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Herbicide Programs for Controlling Glyphosate-Resistant Johnsongrass (*Sorghum halepense*) in Glufosinate-Resistant Soybean

Dennis B. Johnson, Jason K. Norsworthy, and Robert C. Scott*

Three field experiments were conducted in 2010 and 2012 in a soybean production field near West Memphis, AR, containing glyphosate-resistant johnsongrass. The goal of this research was to develop effective herbicide programs for glyphosate-resistant johnsongrass in glufosinate-resistant soybean. Control of the resistant johnsongrass was greater with glufosinate at 590 and 740 g ai ha^{-1} than at 450 g ha^{-1}. Sequential glufosinate applications were more effective than a single application, irrespective of rate. A PRE application of flumioxazin at 71 g ai ha^{-1} immediately after planting provided no more than 26% johnsongrass control 6 wk after soybean emergence (WAE). The addition of clethodim at 136 g ai ha^{-1} to sequential applications of glufosinate at 450 g ha^{-1} improved control over sequentially applied glufosinate alone. Herbicide programs containing imazethapyr or imazamox in combination with glufosinate followed by clethodim plus glufosinate controlled johnsongrass at least 94% at 10 WAE and provided three distinct mechanisms of action, a highly effective resistance management strategy. Results from this research indicate that a high level of glyphosate-resistant johnsongrass control can be achieved through the use of several herbicide options in glufosinate-resistant soybean.

Nomenclature: Clethodim; flumioxazin; fomesafen; glufosinate; glyphosate; imazamox; imazethapyr; johnsongrass, *Sorghum halepense* (L.) Pers.; soybean, *Glycine max* (L.) Merr.
Key words: Glufosinate resistance, resistance management, weed control.

En 2010 y 2012, se realizaron tres experimentos en campos de producción de soya cerca de Memphis Oeste, AR, que tenían *Sorghum halepense* resistente a glyphosate. El objetivo de esta investigación fue desarrollar programas efectivos de herbicidas para el control de *S. halepense* resistente a glyphosate en soya resistente a glufosinate. El control de *S. halepense* resistente fue mayor con glufosinate a 590 y 740 g ai ha^{-1} que a 450 g ha^{-1}. Aplicaciones secuenciales de glufosinate fueron más efectivas que aplicaciones sencillas, independientemente de la dosis. Una aplicación PRE de flumioxazin a 71 g ai ha^{-1} inmediatamente después de la siembra brindó no más de 26% control de *S. halepense*, 6 semanas después de la emergencia de la soya (WAE). La adición de clethodim a 136 g ai ha^{-1} a las aplicaciones secuenciales de glufosinate a 450 g ha^{-1} mejoraron el control en comparación con las aplicaciones secuenciales de glufosinate solo. Los programas de herbicidas que contenían imazethapyr o imazamox en combinación con glufosinate seguido de clethodim más glufosinate controlaron *S. halepense* en al menos 94% a 10 WAE y brindaron tres modos de acción distintos, lo que es una estrategia altamente efectiva para el manejo de resistencia. Los resultados de esta investigación indican que se puede alcanzar un alto nivel de control de *S. halepense* resistente a glyphosate mediante el uso de varias opciones de herbicidas en soya resistente a glufosinate.

Johnsongrass has historically been one of the most problematic weeds infesting row crops in the southern United States (Buchanan 1974; Elmore 1983; Webster and Coble 1997). Traditional johnsongrass control tactics consisted of soil-incorporated dinitroanaline herbicides before crop sowing, in-row cultivation, physical plant removal, and spot treatments with nonselective POST herbicides (McWhorter 1989). Control options were improved in the 1980s through the release of several POST acetyl-CoA carboxylase (ACCase)–inhibiting and acetolactate synthase (ALS)–inhibiting herbicides (Bridges 1989; Camacho et al. 1991; Foy and Witt 1990; McWhorter 1989; Obrigawitch et al. 1990). These herbicides provided highly effective control of many troublesome grass weeds, including johnsongrass. The dinitroanaline, ACCase, and ALS herbicides were repeatedly relied upon, which subsequently led to the evolution of herbicide-resistant johnsongrass (Burke et al. 2006; Heap

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* First and second authors: Research Associate and Professor, Department of Crop, Soil, and Environmental Sciences, 1366 West Altheimer Drive, Fayetteville, AR 72704; third author: Professor, Department of Crop, Soil, and Environmental Sciences, Box 357, Lonoke, AR 72086. Corresponding author's E-mail: dbj03@uark.edu

2013; Smeda et al. 1997). Fortunately, confirmation of johnsongrass biotypes resistant to the ACCase- and ALS-inhibiting herbicides coincided with the commercialization of glyphosate-resistant crop technology. Because of the effectiveness of this technology on a broad spectrum of weed species at various growth stages, growers began to rely solely on glyphosate for weed control and quite commonly glyphosate was applied at reduced rates (Riar et al. 2011). Repeated use of a single mechanism of action (MOA), use of reduced rates, and application of herbicides to weeds that are too large are several factors that can contribute to the evolution of resistance to a particular herbicide or family of herbicides (Norsworthy et al. 2012).

