*Commelina diffusa* Burm. F.), and red rice (*Oryza sativa* L.) (Smith 1968, 1974, 1983, 1984, 1988). Major broadleaf weeds occurring in rice production consists of eclipta (*Eclipta prostrata* L.), hemp sesbania [*Sesbania herbacea* (Mill.) McVaugh], Indian jointvetch (*Aeschynomene indica* L.), and Texasweed [*Caperonia palustris* (L.) St. Hil.] (Smith 1968, 1984, 1988). Troublesome sedge species occurring in rice cropping systems include yellow nutsedge (*Cyperus esculentus L.*) and rice flatsedge (*Cyperus iria* L.) (Smith 1968, 1988). Troublesome aquatic weeds in Louisiana rice production include alligatorweed [*Alternathera philoxeroides* (Mart.) Griseb.] pickerelweed (*Pontederia chordata* L.), ducksalad [*Heteranthera limosa* (Sw.) Willd.], creeping burhead [*Echinodorus cordifolius* (L.) Griseb.], grassy arrowhead (*Sagittaria graminea* Michx. var. *graminea*), and common arrowhead (*Sagittaria latifolia* Willd.)(Webster 2014).

If uncontrolled, weeds infesting rice production in the southern United States may decrease yields by up 82% (Smith 1988). The severity of competition between rice and weeds depends on the individual weed species and the duration of weed interference. Yield losses from heavy, season long weed competition from red rice, barnyardgrass, bearded sprangletop [*Diplachne fascicularis* var. *panicoides* (Lam.) Grey], amazon sprangletop, broadleaf signalgrass, and spreading dayflower are 82, 70, 36, 35, 32, and 18%, respectively (Diarra et al. 1985; McGregor et al. 1988; Smith 1968, 1974, 1975, 1983, 1984). Season long competition from ducksalad, hemp sesbania, Indian jointvetch, and eclipta can reduce yield by 21, 19, 17, and 10%, respectively (Smith 1968).

There are certain crop management practices that can directly influence the presence and abundance of certain weed species in rice fields. Water management, which is closely related to seeding method, dry or water-seeded, has a heavy influence on weed presence and pressure (Smith 1988). Water seeded rice, the broadcasting of dry or sprouted seed directly into floodwater, has been greatly utilized in Louisiana as a means of cultural control of red rice (Harrell and Saichuk 2014). In return, dry-seeded rice production encompasses broadcasting or drilling seed directly onto prepared soil that is followed by a permanent flood at the four- to five leaf stage. Webster (2014) states that the weed spectrum from dry-seeded rice, which tends to be mostly terrestrial, annual grasses, can shift to a more aquatic weed spectrum in water-seeded rice production. Repeated herbicide use to control annual grasses can often lead to an increased presence of perennial weeds that can be harder to control with cultural-herbicide practices (Smith 1988). Crop rotation and tillage also has an impact on presence and pressure of different weed species in rice fields. In dry seeded rice production, multiple tillage events at one-to three-weeks before seeding reduces barnyardgrass, sprangletop, and other annual grasses, but can increase the presence of other species like ducksalad and rice flatsedge (Smith et al. 1977). In contrast, red rice control can best be managed by minimal tillage for it allows the seeds, from the previous harvest, to sit on top of the soil surface and decompose instead of being buried and stored in the soil seedbank (Webster 2014).

Both dry and water-seeded planting methods are utilized in Louisiana rice production (Harrell and Saichuk 2014). In past years, water-seeding has been predominantly used in southern Louisiana as it creates an anaerobic environment that suppresses red rice seed germination (Levy et al. 2006). However, since the commercial release of imidazolinone-resistant (IR) rice in 2002, growers have been able to rely on a chemical means for their red rice control when planting IR rice varieties (Levy et al. 2006; Webster and Masson 2001).

Imidazolinone herbicides belong to specific site of action within the much larger Group 2 herbicides that inhibit acetolactate synthase (ALS) (Webster and Masson 2001). Two specific actives within the imidazolinone family that are labeled for use in IR rice production are imazethapyr (2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid) and imazomox [(2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5- oxo-1Himidazol-2-yl]-5-(methoxymethyl)-3- pyridinecarboxylic acid] at rates between 70 to 105 and 35 to 53 g ai ha^{-1}, respectively (Anonymous 2011, 2016; Webster 2014; Shaner 2014).

The adoption of IR rice technology by growers in southern Louisiana has broadened the tillage and cultural practices of red rice suppression in a drill-seeded production system. In 2017, approximately 66% of Louisiana rice acreage was planted utilizing the drill-seeded planting method (Harrell 2017). With more acres going to dry-seeded planting, farmers are relying more on preemergence (PRE), delayed preemergence (DPRE), and postemergence (POST) herbicides to suppress weeds until the permanent flood is established (Webster 2014).

A PRE herbicide application is applied within 24- to 48- hours after the planting of rice and requires a surface irrigation or rainfall event for activation (Webster 2014). A PRE application of a herbicide allows a rice crop to germinate and establish a stand which will give rice a competitive advantage over weeds prior to weed emergence. A DPRE application is applied four to seven days after planting and allows the rice seed to begin the germination process by imbibing water and starting its initial growth before coming in contact with the herbicide. A POST application is one applied any time after crop emergence.

Weeds resistance to several different herbicides has become a developing problem within US rice production. Beginning with barnyardgrass resistance to propanil [N-(3,4-dichlorophenyl) propionamide] in the early 1990s, several other documented cases of weed resistance have been confirmed in the past several years (Baltazar and Smith 1994). Along with propanil, barnyardgrass has also been documented having resistance to quinclorac (3,7-Dichloro-8-quinolinecarboxylic acid) in 1999 (Malik et al. 2010), clomazone [2-(2-Chlorophenyl)methyl-4,4-dimethyl-3-isoxazolidinone] in 2007 and imazethapyr in 2008 (Dilpreet et al. 2013; Wilson et al. 2014). Rice flatsedge has also been documented to be resistant to ALS inhibiting herbicides in Arkansas, Louisiana, and Mississippi (Heap 2018; Norsworthy et al. 2013).

There are several measures that growers can take to prevent herbicide weed resistance including crop rotation, increased tillage, higher herbicide application rates, rotating herbicide modes of action, and the use of herbicide resistant crops (Webster 2014). Another effective measure is to apply a mixture of herbicides, with different modes of action, within the same application. This method ensures that even if there is a weed resistant issue in a field, the resistant weeds will be susceptible to at least one of the herbicides applied.

Herbicides applied within the same application have three possible interactions: additive/neutral, synergistic, or antagonistic (Blouin et al. 2004; Colby 1967; Flint et al. 1988; Morse 1978; Streibig et al. 1998). Herbicide additivity is the cooperative action of two herbicides which equal the expected response of each herbicide applied separately. Herbicide synergism is when two jointly applied herbicides perform greater than the expected outcome of the herbicides applied alone. In contrast, jointly applied herbicides are considered antagonistic when the observed response is less than the expected response of each herbicide applied alone. One of the most widely used equations for determining the expected response of jointly applied herbicides is Colby's equation (Colby 1967). Colby's equation is a statistical linear model where the expected response is equal to the percent response of each herbicide applied alone, multiplied by one another, and then divided by one-hundred (Colby 1967, Flint et al. 1988). Colby's equation has been the benchmark for determining herbicide mixture interactions for the past several decades due to its simple and straightforward equation and its ability to analyze anything from visual observations, dry/fresh weights, weed counts, etc. However, Blouin et al. (2004) argues that the expected response is defined as multiplicative, non-linear function of the means for herbicides when applied alone, rather than a linear standard model for tests of hypotheses that does not directly depict the correct expected response for the herbicide mixture. Thus, Blouin et al. (2004) developed a nonlinear mixed model that is more sensitive than Colby's linear model in detecting significant differences in herbicides responses. Blouin et al. (2010) revised his previous model into an augmented mixed model, which proved to be more versatile than his previous model.

Fish et al. (2015) employed Blouin et al. (2010) nonlinear model when concluding that a pre-packaged mixture of propanil plus thiobencarb consistently provided synergism when mixed with imazethapyr for red rice and barnyardgrass control. Fish et al. (2016) and Webster et al. (2017) used Blouin's modified Colby's nonlinear model to determine that a synergistic response occurred in red rice control when propanil was mixed with imazamox or imazethapyr.

Clomazone is a diterpene synthesis inhibiting (Group 13) herbicide that acts by interfering with chloroplast development and reduces the accumulation of plastid pigments in susceptible weed species (Ferhatoglu and Barrett 2005). Clomazone was first labeled for use in soybean (*Glycine max* L.) in 1985 and was subsequently labeled in cotton (*Gossypium hirsutum* L.) where it must be applied with an organophosphate insecticide to reduce phytotoxicity (Webster et al. 1999). Clomazone is taken up by plant roots and shoots and translocates primarily in the xylem to meristematic regions of the plant and leaves (Lee et al. 2004). Symptoms of susceptible species that are exposed to clomazone show bleaching followed by cellular necrosis and eventually plant death (Ferhatoglu and Barrett 2005; Webster et al. 1999). Webster et al. (1999) indicates that a preplant incorporated (PPI), PRE, DPRE, or POST application of clomazone has activity on susceptible weed species at rates from 0.45 to 0.67 kg ai ha^{-1}. Soil type and different rice cultivars play a role in phytotoxicity with rates as low as 0.34 kg ha^{-1} of clomazone showing visual symptoms (Scherder et al. 2003). However, early season applications of clomazone on silt loam soils only reduced rice yields at rates above 1.7 kg ha^{-1}; while Bollich et al. (2000) reports 0.84 kg ha^{-1} reduce yields (Jordan et al. 1998). From 2005 to 2007 Willingham et al. (2008) evaluated weed control of clomazone at PRE and EPOST with rates at 0.39, 0.44, 0.56, or 0.67 kg ha^{-1} on coarse textured soil. At 14 days after treatment (DAT), clomazone controlled barnyardgrass at 96 to 97% when applied PRE and 85% when applied at EPOST. Broadleaf signalgrass was controlled 88 to 93% when applied at either PRE or EPOST. Clomazone was able to suppress annual sedge at 63 to 67% a crossed all application timings and rates. Hemp sesbania was controlled 81 to 84% across all application timings and rates.

Pendimethalin [N-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine] is a dinitroaniline (Group 3) herbicide that acts by disrupting mitotic cellular division through inhibition of microtubule proteins in susceptible weed species (Shaner 2014). Pendimethalin was first labeled in corn (*Zea mays* L.) and cotton in 1975, soybean in 1976, rice in 1981, and several other grain and vegetable crops since (Hatzinikolaou et al. 2003). Pendimethalin is a soil applied herbicide that is absorbed by germinating plant roots and coleoptiles, resulting in lack of proper cellular division and elongation, causing highly susceptible weed species to die prior to or shortly after emergence. Susceptible, emerged plants will display hypocotyl swelling along with thick stubby roots.

In 2012 and 2013, a study was conducted by Ahmad and Chauhan (2015) to evaluate DPRE applications of pendimethalin at rates of 800, 1200, and 1600 g ai ha^{-1} on weed biomass and rice grain yield. Weed plant biomass was 125, 95, and 70 g m^{-2} at 800, 1200, and 1600 g ha^{-1}, respectively. Rice treated with pendimethalin at rates of 800, 1200, and 1600 g ha^{-1} resulted in yields of 3.5, 3.2, and 2.8 tons ha^{-1}, respectively, inferring that pendimethalin applications over the recommended 800 g ha^{-1} were more effective in weed control, but this caused an overall yield reduction due to rice stand reductions caused by phytotoxicity.

Weed spectrum controlled with pendimethalin applications was evaluated on common weed species occurring in India dry-seeded rice production (Mahajan and Chauhan 2013). Rice flatsedge, purple nutsedge (*Cyperus rotundus* L.), large crabgrass [*Digitaria sanguinalis* (L.) Scop], Chinese sprangletop (*Leptochloa chinensis* L.), crowfootgrass (*Dactyloctenium aegyptium* L.), and junglerice were all evaluated when treated with 750 g ha^{-1} of pendimethalin applied at DPRE. Pendimethalin controlled large crabgrass, crowfootgrass, Chinese sprangletop, and junglerice at 89, 65, 75, and 90%, respectively, and offered little activity on sedges.

The benefits to co-applying herbicides include a broadened spectrum of weed control, economical benefits due to a single application versus multiple applications, and the prevention or delay of weed species becoming herbicide resistant (Carlson et al. 2011). Previous research conducted in Louisiana reported that herbicide mixtures used in rice production can broaden the weed control spectrum and increase weed control (Carlson et al. 2011; Fish et al. 2015, 2016; Pellerin et al. 2004). Co-applying herbicides in a timely manner in the early growing season can help protect rice yield and prevent weed competition (Webster et al. 2012).

RiceOne (RiceCo LLC, Memphis, TN 38137) is a pre-packaged mixture of pendimethalin and clomazone in a two aqueous capsule suspension formulation, at 313 and 130 g L^{-1}, respectively. RiceOne was available commercially in 2017 for use in Arkansas, Mississippi, Louisiana, Missouri and Texas for weed management in rice production. The targeted single application rate of RiceOne will be 2.55 L ha^{-1}, 784 g ha^{-1} of pendimethalin and 327 g ha^{-1} of clomazone, on coarse textured soils and 3.65 L ha^{-1}, 1120 g ha^{-1} of pendimethalin and 468 g ha^{-1} of clomazone on fine textured soils. Louisiana dry-seeded rice production systems could benefit from this, pre-packaged mixture that offers residual control.

The objective of this research is to evaluate the interaction of a pre-packaged mixture of clomazone plus pendimethalin mixed with other postemergence herbicides that are labeled in rice for weed management. Also a study was conducted to determine the proper application timing of the pre-packaged mixture of clomazone plus pendimethalin in correlation with other residual herbicide combination timings.

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Chapter 2
Residual Overlay of Clomazone plus Pendimethalin with Other Residual Herbicides Labeled in Rice (*Oryza sativa* L.)

Introduction

Rice (*Orzya sativa* L.) is a highly valued grain crop in the United States with approximately 1 million hectares planted in 2017 (USDA 2018). Louisiana ranked third among the states in rice production with nearly 162,000 hectares planted worth an estimated 312 million dollars in 2017 (USDA 2017). One of the most important decisions a grower must make in order to produce a marketable rice crop is deciding on a weed management program. During a given year, approximately 9% of total inputs are spent on pesticides which include a grower's chemical weed control program (Salassi et al 2015).

Weeds interfere with rice production by directly competing with rice for water, nutrients, and sunlight; this competition can result in the direct reduction of total rough rice yield and quality (Smith 1968, 1983, 1984, 1988). Indirect impacts of weeds consist of: reduced grain quality, reduced harvesting efficiency, increased insect and disease pressure, and an increase of weed seeds in the soil seedbank.

While there are more than 70 different weed species that are prone to infest rice production in the southern United States, barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv], yellow nutsedge (*Cyperus esculentus L.*), and rice flatsedge (*Cyperus iria* L.) can be a few of the most troublesome weeds to control (Smith 1968, 1974, 1988). Smith (1974) reported rough rice yield losses of up to 70% from heavy, season long barnyardgrass pressure. Yellow nutsedge and rice flatsedge can reduce rough rice yields by 59 and 40%, respectively (Keeley 1987).

Since the early 1960s, propanil [N-(3,4-dichlo- rophenyl)propanamid] has been a staple in many rice herbicide programs for its ability to successfully control barnyardgrass. By the early

1990s over 70% of the rice acreage in the United States was receiving one or more applications of propanil or of a propanil containing herbicide mixture (Crawford and Jordan 1995). However, this repeated use of propanil effectively selected for resistant biotypes of barnyardgrass.

In 2017, approximately 66% of Louisiana rice acreage utilized the drill-seeded planting method (Harrell 2017). With more acres going to dry-seeded planting, producers are relying more on preemergence (PRE), delayed preemergence (DPRE), and postemergence (POST) herbicides to suppress weeds until the permanent flood is established (Webster 2014).

In order for producers to suppress their weed pressure until the permanent flood is established, one of the most utilized tactics is the multiple applications of residual herbicides, which is often referred to as overlaying herbicides. A residual herbicide is defined as “a herbicide that persists in the soil and injures or kills germinating weed seedlings for a relatively short period of time after application” (Shaner 2014). This approach is achieved by applying residual herbicides sequentially in order to overlay the second application of herbicide before the first herbicide dissipates and weed emergence occurs. This method of pro-active weed management helps producers protect their rice yields during the most important time in regards to weed competition. Smith (1988) reported that most grass species are highly competitive with rice early in the growing season and should be controlled shortly after emergence to protect the yield potential of the rice crop.

Not only does this technique of overlaying residual herbicides help producers control weeds early in the season, but it also decreases the pressure on postemergence herbicides to control weeds later in the season. Riar et al. (2013) suggests that the best management practice to control herbicide-resistant weeds is to start weed-free at planting and to follow it up by applying sequential applications of residual herbicides that offer multiple modes of action. This practice will ultimately prolong the usefulness of postemergence grass herbicides like propanil, quinclorac, cyhalofop, and penoxsulam.

In 2000, clomazone [2-(2-Chlorophenyl)methyl-4,4-dimethyl-3-isoxazolidinone] was labeled for use in rice production. Clomazone is a diterpene synthesis inhibiting (Group 13) herbicide that acts by interfering with chloroplast development and reduces the accumulation of plastid pigments in susceptible weed species (Ferhatoglu and Barrett 2005). Clomazone applied preemergence (PRE) to rice on a course textured soil controlled barnyardgrass 96 to 97%, and barnyardgrass treated with clomazone applied postemergence (POST), at the one- to two-leaf stage, was controlled 85% (Willingham et al. 2008). The first confirmation of clomazone resistant barnyardgrass occurred in Arkansas in 2008 (Norsworthy et al. 2008).

Pendimethalin [N-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine] is a dinitroaniline (Group 3) herbicide that acts by disrupting mitotic cellular division through inhibition of microtubule proteins in susceptible weed species (Vaughn and Lehnen 1991). Pendimethalin is a soil applied herbicide that is absorbed by germinating plant roots and coleoptiles causing highly susceptible weed species to not emerge or die soon after emergence. Pendimethalin has shown to be active on grass and small seeded broadleaf weeds infesting rice when applied at different timings (Malik et al. 2010; Stauber et al. 1991; Bond et al. 2009).

RiceOne (RiceOne label, RiceCo LLC, Memphis, TN 38137) is a pre-packaged mixture of pendimethalin plus clomazone in an aqueous capsule suspension formulation. Both clomazone and pendimethalin are soil applied PRE or an early postemergence (EPOST) herbicides that offer residual activity. The objective of this study was to 1) determine whether the pre-packaged mixture of clomazone plus pendimethalin should be applied DPRE or EPOST within a herbicide residual overlay weed management program. 2) determine a residual overlay weed management program that encompasses a pre-package mixture of clomazone and pendimethalin in combination with other residual herbicide combinations in regard to weed control and rough rice yield.

Materials and Methods

A study was conducted at the Louisiana State University Agricultural Center's H. Rouse Caffey Rice Research Station (RRS) near Crowley, Louisiana in 2017 and 2018 on a Crowley silt loam soil (fine montmorillonitic, nonacid, Vertic Haplaquept) with a pH 6.4 and 1.4% organic matter. Field preparation consisted of a fall and spring disking followed by two passes in opposite directions with a two-way bed conditioner consisting of rolling baskets and S-time harrows set a 6 cm depth. A preplant fertilizer of 8-24-24 (N-P_2O_5-K_2O) was applied at 280 kg ha^{-1} followed by a preflood application of 365 kg ha^{-1} of 46-0-0 fertilizer was applied to the study area.

The long grain rice imidazolinone-resistant rice cultivar 'CL111' and long grain ACCase-resistant rice cultivar 'PVL01' were drill seeded at 84 kg ha^{-1} on 18 cm rows on April 4th in 2017 and March 22nd in 2018, respectively. Plot size was 5.1 by 2.2 m^{-2}. A total of 270- and 150-mm of rainfall was recorded from planting to the establishment of the permanent flood. An 80-mm flood was than established when the rice achieved the one-tiller growth stage and maintained until 3 weeks prior harvest.

The experimental design was a two-factor factorial in a randomized complete block with four replications. Factor A consisted of overlaying residual herbicides of either a pre-packaged mixture of clomazone plus pendimethalin applied at 1020 g ai ha^{-1} applied DPRE followed by (fb) POST applications of either clomazone at 335 g ha^{-1}, quinclorac at 420 g ha^{-1}, or saflufenacil at 50 g ha^{-1} or a PRE application of clomazone at 335 g ha^{-1}, quinclorac at 420 g ha^{-1}, or saflufenacil at 50 g ha^{-1} fb a POST application of clomazone plus pendimethalin at 1020 g ha^{-1} (Table 2.1.). Factor B consisted of POST applications of halosulfuron at 50 g ha^{-1} or penoxsulam at 40 g ha^{-1}.

Table 2.1. Source of Materials for all products used in the study[a]

Herbicide/ Product	Trade Name	g L	Manufacturer
Clomazone + pendimethalin	RiceOne	130 + 313	RiceCo LLC, Memphis, TN
Clomazone	Command	360	FMC Corporation, Philadelphia, PA
Quinclorac	Facet	180	BASF Corporation, Research Triangle Park, NC
Saflufenacil	Sharpen	341	BASF Corporation, Research Triangle Park, NC
Halosulfuron	Permit	-[a]	Gowan Company, Yuma, AZ
Penoxsulam	Grasp	240	Dow AgroSciences LLC, Indianapolis, IN
Crop oil concentrate	Agri-Dex	-[b]	Helena Agri-Enterprises, Collierville, TN

[a]The formulation for halosulfuron is a water dispersible granule that contains 75% ai by weight
[b]The crop oil concentrate is formulated at 17% non-ionic surfactant and 83% unsulfonated oil residue

Herbicide applications were applied utilizing a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} at 190 kPa. The spray boom consisted of five flat-fan 110015 nozzles (Flat Fan AirMix Venturi Nozzle, Greenleaf Technologies, Covington, LA 70434) at 38 cm spacing. All herbicide applications were applied when the rice reached the one- to two-leaf stage. A COC at 1% v v^{-1} was added to all POST treatments (Table 2.1.).

The research area had a natural population of barnyardgrass, yellow nutsedge, rice flatsedge, and Texasweed. The PRE treatments were applied immediately after planting and there were no emerged weeds at application. An activating 40- and 20-mm rainfall was recorded within five days of the PRE applications in 2017 and 2018, respectively. The DPRE applications were applied one week after planting on barnyardgrass, rice flatsedge, and Texasweed that were all one- to two-cm in height. An activating 20- and 50-mm rainfall was recorded within five days of the DPRE applications in 2017 and 2018, respectively. The POST applications were applied on barnyardgrass that was at the two- to three-leaf stage and was three- to five-cm in height with a population density of 40 plants m^{-2}. Rice flatsedge and yellow nutsedge had three- to six-leaves and 5- to 10-cm in height with populations of 40 to 50 and 20 to 25 plants m^{-2}, respectively. Texasweed was two- to three-leaf stage and was 8- to 10-cm in height with a population density of 10 to 15 plants m^{-2} at POST application. Rice was eight- to 10-cm in height and was at the two- to three-leaf stage at the POST application timing.

Visual evaluations included crop injury, barnyardgrass, rice flatsedge, yellow nutsedge, and Texasweed control on a scale of 0 to 100%, where 0 meaning no injury or control and 100 meaning complete plant death at 14, 28, and 42 DAT. Rice plant height was recorded immediately prior to harvest by measuring four plants in each plot from the ground to the tip of the extended panicle. The center four rows of each plot were harvested utilizing a Mitsubishi VM3 (Mitsubishi Corporation, 3-1, Marunouchi 2- chome, Chiyoda-ky, Tokyo, Japan). Grain moisture was than adjusted to 12%.

Data were analyzed as repeated measures and subjected to the mixed procedure of SAS (SAS 2013). Location, years, replication (nested within year), and all interactions including any of these effects were consider random effects. Considering the combination of year as random effects allows for inferences from treatments over a range of environments (Carmer et al. 1989; Hager et al. 2003; McKnight et al. 2018). The fixed effects of this model were herbicide treatments and evaluation dates. Normality of treatment effects over all DAT was checked with the UNIVARIATE procedure (SAS 2013). Significant normality problems were not observed. Type III statistics were used to test all possible interactions of these fixed effects. Tukey's test was used to separate means at the 5% probability level ($P \leq 0.05$).

Results and Discussion

An interaction occurred for the residual herbicide program, by POST herbicides, by evaluation date for the control of barnyardgrass (Table 2.2.). There were no differences in barnyardgrass control at 14 DAT across all treatments with 92 to 98% control. At 42 DAT, barnyardgrass treated with either clomazone plus pendimethalin applied at either timing in combination with either clomazone or quinclorac applied POST controlled barnyardgrass 95 to 96%. However, when saflufenacil was applied PRE regardless of the POST herbicide or when saflufenacil was applied POST with halosulfuron resulted in reduced barnyardgrass control, 78 to 81%, compared with control with all other residual combinations, 95 to 96%. A similar trend was observed at 28 DAT. This decrease in barnyardgrass control may have been caused by

Table 2.2. Barnyardgrass control with overlaying residual herbicides coupled with either halosulfuron or penoxsulam in 2017 and 2018.[a]

Residual Herbicides[b]	Rate	Timing	Halosulfuron (50 g ha^{-1})	Penoxsulam (40 g ha^{-1})
	— g ha^{-1}—		% of control	
14 DAT[c]				
Clomazone fb	335	PRE	96 ab	96 ab
clomazone + pendimethalin	1020	POST		
Quinclorac fb	420	PRE	93 abc	97 a
clomazone + pendimethalin	1020	POST		
Saflufenacil fb	50	PRE	92 a-d	94 abc
clomazone + pendimethalin	1020	POST		
Clomazone + pendimethalin fb	1020	DPRE	98 a	97 a
clomazone	335	POST		
Clomazone + pendimethalin fb	1020	DPRE	98 a	98 a
quinclorac	420	POST		
Clomazone + pendimethalin fb	1020	DPRE	97 a	96 ab
saflufenacil	50	POST		

Table 2.2. Continued.

Residual Herbicides[b]	Rate	Timing	Halosulfuron (50 g ha^{-1})	Penoxsulam (40 g ha^{-1})
	— g ha^{-1}—		——— % control———	
28 DAT[c]				
Clomazone fb clomazone + pendimethalin	335 1020	PRE POST	92 a-d	93 abc
Quinclorac fb clomazone + pendimethalin	420 1020	PRE POST	88 a-e	93 abc
Saflufenacil fb clomazone + pendimethalin	50 1020	PRE POST	86 b-f	84 c-f
Clomazone + pendimethalin fb clomazone	1020 335	DPRE POST	91 a-e	92 a-d
Clomazone + pendimethalin fb quinclorac	1020 420	DPRE POST	93 abc	94 abc
Clomazone + pendimethalin fb saflufenacil	1020 50	DPRE POST	79 f	93 abc
42 DAT				
Clomazone fb clomazone + pendimethalin	335 1020	PRE POST	95 ab	95 ab
Quinclorac fb clomazone + pendimethalin	420 1020	PRE POST	96 ab	95 ab
Saflufenacil fb clomazone + pendimethalin	50 1020	PRE POST	81 ef	78 f
Clomazone + pendimethalin fb clomazone	1020 335	DPRE POST	95 ab	96 ab
Clomazone + pendimethalin fb quinclorac	1020 420	DPRE POST	96 ab	95 ab
Clomazone + pendimethalin fb saflufenacil	1020 50	DPRE POST	79 f	95 ab

[a]Means within a column followed by the same letter were not statistically different according to Tukey’s HSD at P=0.05.

[b]Respective herbicide residual overlay.

[c]Evaluation dates for each herbicide residual overlay combination are in days after treatment (DAT).

applying saflufenacil as the accompanying residual herbicide which has limited residual activity on grass weeds (Anonymous 2015a).

A POST application of halosulfuron or penoxsulam by evaluation dates interaction occurred for yellow nutsedge control; therefore, data were averaged over residual program (Table 2.3.). Yellow nutsedge was controlled 92, 92, and 94% when treated with halosulfuron at 14, 28, and 42 DAT, respectively, and control was reduced when yellow nutsedge was treated penoxsulam with 54 to 79% control across all rating dates. The results are similar to the observed activity of halosulfuron vs penoxsulam for yellow nutsedge control (Webster 2017).

Table 2.3. Yellow nutsedge control with POST applications of halosulfuron or penoxsulam averaged over residual herbicide program, 2017 and 2018.[a]

Herbicide	Rate	Timing	Yellow nutsedge Control
	— g ha^{-1}—		—— % of control ——
14 DAT[b]			
Halosulfuron	50	POST	92 a
Penoxsulam	40	POST	54 d
28 DAT			
Halosulfuron	50	POST	92 a
Penoxsulam	40	POST	66 c
42 DAT			
Halosulfuron	50	POST	94 a
Penoxsulam	40	POST	79 b

[a]Means within a column followed by the same letter were not statistically different according to Tukey's HSD at P=0.05.
[b]Evaluation dates for each respective herbicide residual overlay combination are in days after treatment (DAT).

A POST application of halosulfuron or penoxsulam by evaluation dates interaction occurred for rice flatsedge control; therefore, data were averaged over residual herbicide program (Table 2.4.). Rice flatsedge was controlled 93, 94, and 95% when treated with halosulfuron at 14, 28, and 42 DAT, respectively; however, penoxsulam treated rice flatsedge control decreased to 69 to 84% across all rating dates. Webster (2017) reported similar activity on rice flatsedge with halosulfuron and penoxsulam.

Table 2.4. Rice flatsedge control with POST applications of halosulfuron or penoxsulam averaged over residual program, 2017 and 2018.[a]

Herbicide	Rate	Timing	Yellow nutsedge Control
	— $g\ ha^{-1}$ —		— % of control —
14 DAT[b]			
Halosulfuron	50	POST	93 a
Penoxsulam	40	POST	69 d
28 DAT			
Halosulfuron	50	POST	94 a
Penoxsulam	40	POST	75 c
42 DAT			
Halosulfuron	50	POST	95 a
Penoxsulam	40	POST	84 b

[a]Means within a column followed by the same letter were not statistically different according to Tukey's HSD at P=0.05.
[b]Evaluation dates for each respective herbicide residual overlay combination are in days after treatment (DAT).

An interaction occurred for the residual herbicide program, by POST herbicides, by evaluation date for Texasweed control (Table 2.5.). At 28 and 42 DAT, Texasweed treated with saflufenacil PRE regardless of POST apllications was controlled 83 and 87%, and this was greater than clomazone or quinclorac applied PRE regardless of POST herbicide program. The results are similar to the expected effectiveness of saflufenacil control of Texasweed compared with clomazone or quinclorac (Webster 2017). Texasweed control was 73 to 78% when treated with saflufenacil applied POST regardless of the addition of halosulfuron or penoxsulam across all rating dates. These data indicate that when applying the pre-packaged mixture of clomazone plus pendimethalin mixed with halosulfuron or penoxsulam, saflufenacil should be applied as a

Table 2.5. Texasweed control with overlaying residual herbicides coupled with either halosulfuron or penoxsulam in 2017 and 2018.[a]

Residual Herbicides[b]	Rate	Timing	Halosulfuron (50 g ha^{-1})	Penoxsulam (40 g ha^{-1})
	— g ha^{-1}—		——— % of control———	
14 DAT[c]				
Clomazone fb	335	PRE	33 k	38 jk
clomazone + pendimethalin	1020	POST		
Quinclorac fb	420	PRE	65 c-g	43 ijk
clomazone + pendimethalin	1020	POST		
Saflufenacil fb	50	PRE	76 a-d	75 a-d
clomazone + pendimethalin	1020	POST		
Clomazone + pendimethalin fb	1020	DPRE	35 jk	36 jk
clomazone	335	POST		
Clomazone + pendimethalin fb	1020	DPRE	76 a-d	46 d-k
quinclorac	420	POST		
Clomazone + pendimethalin fb	1020	DPRE	74 a-d	78 a-d
saflufenacil	50	POST		
28 DAT[c]				
Clomazone fb	335	PRE	43 ijk	49 f-k
clomazone + pendimethalin	1020	POST		
Quinclorac fb	420	PRE	61 d-i	53 e-j
clomazone + pendimethalin	1020	POST		
Saflufenacil fb	50	PRE	83 abc	87 a
clomazone + pendimethalin	1020	POST		
Clomazone + pendimethalin fb	1020	DPRE	35 jk	53 e-j
clomazone	335	POST		
Clomazone + pendimethalin fb	1020	DPRE	68 b-f	60 d-i
quinclorac	420	POST		
Clomazone + pendimethalin fb	1020	DPRE	74 a-d	73 a-d
saflufenacil	50	POST		

Table 2.2. continued.

Residual Herbicides[b]	Rate	Timing	Halosulfuron (50 g ha^{-1})	Penoxsulam (40 g ha^{-1})
	— g ha^{-1}—		—— % of control ——	
42 DAT				
Clomazone fb	335	PRE	51 e-k	45 h-k
clomazone + pendimethalin	1020	POST		
Quinclorac fb	420	PRE	61 d-i	51 e-k
clomazone + pendimethalin	1020	POST		
Saflufenacil fb	50	PRE	84 abc	86 ab
clomazone + pendimethalin	1020	POST		
Clomazone + pendimethalin fb	1020	DPRE	51 e-k	51 e-k
clomazone	335	POST		
Clomazone + pendimethalin fb	1020	DPRE	68 b-f	60 d-i
quinclorac	420	POST		
Clomazone + pendimethalin fb	1020	DPRE	73 a-d	73 a-d
saflufenacil	50	POST		

[a]Means within a column followed by the same letter were not statistically different according to Tukey’s HSD at P=0.05.
[b]Respective herbicide residual overlay.
[c]Evaluation dates for each respective herbicide residual overlay combination are in days after treatment (DAT).

PRE over clomazone or quinclorac when a potential Texasweed problem exists. When applying clomazone plus pendimethalin DPRE, producers should apply saflufenacil over clomazone or quinclorac when overlaying residuals for Texasweed control.

Crop injury was less than 10% across all herbicide treatments and evaluation timings, 0 to 10% (data not shown). Rice plant height was similar regardless of herbicide program, 104 to 108 cm (data not shown). A main effect of residual overlay program occurred for rice yield (Table 2.6.). Rough rice yield was 5690 to 5700 kg ha^{-1} when rice was treated in combination with clomazone and clomazone plus pendimethalin regardless of application timing. These residual combinations controlled barnyardgrass 95 to 96% which may contribute to the increase in rough rice yield (Table 2.2.). No difference in rough rice yield was observed when saflufenacil or quinclorac were applied POST following the pre-packaged mixture; however, rough rice yield decreased with saflufenacil or quinclorac applied PRE compared with rice treated with clomazone PRE or DPRE of the pre-packaged mixture combination regardless of the addition of halosulfuron or penoxsulam. In order to achieve similar results to the residual program of clomazone and clomazone plus pendimethalin, saflufenacil and quinclorac must be applied POST.

Table 2.6. Rough rice yield when overlaying residual herbicides in 2017 and 2018.[a]

Residual Herbicides[b]	Rate	Timing	Rough rice yield
	— g ha^{-1} —		— kg ha^{-1} —
Clomazone fb	335	PRE	5700 a
clomazone + pendimethalin	1020	POST	
Quinclorac fb	420	PRE	4740 b
clomazone + pendimethalin	1020	POST	
Saflufenacil fb	50	PRE	4740 b
clomazone + pendimethalin	1020	POST	
Clomazone + pendimethalin fb	1020	DPRE	5690 a
clomazone	335	POST	
Clomazone + pendimethalin fb	1020	DPRE	5510 ab
quinclorac	420	POST	
Clomazone + pendimethalin fb	1020	DPRE	5340 ab
saflufenacil	50	POST	

[a]Means within a column followed by the same letter were not statistically different according to Tukey's HSD at P=0.05.
[b]Respective herbicide residual overlay.

In conclusion, it is important that one understand the advantages and disadvantages of overlaying residual herbicides with different active ingredients. These data suggests that producers should tailor herbicide residual programs to the specific weeds that are present in fields. Overlaying combinations of clomazone or quinclorac with clomazone plus pendimethalin offers the greatest, season long control of barnyardgrass across all evaluations (Table 2.2.).

However, in regards to Texasweed control, saflufenacil with clomazone plus pendimethalin overlay weed control programs offered increased control compared with clomazone applied in combination with clomazone plus pendimethalin. In regards to rough rice yield, these data suggests that a producer apply clomazone over quinclorac or saflufenacil PRE in a program with clomazone plus pendimethalin POST due to the activity on barnyardgrass. When applying clomazone plus pendimethalin DPRE, any residual herbicide can be applied POST.

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Chapter 3
Interactions of Clomazone plus Pendimethalin Mixed with Propanil in Rice (*Oryza sativa* L.)

Introduction

Over the past several decades, advances in chemical weed management technology have played an important role in the development of the rice (*Oryza sativa* L.) industry (Ashton and Monaco 1991; Carlson et al. 2011). Often, a grower's weed management program will drive the overall production system depending on the presence and pressure of certain weed species (Norsworthy et al. 2007; Webster 2014).

Barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv] is one of the most noxious and prolific weed species that infest rice acres in the southern United States (Norsworthy et al. 2013). Barnyardgrass can reduce rice yields by 30% and potentially cause complete crop loss if left uncontrolled (Bagavathiannan et al. 2014; Johnson et al. 1998). Barnyardgrass is highly competitive with rice due to its rapid growth, its C_4 photosynthetic pathway, and its ability to mass produce seed (Holm et al. 1977; Vengris et al. 1966).

Since the early 1960s, propanil [N-(3,4-dichlo-rophenyl)propanamid] has been a staple in many rice herbicide programs for its ability to successfully control barnyardgrass along with other annual grasses and broadleaf weeds that are common in rice production (Carlson et al. 2011; Fish et al. 2015, 2016; Pellerin et al. 2004; Shaner 2014; Smith 1965). By the 1990s, at least one application of propanil was applied on 98% of the rice acreage in the southern United States (Carey et al. 1995). Propanil-resistant barnyardgrass was identified in Arkansas in the early 1990s, and it was determined that these resistant populations may require 2.5 to 20 times the use rate of propanil in order to achieve control (Baltazar and Smith 1994).

In 2000, clomazone [2-(2-Chlorophenyl)methyl-4,4-dimethyl-3-isoxazolidinone] was labeled for use in rice production. Clomazone is a diterpene synthesis inhibiting (Group 13) herbicide that acts by interfering with chloroplast development and reduces the accumulation of plastid pigments in susceptible weed species (Ferhatoglu and Barrett 2005). Clomazone applied preemergence (PRE) to rice on a course textured soil controlled barnyardgrass 96 to 97%, and when clomazone was applied postemergence (POST) to barnyardgrass at the one- to two-leaf stage, control was 85% (Willingham et al. 2008). The first confirmation of clomazone resistant barnyardgrass occurred in Arkansas in 2008 (Norsworthy et al. 2008).

Pendimethalin [N-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine] is a dinitroaniline (Group 3) herbicide that acts by disrupting mitotic cellular division through inhibition of microtubule proteins in susceptible weed species (Shaner 2014). Pendimethalin is a soil applied herbicide that is absorbed by germinating plant roots and coleoptiles causing highly susceptible weed species to not to emerge or die soon after emergence. Pendimethalin has shown to be active on grass and small seeded broadleaf weeds infesting rice when applied at different timings (Malik et al. 2010; Stauber et al. 1991; Bond et al. 2009).

The benefits to co-applying herbicides include: a broadened spectrum of weed control, economical benefits due to a single application versus multiple applications, and the prevention or delay of weed species becoming herbicide resistant (Carlson et al. 2011). Previous research completed in Louisiana reported that herbicide mixtures used in rice production can broaden the weed control spectrum and increase weed control (Carlson et al. 2011; Fish et al. 2015, 2016; Pellerin et al. 2004). Co-applying herbicides in a timely manner in the early growing season can help protect rice yield and prevent weed competition (Webster et al. 2012).

Herbicides applied within the same application have three possible interactions: additive/neutral, synergistic, or antagonistic (Blouin et al. 2004; Colby 1967; Flint et al. 1988; Morse 1978; Streibig et al. 1998). Synergism is when two jointly applied herbicides perform greater than the expected outcome of the herbicides applied alone (Colby 1967). In contrast, an antagonistic response is an interaction of two or more agrichemicals such that the effect when combined is less than the predicted effect based on the activity of each chemical applied separately. A neutral response is when the observed response of two jointly applied herbicides equals the expected response of each herbicide applied alone.

Colby's equation has been the benchmark for determining herbicide mixture interactions due to its simple and straightforward equation and its ability to analyze anything from visual observations, dry/fresh weights, weed counts, etc (Colby 1967). Colby's equation is a statistical linear model where the expected response is equal to the percent response of each herbicide applied alone, multiplied by one another, and then divided by one-hundred (Colby 1967, Flint et al. 1988). However, Blouin et al. (2004) argues that the expected response is defined as a multiplicative, non-linear function of the means for herbicides when applied alone, and a linear standard model for tests of hypotheses does not directly depict the correct expected response for the herbicide mixture. Thus, Blouin et al. (2004) developed a non-linear mixed model that is more sensitive than Colby's linear model in detecting significant differences in herbicides responses. Blouin et al. (2010) revised his previous model into an augmented mixed model, which proved to be more versatile than his previous model, and this analysis is often referred to as Blouin's modified Colby's.

Fish et al. (2015) reported a pre-packaged mixture of propanil plus thiobencarb co-applied with imazethapyr resulted in a synergistic response for red rice and barnyardgrass control. The same model was used to evaluate the interactions of propanil when mixed with imazamox or imazethapyr, and both synergistic and antagonistic responses occurred (Fish et al. 2015, 2016). Rustom et al. (2018) also employed Blouin's modified Colby's and reported antagonism when quizalofop was mixed with acetolactate synthase (ALS) enzyme inhibiting herbicides in rice.

The objective of this research was to evaluate the interaction between various rates of a pre-packaged mixture of clomazone plus pendimethalin along with various rates of propanil in order to control barnyardgrass, rice flatsedge (*Cyperus iria* L.), and yellow nutsedge (*Cyperus esculentus* L.). Blouin's modified Colby's equation was used to determine whether each mix is either: synergistic, antagonistic, or additive (Blouin et al. 2010). From this point forward, an additive response will be reported as a neutral response.

Materials and Methods

A study was conducted at the Louisiana State University Agricultural Center's H. Rouse Caffey Rice Research Station (RRS) near Crowley, Louisiana in 2017 and 2018 on a Crowley silt loam soil (fine montmorillonitic, nonacid, Vertic Haplaquept) with a pH 6.4 and 1.4% organic matter. Field preparation consisted of a fall and spring disking followed by two passes in opposite directions with a two-way bed conditioner consisting of rolling baskets and S-tine harrows set a 6-cm depth in the study area. A preplant fertilizer of 8-24-24 (N-P_2O_5-K_2O) was applied at 280 kg ha^{-1} followed by a preflood application of 365 kg ha^{-1} of urea fertilizer, 46-0-0.

The long grain rice imidazolinone-resistant rice cultivar 'CL111' and long grain ACCase-resistant rice cultivar 'PVL01' were drill seeded at 84 kg ha^{-1} on 18 cm rows on April 4th in 2017 and March 22nd in 2018, respectively. Plot size was 5.1 by 2.2 m^{-2}. No surface irrigation was utilized after planting due to 40- and 20-mm of rainfall occurring within five days of planting in

2017 and 2018, respectively. A total of 27- and 15-cm of rainfall was recorded from planting to the establishment of the permanent flood. An 8-cm permanent flood was established when the rice reached the one tiller growth stage and maintained until three weeks prior to harvest.

The experimental design was a two-factor factorial in a randomized complete block with four replications. Factor A consisted of a pre-packaged mix of clomazone plus pendimethalin applied at 0, 760, 1145, or 1540 g ai ha^{-1} (Table 2.1.). Factor B consisted of propanil applied at 0, 1120, 2240, or 4485 g ha^{-1}.

Table 2.1. Source of materials.

Herbicide	Trade Name	Form	g L	Manufacturer
Propanil	Stam M4	EC	480	RiceCo LLC, Memphis TN
Clomazone + pendimethalin	RiceOne	CS	130 + 313	RiceCo LLC, Memphis TN
Halosulfuron	Permit	WG	-[a]	Gowan Company, Yuma, AZ
Crop oil concentrate	Agri-Dex	COC	-[b]	Helena Chemical Company, Collierville, TN

[a]The formulation for halosulfuron is a water dispersible granule that contains 75% ai by weight
[b]The crop oil concentrate is formulated at 17% non-ionic surfactant and 83% unsulfonated oil residue

Herbicide applications were applied utilizing a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} at 190 kPa. The spray boom consisted of five flat-fan 110015 nozzles (Flat Fan AirMix Venturi Nozzle, Greenleaf Technologies, Covington, LA 70434) at 38 cm spacing. All herbicide mixtures were applied when rice reached the one- to two-leaf stage. A crop oil concentrate (COC) at 1% v v^{-1} was added to the treatment that contained only the pre-packaged mixture of clomazone plus pendimethalin (Table 2.1.). No COC was added to any herbicide mixture containing propanil due to its EC formulation. In order to obtain yield data, a standard uniform treatment of halosulfuron was applied at 35 DAT over the entire area at a rate of 53 g ha^{-1}.

The research area had a natural population of barnyardgrass, rice flatsedge, and yellow nutsedge. At the POST application timing, barnyardgrass were one- to two-leaf and two- to five-cm in height at a density of 30 to 40 plants m^{-2}. Both rice flatsedge and yellow nutsedge were at one set of three leaves and 3- to 5-cm in height at a density of 20 to 25 plants m^{-2} for rice flatsedge and 5 to 10 plants m^{-2} for yellow nutsedge. An activating 130- and 30-mm rainfall was recorded within five days of the POST applications in 2017 and 2018, respectively.

Visual evaluations included crop injury, barnyardgrass, rice flatsedge, and yellow nutsedge control on a scale of 0 to 100%, where 0 indicates no injury or control and 100 indicates complete plant death at 14, 28, 42, and 56 DAT. Rice flatsedge and yellow nutsedge were only rated at 14 and 28 DAT due to the uniform standard treatment of halosulfuron applied at 35 DAT. Rice plant height was recorded immediately prior to harvest by measuring four plants in each plot from the ground to the tip of the extended panicle. The center four rows of each plot were harvested utilizing a Mitsubishi VM3 (Mitsubishi Corporation, 3-1, Marunouchi 2- chome, Chiyoda-ky, Tokyo, Japan). Grain moisture was than adjusted to 12%.

Control data were analyzed using the Blouin et al. (2010) augmented mixed model to determine synergistic, antagonistic, or neutral responses for herbicide mixtures by comparing an expected control calculated based on activity of each herbicide applied alone to an observed control (Fish et al. 2015, 2016; Webster et al. 2017; Rustom et al. 2018). Rough rice yield and plant height data were analyzed using the MIXED procedure of SAS (SAS 2013). Tukey's HSD test was used to separate yield means at the 5% probability level. The fixed effects for all models were the herbicide treatments and evaluation timings. The random effects for the model were year, replication within year, and plot. Considering year or combination of years as a random effect accounts for different environmental conditions each year having an effect on herbicide treatments for that year (Carmer et al. 1989; Hager et al. 2003; Rustom et al. 2018). Normality of effects over all DAT was checked using the UNIVARIATE procedure of SAS. Assumptions of normality were met (SAS 2013)

Results and Discussion

At 14 days after treatment (DAT), antagonism occurred for barnyardgrass control when treated with clomazone plus pendimethalin at 1145 and 1540 g ha^{-1} mixed with 1120 g ha^{-1} of propanil, with an observed control of 79 and 81% compared with an expected control of 90 and 93%, respectively (Table 3.2.). However, these same mixtures were synergistic at 56 DAT. A synergistic response occurred when barnyardgrass was treated with 2240 and 4485 g ha^{-1} of propanil mixed with any rate of clomazone plus pendimethalin at 42 and 56 DAT. These data suggests that mixing a pre-packaged mixture of clomazone plus pendimethalin with propanil will increase barnyardgrass control later in the growing season compared with applying the herbicides individually. This increase in control is likely due to residual activity of both clomazone and pendimethalin that provides extended suppression of barnyardgrass after the initial application was applied. Similar results of synergism were observed for barnyardgrass control when propanil was mixed with imazethapyr or imazamox (Fish et al. 2015, 2016).

At 14 DAT, antagonism was observed for yellow nutsedge treated with 760, 1145, or 1540 g ha^{-1} of clomazone plus pendimethalin mixed with 1120 g ha^{-1} of propanil with an observed control 51, 54, and 56% observed control compared with the expected control of 59, 62, and 67%, respectively (Table 3.3.). An antagonistic response occurred for yellow nutsedge control when treated with clomazone plus pendimethalin at 1145 g ha^{-1} mixed with all rates of

Table 3.2. Barnyardgrass control and interactions with various rates of a pre-packaged mixture of clomazone plus pendimethalin mixed with various rates of propanil using Blouin's modified Colby's analysis, 2017 and 2018.[bc]

		Clomazone plus Pendimethalin (g ha^{-1})									
		0	760			1145			1540		
Herbicide Mixture[a]	Rate	Observed	Expected	Observed	P value	Expected	Observed	P value	Expected	Observed	P value
	g ha^{-1}	% control									
14 DAT[d]											
Propanil	0	0	-	73	-	-	80	-	-	85	-
Propanil	1120	52	88	78	0.0528	90	79-	0.0230	93	81-	0.0179
Propanil	2240	61	90	80	0.0606	92	84	0.1229	94	86	0.1460
Propanil	4485	65	91	85	0.2867	93	87	0.3193	95	93	0.7898
28 DAT											
Propanil	0	0	-	66	-	-	70	-	-	72	-
Propanil	1120	37	79	73	0.1929	81	77	0.2931	82	78	0.2636
Propanil	2240	38	79	65-	0.0023	82	78	0.3118	83	79	0.4403
Propanil	4485	37	78	75	0.4767	81	84	0.5841	82	84	0.8228
42 DAT											
Propanil	0	0	-	36	-	-	49	-	-	52	-
Propanil	1120	14	45	55+	0.0482	56	66+	0.0297	59	66	0.1273
Propanil	2240	14	45	60+	0.0031	56	70+	0.0032	59	73+	0.0026
Propanil	4485	16	46	71+	0.0001	57	76+	0.0001	60	84+	0.0001
56 DAT											
Propanil	0	0	-	27	-	-	38	-	-	44	-
Propanil	1120	7	32	47+	0.0054	43	56+	0.0091	49	72+	0.0001
Propanil	2240	11	35	61+	0.0001	45	70+	0.0001	50	77+	0.0001
Propanil	4485	12	36	62+	0.0000	45	71+	0.0001	51	82+	0.0001

[a]Evaluation dates for each respective herbicide mixture.

[b]Observed means followed by a plus (+) are significantly different from Blouin's modified Colby's expected responses at the 5% level indicating a synergistic response. A minus (-) indicates an antagonistic response. No sign indicates a neutral response.
[c]P < 0.05 indicates antagonistic or synergistic response, P > 0.05 indicates an additive response.
[d]DAT, days after treatment.

Table 3.3. Yellow nutsedge control and interactions with various rates of a pre-packaged mixture of clomazone and pendimethalin mixed with various rates of propanil using Blouin's modified Colby's analysis, 2017 and 2018.[bc]

		Clomazone plus Pendimethalin (g ha^{-1})									
		0	760			1145			1540		
Herbicide Mixture[a]	Rate	Observed	Expected	Observed	P value[c]	Expected	Observed	P value	Expected	Observed	P value
	g ha^{-1}	% of control									
14 DAT[d]											
Propanil	0	0	-	39	-	-	44	-	-	51	-
Propanil	1120	32	59	51-	0.0309	62	54-	0.0137	67	56-	0.0015
Propanil	2240	32	59	55	0.3689	62	53-	0.0082	67	69	0.4268
Propanil	4485	37	62	55	0.0694	65	57-	0.0253	69	69	0.8807
28 DAT											
Propanil	0	0	-	39	-	-	41	-	-	46	-
Propanil	1120	17	49	31-	0.0001	52	35-	0.0001	55	41-	0.0001
Propanil	2240	24	54	38-	0.0001	56	42-	0.0003	59	42-	0.0001
Propanil	4485	35	60	45-	0.0001	61	55	0.0562	64	51-	0.0001

[a]Evaluation dates for each respective herbicide mixture.
[b]Observed means followed by a plus (+) are significantly different from Blouin's modified Colby's expected responses at the 5% level indicating a synergistic response. A minus (-) indicates an antagonistic response. No sign indicates a neutral response.
[c]P < 0.05 indicates antagonistic or synergistic response, P > 0.05 indicates an additive response.
[d]DAT, days after treatment

Table 3.4. Rice flatsedge control and interactions with various rates of a pre-packaged mixture of clomazone and pendimethalin mixed with various rates of propanil using Blouin's modified Colby's analysis, 2017 and 2018.[bc]

		Clomazone plus Pendimethalin (g ha^{-1})									
		0	760			1145			1540		
Herbicide Mixture[a]	Rate	Observed	Expected	Observed	P value[c]	Expected	Observed	P value	Expected	Observed	P value
	g ha^{-1}	% of control									
14 DAT[d]											
Propanil	0	0	-	44	-	-	43	-	-	50	-
Propanil	1120	29	61	66	0.2119	60	69	0.0252	65	66	0.6835
Propanil	2240	22	57	69+	0.0025	56	69	0.0012	61	74+	0.0012
Propanil	4485	37	63	73+	0.0083	62	62	0.8901	67	81+	0.0003
28 DAT											
Propanil	0	0	-	38	-	-	42	-	-	48	-
Propanil	1120	23	52	47	0.1422	56	56	0.9035	60	61	0.7604
Propanil	2240	24	53	59	0.1149	56	66	0.0211	60	61	0.9638
Propanil	4485	25	54	57	0.3429	57	70	0.0015	61	69	0.0539

[a]Evaluation dates for each respective herbicide mixture.

[b]Observed means followed by a plus (+) are significantly different from Blouin's modified Colby's expected responses at the 5% level indicating a synergistic response. A minus (-) indicates an antagonistic response. No sign indicates a neutral response.

[c]$P < 0.05$ indicates antagonistic or synergistic response, $P > 0.05$ indicates an additive response.

propanil. At 28 DAT, antagonism occurred for yellow nutsedge control across all herbicide mixtures except when 1145 g ha^{-1} of clomazone plus pendimethalin was mixed with 4485 g ha^{-1} of propanil which resulted in a neutral response. In order to control the sedge population and obtain yield data, a standard uniform treatment of halosulfuron at 53 g ha^{-1} was applied over the entire test area at 35 DAT.

At 14 DAT, synergism occurred for rice flatsedge control when treated with clomazone plus pendimethalin at 760 g ha^{-1} mixed with propanil at either 2240 or 4485 g ha^{-1}, with an observed control of 69 and 73% compared with an expected control of 57 and 63%, respectively (Table 3.4.). Synergism also occurred at 14 DAT when clomazone plus pendimethalin at 1540 g ha^{-1} was mixed with propanil at either 2240 or 4485 g ha^{-1}, with an observed control of 74 and 81% compared with the expected of 61 and 67%. All other herbicide mixtures produced a neutral interaction across both 14 and 28 DAT. At 14 DAT, the synergism that occurred may have been due to the higher rates of propanil causing more necrosis on the rice flatsedge leaves. Those same herbicide mixtures that were synergistic at 14 DAT were neutral at 28 DAT.

Crop injury was 10 to 15% regardless of herbicide mixture applied at 14 DAT, and injury was less than 5% at all later rating dates, 0 to 5% (Data not shown). A main effect for propanil rate occurred for rice plant height. Rice treated with either 1120, 2240, 4485 g ha^{-1} of propanil resulted in heights of 98, 100, and 100-cm tall, respectively, which was taller than the nontreated rice at 86-cm (Table 3.5.). There was also a main effect for clomazone plus pendimethalin rate for plant height (Table 3.6.). Rice treated with either 1145 or 1540 g ha^{-1} of clomazone plus pendimethalin was 97 and 99-cm tall, respectively, which was taller than rice not treated with clomazone plus pendimethalin at 94-cm in height.

A clomazone plus pendimethalin rate by propanil rate interaction occurred for rice yield. Rough rice yield was 4560, 5360, and 5350 kg ha^{-1} when treated with 1540 g ha^{-1} of clomazone plus pendimethalin mixed with1120, 2240, and 4485 g ha^{-1} of propanil (Table 3.7.). Similarly,

Table 3.5. Rice plant height when treated with different rates of propanil, 2017 and 2018.

	Propanil (g ha^{-1})			
	0	1120	2240	4485
	kg ha^{-1}			
Plant Height[a]	86 b	98 a	100 a	101 a

[a]Means followed by a common letter are not significantly different at P = 0.05 with the use of Fisher's protected LSD.

Table 3.6. Rice plant height when treated with different rates of clomazone plus pendimethalin, 2017 and 2018.

	Clomazone plus pendimethalin (g ha^{-1})			
	0	760	1145	1540
	kg ha^{-1}			
Plant Height[a]	94 c	95 bc	97 ab	99 a

[a]Means followed by a common letter are not significantly different at P = 0.05 with the use of Fisher's protected LSD.

rice treated with 760 and 1145 g ha^{-1} of clomazone plus pendimethalin mixed with the high rate of propanil at 4485 g ha^{-1} yielded 4660 and 4800 kg ha^{-1}, respectively. These mixtures were also synergistic for barnyardgrass control compared with the herbicides applied alone (Table 3.2.). The rough rice yield data indicates that the synergism of clomazone plus pendimethalin mixed with propanil in a postemergence timing on barnyardgrass resulted in the corresponding rough rice yield increases.

In conclusion, the addition of a pre-packaged mixture of clomazone plus pendimethalin mixed with propanil is synergistic for control of barnyardgrass. These results are very similar to who reported increased control of barnyardgrass with propanil-containing herbicides mixed with other residual herbicides labeled in rice (Carlson et al. 2011, 2012; Fish et al. 2015; Pellerin et al.

Table 3.7. Rough rice yield when treated with different rates of clomazone plus pendimethalin mixed with different rates of propanil, 2017 and 2018.[b]

Herbicide Mixture[a]	Rate	Clomazone plus Pendimethalin (g ha^{-1}) 0	760	1145	1540
	g ha^{-1}	kg ha^{-1}			
Propanil	0	0 g	3490 c-f	3210 def	3420 c-f
Propanil	1120	2870 f	3960 b-e	4040 b-e	4560 ab
Propanil	2240	3090 ef	4220 bcd	4240 bcd	5360 a
Propanil	4485	3360 c-f	4660 ab	4800 ab	5350 a

[a]Respective herbicide mixtures

[b]Means followed by a common letter are not significantly different at P = 0.05 with the use of Fisher's protected LSD.

2003; Webster et al 2017) Applying residual herbicides like clomazone plus pendimethalin along with the postemergence herbicide propanil offers producers the ability to control small emerged grasses while providing extended control later in the growing season with the residual combination. If a second POST application is needed later in the season, the synergistic control from the pre-packaged mixture of clomazone plus pendimethalin mixed with propanil could potentially decrease the weed pressure present at the second POST application. An added benefit of applying multiple herbicide modes of action per individual application will help prevent or reduce the development of herbicide-resistant weeds, which can be part of an overall herbicide resistant management strategy (Norsworthy et al. 2012).

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Chapter 4
Herbicide Mixture Interactions with Clomazone and Pendimethalin in ACCase-Resistant Rice

Introduction

Red rice (*Oryza sativa* L.) is considered one of the most problematic weeds hindering rice (*Oryza sativa* L.) production in the southern United States (Carlson et al. 2011). Smith (1968) states that rice yield loss from season long competition of dense populations of red rice can be as high 82%. Red rice can also result in reductions in milling yields and grade (Webster 2014). Due to its genetic similarities to modern cultivated rice, red rice has been difficult to control with traditional labeled herbicides (Carlson et al. 2011; Pellerin et al. 2003, 2004). However, with the development and release of imidazolinone-resistant (IR) rice, also known as Clearfield (CL) (BASF, Research Triangle Park, NC 27709), in 2002, a means for control of red rice with herbicide in crop was finally a viable option for producers (Croughan 1994; Pellerin et al. 2003, 2004; Webster and Masson 2001). Acceptance of IR rice was quick, and by 2004, 27% of rice acreage in Louisiana was planted with IR rice (Shivrain et al. 2007).

The seeds of IR rice hybrids have a history of rapid seed shattering and dormancy, which can become problematic during succeeding growing seasons as a volunteer weed (Rustom et al. 2018; Sudianto et al. 2013). Because cultivated rice and red rice are sexually compatible, IR rice can transfer the herbicide-resistant gene to red rice (Shivrain et al. 2007). This outcrossing event has been reported by several researchers (Chen et al. 2004; Majumder et al. 1997; Messeguer et al. 2004; Rajguru et al. 2005; Song et al. 2002, 2003). The term weedy rice will refer to the entire complex of volunteer hybrid, outcross, and red rice (Rustom et al. 2018).

Barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.] is another problematic weed that negatively impacts rice production throughout the rice producing areas of the United States.

Producers can expect yield reductions up to 79% from barnyardgrass competition that lasts from rice emergence to maturity (Smith 1974). Baltazar and Smith 1994 reported one of the first cases of barnyardgrass resistance to propanil [N-(3,4-dichlorophenyl) propionamide]. This was quickly followed up by documented cases of barnyardgrass resistance to quincloarac (3,7-Dichloro-8-quinolinecarboxylic acid) in 1999 (Malik et al. 2010), clomazone [2-(2-Chlorophenyl)methyl-4,4-dimethyl-3-isoxazolidinone] in 2007 and imazethapyr (2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid) in 2008 (Dilpert et al. 2013; Wilson et al. 2014).

After the evolution of IR weedy rice and several documented cases of barnyardgrass resistance to multiple modes of action, BASF launched an ACCase-resistant (ACCase-R) rice system sold under the trade name Provisia (Provisia Rice®, BASF Corporation, Research Triangle Park, NC). The ACCase-R rice technology will utilize quizalofop as the targeted herbicide at rates of 92 to 155 g ai ha^{-1}, and not to exceed 240 g ha^{-1} per year. Quizalofop provides postemergence (POST) control of weedy rice and other annual and perennial grasses by inhibiting acetyl Coenzyme A carboxylase, the enzyme responsible for catalyzing the first committed step of de novo fatty acid synthesis (Burton et al. 1989; Focke and Lichtenthaler 1987). For the past several decades quizalofop has been utilized in soybean production for a primary means of red rice control at rates of 35 to g ha^{-1} (Askew et al. 1998; Minton et al. 1989; Shaner 2014).

Mixing different herbicides within a single application is a cost effect way for producers to apply herbicide programs. A simple application with multiple herbicides in a mixture reduces costs, saves time, reduces wear and tear on equipment, and may broaden the weed control spectrum (Carlson et al. 2012; Hydrick and Shaw 1995, 1994; Minton et al. 1989; Rhodes and

Coble 1984; Wilson et al. 1985; Shaw and Arnold 2002; Webster and Shaw 1997). Mixing herbicides can result in three different responses: synergism, antagonism, or additive/neutral (Berenbaum 1981; Blouin 2010; Drury 1980; Fish et al. 2015, 2016; Hatzios and Penner 1985; Morse 1978; Nash 1981; Rustom et al. 2018; Streibig et al. 1998). Antagonism is defined by Colby (1967) as an interaction of two or more agrichemicals such that the effect when combined is less than the predicted effect based on the activity of each chemical applied separately. ACCase herbicides can often be antagonized when mixed with other broadleaf herbicides (Barnwell and Cobb 1994; Green 1989; Kim et al. 2006; Rustom et al. 2018; Scherder et al. 2005; Zhang et al. 2005). ACCase antagonism on weedy rice and barnyardgrass has previously been observed by Rustom et al. (2018). Quizalofop activity was reduced when applied in conjunction with penoxsulam, penoxsulam plus triclopyr, halosulfuron, bispyribac, orthosulfamuron plus halosulfuron, orthosulfamuron plus quinclorac, imazosulfuron, and bensulfuron.

In 2000, clomazone [2-(2-Chlorophenyl)methyl-4,4-dimethyl-3-isoxazolidinone] was labeled for use in rice production. Clomazone is a diterpene synthesis inhibiting (Group 13) herbicide that acts by interfering with chloroplast development and reduces the accumulation of plastid pigments in susceptible weed species (Ferhatoglu and Barrett 2005). Clomazone applied preemergence (PRE) to rice on a course textured soil controlled barnyardgrass 96 to 97%, and clomazone applied postemergence (POST) to barnyardgrass at the one- to two-leaf stage, controlled barnyardgrass 85% (Willingham et al. 2008). The first confirmation of clomazone resistant barnyardgrass occurred in Arkansas in 2008 (Norsworthy et al. 2008).

Pendimethalin [N-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine] is a dinitroaniline (Group 3) herbicide that acts by disrupting mitotic cellular division through inhibition of microtubule proteins in susceptible weed species (Vaughn and Lehnen 1991). Pendimethalin is a soil applied herbicide that is absorbed by germinating plant roots and coleoptiles causing highly susceptible weed species to not to emerge or die soon after emergence. Pendimethalin has shown to be active on grass and small seeded broadleaf weeds infesting rice when applied at different timings (Malik et al. 2010; Stauber et al. 1991; Bond et al. 2009). RiceOne (RiceOne label, RiceCo LLC, Memphis, TN 38137) is a pre-packaged mixture of clomazone plus pendimethalin in a dual aqueous capsule suspension formulation, at 130 and 313 grams of active ingredient per liter, respectively.

ACCase-R rice will help preserve the IR rice system by allowing producers to rotate between the two systems while providing a mechanism of control for weedy rice and troublesome grass species in their fields. However, given the history of ACCase herbicides being antagonized when mixed with other herbicides labeled in rice production, it is important for producers to know what type of response will occur when mixing any type of herbicide with and ACCase herbicide. The objective of this research was to determine whether an antagonistic, synergistic, or neutral interaction occurs when quizalofop is mixed with clomazone, pendimethalin, or a pre-package mixture of clomazone plus pendimethalin.

Materials and Methods

A study was conducted in 2017 and 2018 at the Louisiana State University Agricultural Center’s H. Rouse Caffey Rice Research Station (RRS) near Crowley, Louisiana to evaluate the activity of quizalofop applied independently or in a mixture with other herbicides with residual activity. The soil type at the RRS is a Crowley silt loam (fine montmorillonitic, nonacid, Vetic haplaquept) with a pH 6.4 and 1.4% organic matter. Field preparation consisted of a fall and spring disking followed by two passes in opposite directions with a two-way bed conditioner consisting of rolling baskets and S-time harrows set a 6 cm depth. A preplant fertilizer application of 280 kg ha^{-1} of 8-24-24 (N-P_2O_5-K_2O) followed by a preflood application of 365 kg ha^{-1} of urea fertilizer 46-0-0 was applied to the study area.

Long grain ACCase-resistant (ACCase-R) rice cultivar ‘PVL01’ were drill seeded at 84 kg ha^{-1} on April 26^{th} and April 12^{th} in 2017 and 2018, respectively. Plot size was 5.1 by 2.2 m, with eight-19.5 cm wide rows. In order to simulate a weedy rice population, eight rows of IR ‘CL-111’ long grain rice was drill-seeded perpendicular to the ACCase-R rice in the front third of each plot, and eight rows of IR ‘CLXL-745’ hybrid long grain rice was drill-seeded perpendicular to the ACCase-R rice in the back third of each plot. All drill seeded rice was planted to a depth of 15 mm. Awnless red rice was than broadcasted across the study area at a rate of 50 kg ha^{-1} immediately prior to planting. The research area had a natural population of barnyardgrass. The research area was surface irrigated to a depth of 3 cm, 24 h after planting. An 8-cm permanent flood was established when the rice reached the one-tiller growth stage and maintained until three weeks prior to harvest.

The experimental design was a two-factor factorial in a randomized complete block with four replications. Factor A consisted of no mixture herbicide, 335 g ai ha^{-1} of clomazone, 810 g ha^{-1} of pendimethalin, 335 g ha^{-1} of clomazone mixed with 810 g ha^{-1} of pendimethalin, and 1145 g ha^{-1} of a pre-packaged mix of clomazone plus pendimethalin. Clomazone and pendimethalin rates applied alone were equal to the rates found in the pre-packaged mixture of clomazone plus pendimethalin. Factor B consisted of quizalofop applied at 0 or 120 g ha^{-1}. Sources of materials are listed in Table 4.1. In order to stay within the recommended BASF stewardship guidelines; a second application of quizalofop was applied to the entire test area at a rate of 120 g ha^{-1} at 21 day after the initial quizalofop treatment (DAIT) (Anonymous 2017). A crop oil concentrate was added to each herbicide treatment at 1% v v^{-1}. Each herbicide application was applied when ACCase-R rice was at the two- to three-leaf growth stage. Red rice, CL-111, CLXL-745, were also at the two- to three-leaf stage and barnyardgrass was at the two- to four-leaf stage with a population of 30 to 40 plants m^{-2}. An activating 3-cm flush was applied to the entire research area within five days of the POST application in 2017 and 2018. Herbicide applications were applied utilizing a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} at 190 kPa. The spray boom consisted of five flat-fan 110015 nozzles (Flat Fan AirMix Venturi Nozzle, Greenleaf Technologies, Covington, LA 70434) at 38 cm spacing.

Table 4.1. Source of materials.

Herbicide	Trade Name	Form	g L	Manufacturer
Clomazone	Command	EC	360	FMC Corporation, Philadelphia, PA
Pendimethalin	Prowl	H_2O	455	BASF Corporation, Research Triangle Park, NC
Clomazone + pendimethalin	RiceOne	CS	130 + 313	RiceCo LLC, Memphis TN
Quizalofop	Provisia	EC	105	BASF Corporation, Research Triangle Park, NC
Crop oil concentrate	Agri-Dex	COC	-[a]	Helena Chemical Company, Collierville, TN

[a]The crop oil concentrate was used at 1% v v^{-1}.

Visual evaluations of crop injury, and barnyardgrass, red rice, CL-111, and CLXL-745 control on a scale of 0 to 100%, where 0 indicates no injury or control and 100 indicates complete plant death at 7, 14, 28, and 42 DAIT. Rice plant height was recorded immediately prior to harvest by measuring four plants in each plot from the ground to the tip of the extended panicle. The center four rows of each plot were harvested utilizing a Mitsubishi VM3 (Mitsubishi Corporation, 3-1, Marunouchi 2- chome, Chiyoda-ky, Tokyo, Japan). Grain moisture was than adjusted to 12%.

Control data was analyzed using the guidelines described in Blouin et al. (2010) augmented mixed model to determine synergistic, antagonistic, or neutral responses for herbicide mixtures by comparing an expected control calculated based on the activity of each herbicide applied alone to an observed control (Fish et al. 2015, 2016; Webster et al. 2012; Rustom et al. 2018). Rough rice yield and plant height data were analyzed using the MIXED procedure of SAS (SAS 2013). Tukey's HSD test was used to separate yield means at the 5% probability level. The fixed effects of the model were the herbicide treatments and evaluation timings. The random effects for the model were location by year and replications within location by year, and treatment by replication interactions. The dependent variables in the separate analyses were barnyardgrass, CL-111, CLXL-745, and red rice control along with plant height and rough rice yield. The analyses for control were by DAT. Normality of effects over all DAT was checked using the UNIVARIATE procedure of SAS. Assumptions of normality were met (SAS 2013).

Results and Discussion

An antagonistic response was observed for barnyardgrass control at 7 DAIT when quizalofop was mixed with clomazone, clomazone plus pendimethalin, and the pre-packaged mixture of clomazone plus pendimethalin by reducing an excepted control of 99% to an observed control of 94, 94, and 95%, respectively (Table 4.2.). The data indicates that the antagonism may be caused by the addition of clomazone, because the pendimethalin applied alone with quizalofop resulted in neutral responses. Even though antagonism occurred at 7 DAIT, control of barnyardgrass was 94 to 98% across all rating dates. These data indicate that the addition of one of the residuals can be mixed with quizalofop with little negative impact.

A neutral herbicide interaction occurred for CL-111 across all herbicide mixtures and evaluation dates (Table 4.3.). At 7 DAIT, control for CL-111 was 87 to 90% across all herbicide

Table 4.2. Barnyardgrass control and interactions with quizalofop applied alone or mixed with residual herbicides using Blouin's modified Colby's analysis, 2017 and 2018.

		Quizalofop (g ha^{-1})			
		0	120		
Mixture Herbicide[a]	Rate	Observed	Expected	Observed[b]	P value[c]
	—g ha^{-1}—		% of control		
7 DAIT					
None	—	0	—	95	—
Clomazone	335	76	99	94-	0.0031
Pendimethalin	810	54	99	96	0.1662
Clomazone + pendimethalin	1145	74	99	94-	0.0031
PP - Clomazone + pendimethalin[d]	1145	77	99	95-	0.0030
14 DAIT					
None	—	0	—	98	—
Clomazone	335	79	100	97	0.1630
Pendimethalin	810	49	99	98	0.4648
Clomazone + pendimethalin	1145	78	100	97	0.1655
PP - Clomazone + pendimethalin	1145	79	100	97	0.1571
28 DAIT[e]					
None	—	64	—	98	—
Clomazone	335	85	99	97	0.3568
Pendimethalin	810	71	98	98	0.8587
Clomazone + pendimethalin	1145	88	99	97	0.2475
PP - Clomazone + pendimethalin	1145	91	99	98	0.2322
42 DAIT					
None	—	98	—	96	—
Clomazone	335	96	94	96	0.6816
Pendimethalin	810	97	95	97	0.6701
Clomazone + pendimethalin	1145	96	94	97	0.6250
PP - Clomazone + pendimethalin	1145	96	93	97	0.5746

[a]Evaluation dates for each respective herbicide mixture, are in day after initial treatment (DAIT).
[b]Observed means followed by a minus (-) are significantly different from Blouin's modified Colby's expected responses at the 5% level indicating an antagonistic response. No (-) indicates an additive response.
[c]$P < 0.05$ indicates anantagonistic response, $P > 0.05$ indicates an additive response.
[d] PP, pre-packaged mixture. RiceOne® contains 130 g clomazone plus 313 g L^{-1} in a dual encapsulated suspension.
[e]Control observed for each mixture herbicide with an additional independent application of quizalofop applied 21 days after the initial treatment.

Table 4.3. CL-111 control and interactions with quizalofop applied alone or mixed with residual herbicides using Blouin's modified Colby's analysis, 2017 and 2018.

		Quizalofop (g ha^{-1})			
		0	120		
Mixture Herbicide[a]	Rate	Observed	Expected	Observed[b]	P value[c]
	—g ha^{-1}—	% of control			
7 DAIT					
None	—	0	—	89	—
Clomazone	335	0	89	90	0.6293
Pendimethalin	810	0	89	88	0.6874
Clomazone + pendimethalin	1145	0	89	89	0.6873
PP - Clomazone + pendimethalin[d]	1145	0	89	89	0.9358
14 DAIT					
None	—	0	—	98	—
Clomazone	335	0	98	98	0.8112
Pendimethalin	810	0	98	97	0.5989
Clomazone + pendimethalin	1145	0	98	98	0.7530
PP - Clomazone + pendimethalin	1145	0	98	98	0.9355
28 DAIT[e]					
None	—	72	—	98	—
Clomazone	335	75	98	98	0.8974
Pendimethalin	810	71	98	97	0.6382
Clomazone + pendimethalin	1145	71	98	98	0.8305
PP - Clomazone + pendimethalin	1145	75	98	98	0.9827
42 DAIT					
None	—	97	—	97	—
Clomazone	335	97	97	97	0.7334
Pendimethalin	810	97	97	96	0.7724
Clomazone + pendimethalin	1145	97	97	97	0.8939
PP - Clomazone + pendimethalin	1145	97	96	97	0.8175

[a]Evaluation dates for each respective herbicide mixture, are in day after initial treatment (DAIT).
[b]Observed means followed by a minus (-) are significantly different from Blouin's modified Colby's expected responses at the 5% level indicating an antagonistic response. No (-) indicates an additive response.
[c]P < 0.05 indicates anantagonistic response, P > 0.05 indicates an additive response.
[d] PP, pre-packaged mixture. RiceOne® contains 130 g clomazone plus 313 g L^{-1} in a dual encapsulated suspension.
[e]Control observed for each mixture herbicide with an additional independent application of quizalofop applied 21 days after the initial treatment.

mixtures; however, by 14 DAIT, control was increased to 98%. These results are similar to Minton et al. (1989) who reported increased control of red rice at 91% three weeks after treatment compared with 83% at 1 week after treatment inferring that quizalofop takes longer than 7 days to fully control weedy rice.

A neutral herbicide interaction occurred for CLXL-745 across all herbicide mixtures and evaluation dates (Table 4.4.). Similar results occurred compared with CL-111 control for control of CLXL-745 with 87 to 90% control at 7 DAIT across all herbicide mixtures. However, by 14 DAIT, control was increased to 98%. These results are similar to those reported by Minton et al. (1989).

A neutral herbicide interaction occurred for red rice across all herbicide mixtures and evaluation dates (Table 4.5.). At 7 DAIT, control of red rice was 82 to 85% across all herbicide mixtures; however, by 14 DAIT, control increased to 98 to 99%. Red rice has been reported to have faster emergence, higher tillering rate, taller growth habit, and produce more straw material than cultivated rice (Diarra et al. 1985). These morphological features may play an important rule on the speed of herbicide translocation by having more vegetative growth, making the herbicide translocate farther to the site of action and ultimately lowering the control of red rice over CL-111 and CLXL-745 at 7 DAIT. The pre-packaged mixture of clomazone plus pendimethalin had a neutral interaction when mixed with quizalofop as did the mixture of clomazone and pendimethalin when added individually for control of CL-111, CLXL-745, and red rice across all evaluation dates.

Crop injury did not exceed 5% across all herbicide treatments and evaluation dates, 0 to 5% (data not shown). Rice plant height was similar across all herbicide treatments, 104 to 107 cm (data not shown). An interaction occurred for rough rice yield by quizalofop application

Table 4.4. Hybrid CLXL-745 control and interactions with quizalofop applied alone or mixed with residual herbicides using Blouin's modified Colby's analysis, 2017 and 2018.

		Quizalofop (g ha^{-1})			
		0	120		
Mixture Herbicide[a]	Rate	Observed	Expected	Observed[b]	P value[c]
	—g ha^{-1}—		% of control		
7 DAIT					
None	—	0	—	90	—
Clomazone	335	0	90	90	0.6007
Pendimethalin	810	0	90	89	0.5420
Clomazone + pendimethalin	1145	0	90	87	0.1232
PP - Clomazone + pendimethalin[d]	1145	0	90	89	0.6626
14 DAIT					
None	—	0	—	99	—
Clomazone	335	0	98	98	0.7377
Pendimethalin	810	0	98	98	0.6819
Clomazone + pendimethalin	1145	0	98	98	0.6306
PP - Clomazone + pendimethalin	1145	0	98	98	0.8625
28 DAIT[e]					
None	—	74	—	98	—
Clomazone	335	71	98	98	0.9778
Pendimethalin	810	74	98	98	0.9303
Clomazone + pendimethalin	1145	71	98	98	0.8454
PP - Clomazone + pendimethalin	1145	71	98	98	0.8453
42 DAIT					
None	—	98	—	96	—
Clomazone	335	96	94	98	0.1661
Pendimethalin	810	97	96	97	0.6789
Clomazone + pendimethalin	1145	97	96	97	0.4836
PP - Clomazone + pendimethalin	1145	97	96	96	0.6759

[a]Evaluation dates for each respective herbicide mixture, are in day after initial treatment (DAIT).

[b]Observed means followed by a minus (-) are significantly different from Blouin's modified Colby's expected responses at the 5% level indicating an antagonistic response. No (-) indicates an additive response.

[c]P < 0.05 indicates anantagonistic response, P > 0.05 indicates an additive response.

[d] PP, pre-packaged mixture. RiceOne® contains 130 g clomazone plus 313 g L^{-1} in a dual encapsulated suspension.

[e]Control observed for each mixture herbicide with an additional independent application of quizalofop applied 21 days after the initial treatment.

Table 4.5. Red rice control and interactions with quizalofop applied alone or mixed with residual herbicides using Blouin's modified Colby's analysis, 2017 and 2018.

		Quizalofop (g ha^{-1})			
		0	120		
Mixture Herbicide[a]	Rate	Observed	Expected	Observed[b]	P value[c]
	—g ha^{-1}—		% of control		
7 DAIT					
None	—	0	—	85	—
Clomazone	335	0	85	82	0.2915
Pendimethalin	810	0	85	85	0.9187
Clomazone + pendimethalin	1145	0	85	84	0.9593
PP - Clomazone + pendimethalin[d]	1145	0	85	85	0.8383
14 DAIT					
None	—	0	—	99	—
Clomazone	335	0	99	99	0.9590
Pendimethalin	810	0	99	98	0.9590
Clomazone + pendimethalin	1145	0	99	98	0.8439
PP - Clomazone + pendimethalin	1145	0	99	99	0.9590
28 DAIT[e]					
None	—	72	—	99	—
Clomazone	335	74	99	98	0.7757
Pendimethalin	810	71	99	98	0.9694
Clomazone + pendimethalin	1145	71	99	99	0.9496
PP - Clomazone + pendimethalin	1145	72	99	98	0.9590
42 DAIT					
None	—	96	—	97	—
Clomazone	335	97	97	97	0.9596
Pendimethalin	810	97	97	96	0.8554
Clomazone + pendimethalin	1145	97	97	97	0.9354
PP - Clomazone + pendimethalin	1145	97	98	97	0.9094

[a]Evaluation dates for each respective herbicide mixture, are in day after initial treatment (DAIT).

[b]Observed means followed by a minus (-) are significantly different from Blouin's modified Colby's expected responses at the 5% level indicating an antagonistic response. No (-) indicates an additive response.

[c]$P < 0.05$ indicates anantagonistic response, $P > 0.05$ indicates an additive response.

[d] PP, pre-packaged mixture. RiceOne® contains 130 g clomazone plus 313 g L^{-1} in a dual encapsulated suspension.

[e]Control observed for each mixture herbicide with an additional independent application of quizalofop applied 21 days after the initial treatment.

averaged over herbicide residual herbicides (Table 4.6.). Rice treated with an initial application of quizalofop yielded 5440 kg ha^{-1}. Rice yield decreased to 4360 kg ha^{-1} when not receiving the initial quizalofop application. This decrease in yield was likely due to the increased competition from the CL-111, CLXL-745, and red rice however, the second quizalofop application helped recover some yield.

Table 4.6. Rough rice yield when treated with 0 or 120 g ha^{-1} of quizalofop, 2017 and 2018.[a]

Herbicide	Rate	Rough rice yield
	—g ha^{-1}—	——— kg ha^{-1} ———
Quizalofop	0	4360 b
Quizalofop[b]	120	5440 a

[a]Means followed by a common letter are not significantly different at P = 0.05 with the use of Tukey's HSD test.
[b]Rough rice yield with an additional independent application of quizalofop applied 21 days after the initial treatment.

In conclusion, the addition of a pre-packaged mixture of clomazone plus pendimethalin in mixture with quizalofop offers a neutral interaction for control of weedy rice and barnyardgrass. Combining quizalofop with clomazone plus pendimethalin offers producers the ability to apply a postemergence herbicide to control already emerged grasses while providing residual activity for later into the growing season. Quizalofop can often be antagonized in regards to weedy rice and barnyardgrass control when mixed with other ALS-inhibiting herbicides (Rustom et al. 2018). A benefit of applying a mixture of quizalofop with clomazone plus pendimethalin in the first application is that this mixture provides producers the ability to mix broadleaf specific herbicides with their second application of quizalofop with less fear of antagonism due to the decreased abundance and size of the grass species (Eric Webster, LSU AgCenter Extension Weed Scientist, personal communication).

The addition of multiple herbicides with different modes action per individual application can help prevent or reduce the chance of herbicide resistance weeds developing, and can be part of an overall strategy to manage the development of herbicide resistance (Norsworthy et al. 2012). There are multiple weed species that infest rice fields in Louisiana and rarely is there single monoculture of weed species in a particular field (Braverman 1995). The ACCase-R rice production system can be effective at controlling grass weed species; however, quizalofop has no activity on broadleaf weeds like Indian jointvetch (*Aeschynomene indica* L.) or hemp sesbania; [*Sesbania herbacea* (Mill.) McVaugh] therefore, a herbicide mixture that contains a broadleaf herbicide may be needed. The combination of quizalofop with clomazone plus pendimethalin provides a mixture with three different modes of action, and can help broaden the weed control spectrum within a single application (Carlson et al. 2011, 2012; Webster and Masson 2001; Norsworthy et al. 2007; Pellerin et al. 2004; Webster et al. 2012). This herbicide mixture will also offer growers a herbicide resistance management program in their ACCase-R rice production system.

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Chapter 5

Summary

Over the past several decades, advances in chemical weed management technology have played an important role in the development of the rice (*Oryza sativa L.*) industry (Ashton and Monaco 1991; Carlson et al. 2011). Often, a grower's weed management program will drive the overall production system depending on the presence and pressure of certain weed species (Norsworthy et al. 2007; Webster 2014).

Barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv] is one of the most noxious and prolific weeds that infest rice acres in the southern United States (Norsworthy et al. 2013). Barnyardgrass can reduce rice yields by 30% and potentially cause complete crop loss if left uncontrolled (Bagavathiannan et al. 2014; Johnson et al. 1998). Barnyardgrass is highly competitive with rice due to its rapid growth, its C_4 photosynthetic pathway, and its ability to mass produce seed (Holm et al. 1977; Vengris et al. 1966). Since the 1990s barnyardgrass has been documented being resistant to different active ingredients including: propanil in 1994, quinclorac in 1999, clomazone in 2007 and imazethapyr in 2008 (Baltazar and Smith 1994; Dilpert et al. 2013; Malik et al. 2010; Wilson et al. 2014).

The benefits to co-applying herbicides include a broadened spectrum of weed control, economical benefits due to a single application versus multiple applications, and the prevention or delay of weed species becoming herbicide resistant (Carlson et al. 2011). Previous research conducted in Louisiana reported that herbicide mixtures used in rice production can broaden the weed control spectrum and increase weed control (Carlson et al. 2011; Fish et al. 2015, 2016; Pellerin et al. 2004). Co-applying herbicides in a timely manner in the early growing season can help protect rice yield and prevent weed competition (Webster et al. 2012).

Herbicides applied within the same application have three possible interactions: additive/neutral, synergistic, or antagonistic (Blouin et al. 2004, 2010; Colby 1967; Flint et al. 1988; Morse 1978; Streibig et al. 1998). Synergism is when two jointly applied herbicides perform greater than the expected outcome of the herbicides applied alone (Colby 1967). In contrast, an antagonistic response is an interaction of two or more agrichemicals such that the effect when combined is less than the predicted effect based on the activity of each chemical applied separately. A neutral response is when the observed response of two jointly applied herbicides equals the expected response of each herbicide applied alone.

The objective of this research was to evaluate the interaction of a pre-packaged mixture of clomazone plus pendimethalin mixed with other postemergence herbicides that are labeled in rice for weed management. In addition, a study was conducted to determine the proper application timing of the pre-packaged mixture of clomazone plus pendimethalin in correlation with other residual herbicide combination timings.

A study was conducted at the Louisiana State University Agricultural Center's H. Rouse Caffey Rice Research Station (RRS) near Crowley, Louisiana in 2017 and 2018 to evaluate whether the pre-packaged mixture of clomazone plus pendimethalin should be applied delayed preemergence (DPRE) or postemergence (POST) within a herbicide residual overlay weed management program with saflufenacil, clomazone, or quinclorac. POST applications also included penoxsulam or halosulfuron in combination with the second residual application. Visual evaluations for the study included crop injury, barnyardgrass, rice flatsedge (*Cyperus iria* L.), yellow nutsedge (*Cyperus esculentus* L.), and Texasweed [*Caperonia palustris* (L.) St. Hil.] at 14, 28, and 42 days after treatment (DAT). Yield data was also recorded.

There were no differences in barnyardgrass control at 14 DAT across all treatments with 92 to 98% control. At 42 DAT, barnyardgrass treated with either clomazone plus pendimethalin applied at either timing in combination with either clomazone or quinclorac applied POST controlled barnyardgrass 95 to 96%. However, when saflufenacil was applied PRE regardless of the POST herbicide or when saflufenacil was applied POST with halosulfuron resulted in reduced barnyardgrass control, 78 to 81%, compared with control with all other residual combinations, 95 to 96%. A POST application of halosulfuron or penoxsulam by evaluation dates interaction occurred for rice flatsedge and yellow nutsedge control, data averaged over residual herbicide program. Yellow nutsedge and rice flatsedge control was higher when treated with halosulfuron over penoxsulam over all evaluation dates. Rough rice yield was 5690 to 5700 kg ha^{-1} when rice was treated in combination with clomazone and clomazone plus pendimethalin regardless of application timing. No difference in rough rice yield was observed when saflufenacil or quinclorac were applied POST following the pre-packaged mixture; however, rough rice yield decreased with saflufenacil or quinclorac applied PRE compared with rice treated with clomazone PRE or DPRE pre-packaged mixture combination regardless of the addition of halosulfuron or penoxsulam.

A study was conducted at the RRS in 2017 and 2018 to evaluate the interaction between various rates of clomazone plus pendimethalin mixed with various rates of propanil. Visual evaluations for this study included crop injury, barnyardgrass, rice flatsedge, and yellow nutsedge control at 14, 28, 42, and 56 DAT. Yield data was also recorded.

At 14 days after treatment, antagonism occurred for barnyardgrass control when treated with clomazone plus pendimethalin at 1145 and 1540 g ha^{-1} mixed with 1120 g ha^{-1} of propanil, with an observed control of 79 and 81% compared with an expected control of 90 and 93%, respectively. However, these same mixtures were synergistic at 56 DAT. A synergistic response occurred when barnyardgrass was treated with 2240 and 4485 g ha^{-1} of propanil mixed with any rate of clomazone plus pendimethalin at 42 and 56 DAT. At 28 DAT, antagonism occurred for yellow nutsedge control across all herbicide mixtures except when 1145 g ha^{-1} of clomazone plus pendimethalin was mixed with 4485 g ha^{-1} of propanil which resulted in a neutral response. For yellow nutsedge control, all herbicide mixtures were neutral at 28 DAT. Rough rice yield was 4560, 5360, and 5350 kg ha^{-1} when treated with 1540 g ha^{-1} of clomazone plus pendimethalin mixed with1120, 2240, and 4485 g ha^{-1} of propanil. Similarly, rice treated with 760 and 1145 g ha^{-1} of clomazone plus pendimethalin mixed with the high rate of propanil at 4485 g ha^{-1} yielded 4660 and 4800 kg ha^{-1}, respectively.

A study was conducted in 2017 and 2018 at the RRS to evaluate the activity of quizalofop applied independently or in a mixture with clomazone, pendimethalin, clomazone plus pendimethalin, and a prepackaged mixture of clomazone plus pendimethalin in ACCase resistant (ACCase-R) rice. Visual evaluations for this study included crop injury, and barnyardgrass, red rice, CL-111, and CLXL-745 control at 7, 14, 28, and 42 days after initial treatment (DAIT). Rice yield data was also recorded. Additionally, a second application of quizalofop was applied to all treatments at 21 DAIT.

An antagonistic response was observed for barnyardgrass control at 7 DAIT when quizalofop was mixed with clomazone, clomazone plus pendimethalin, and the pre-packaged mixture of clomazone plus pendimethalin by reducing an excepted control of 99% to an observed control of 94, 94, and 95%, respectively. AT 14, 28, and 42 DAIT, all herbicide mixtures produced a neutral interaction. A neutral herbicide interaction occurred for CL-111, CLXL-745, and red rice control across all herbicide mixtures and evaluation dates. An interaction occurred for rough rice yield by quizalofop application averaged over herbicide residual herbicides. Rice treated with an initial application of quizalofop yielded 5440 kg ha^{-1}. Rice yield decreased to 4360 kg ha^{-1} when not receiving the initial quizalofop application.

In conclusion, applying residual herbicides like clomazone and pendimethalin along with other postemergence herbicides like propanil, quizalofop, halosulfuron, or penoxsulam offers producers the ability to control small emerged grasses while providing extended control later in the growing season with the residual combination. If a second POST application is needed later in the season, the control from the pre-packaged mixture of clomazone plus pendimethalin mixed with any POST herbicides could potentially decrease the weed pressure present at the second POST application.

Also, the addition of multiple herbicides with different modes action per individual application can help prevent or reduce the chance of herbicide resistance weeds developing, and can be part of an overall strategy to manage the development of herbicide resistance (Norsworthy et al. 2012). There are multiple weed species that infest rice fields in Louisiana and rarely is there single monoculture of weed species in a particular field (Braverman 1995). The ACCase-R rice production system can be effective at controlling grass weed species; however, quizalofop has no activity on broadleaf weeds like Indian jointvetch (*Aeschynomene indica* L.) or hemp sesbania; [*Sesbania herbacea* (Mill.) McVaugh] so, a herbicide mixture that contains a broadleaf herbicide may be needed. The combination of quizalofop with clomazone plus pendimethalin provides a mixture with three different modes of action, and can help broaden the weed control spectrum within a single application (Carlson et al. 2011, 2012; Webster and Masson 2001; Norsworthy et al. 2007; Pellerin et al. 2004; Webster et al. 2012). This herbicide mixture will also offer growers a herbicide resistance management program in their rice production system.

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Vita

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