Glyphosate-resistant johnsongrass was documented in Arkansas after repeated sole use of glyphosate in glyphosate-resistant soybean (Riar et al. 2011). Furthermore, glyphosate-resistant johsongrass has been confirmed at additional sites across the state (Bagavathiannan and Norsworthy, unpublished data; Johnson and Norsworthy 2010) as well as sites in Louisiana and Mississippi (Heap 2013). With the loss of glyphosate as an effective johnsongrass control option in some fields, along with the wide-spread occurrence of other glyphosate-resistant weeds throughout the midsouthern United States, growers may choose to switch to glufosinate-resistant soybean as a means of controlling these glyphosate-resistant biotypes.

Glufosinate is a nonselective POST-applied herbicide that prevents the transformation of glutamate and ammonia into glutamine, which subsequently results in destruction of the chloroplast and the eventual cessation of photosynthesis (Coetzer and Al-Khatib 2001; Devine et al. 1993). Before the release of glufosinate-resistant crops, glufosinate was primarily used for weed control in vineyards, orchard floors, and before planting in minimum or no-till production systems (Bruce and Kells 1990; Lyon 1991; Wilson et al. 1985). Glufosinate provides effective control of a broad spectrum of weeds, many of which are troublesome weeds in crop production fields of the southern United States (Corbett et al. 2004; Culpepper et al. 2000; Steckel et al. 1997). Generally, glufosinate is more effective on annual broadleaf species than grasses, especially large grasses (Corbett et al. 2004; Culpepper and York 1999; Culpepper et al. 2000; Gardner et al. 2006; Steckel et al. 1997). Inconsistent control of perennial species has also been reported with glufosinate (Welch and Ross 1997). The inability of glufosinate to control perennial species sufficiently is a result of inadequate translocation of the herbicide belowground to reproductive structures (Bromilow et al. 1993). Therefore, effective control of a perennial grass species such as johnsongrass would ultimately require multiple applications of glufosinate or tank mixtures of glufosinate with selective grass herbicides. However, Gardner et al. (2006) reported that the addition of glufosinate with POST-applied graminicides antagonized control of annual grasses and johnsongrass. Similarly, Burke et al. (2005) concluded that glufosinate antagonized goosegrass (*Eleusine indica* L. Gaertn.) control with clethodim.

Recent confirmation of glyphosate-resistant johnsongrass in Arkansas, Louisiana, and Mississippi, along with known resistance to other MOAs, renews concerns pertaining to the future management options for this once widely troublesome weed. Furthermore, with the increased adoption of glufosinate-resistant soybean in the midsouthern United States in recent years (Riar et al. 2013), there is a need to evaluate control options for glyphosate-resistant johnsongrass in glufosinate-resistant soybean systems. Therefore, the objective of this research was to develop effective herbicide programs for the control of glyphosate-resistant johnsongrass in glufosinate-resistant soybean production systems.

Materials and Methods

General Procedures. Three field experiments were conducted in 2010 and 2012 in the same production field near West Memphis, AR, where the first glyphosate-resistant johnsongrass biotype was found (Riar et al. 2011). One trial consisted of multiple rates of glufosinate applied in sequential applications with and without a residual herbicide at planting or a single application following a PRE-applied residual herbicide. In another experiment, sequential applications of glufosinate with multiple rates of clethodim in one or both POST applications were evaluated for control of the resistant biotype. In the final glufosinate-resistant soybean experiment, johnsongrass control was evaluated with sequential applications of glufosinate in combination with imazamox or imazethapyr in

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the first or second POST application, with clethodim in the subsequent application or sequential applications of clethodim in combination with glufosinate.

The experimental site was planted to glyphosate-resistant soybean for at least 10 consecutive yr before initiating the research. 'Halomax 494', a glufosinate-resistant soybean cultivar, was drill-seeded at 430,000 seed ha^{-1} on May 19, 2010, and June 14, 2012, in plots 1.6-m wide by 8-m long with a nine-row drill with 18-cm row spacing. Before planting in 2010 and 2012, the trial area was disked multiple times and tilled with a field cultivator. The same trials were initiated at the experimental site in 2011, but the trials were discontinued because of an overspray from the co-operator. The soil at this site was a Sharkey clay (very fine montmorillonitic, nonacid, thermic, Vertic Haplaquepts) with 1.8% organic matter and pH 6.2. In 2010, all experiments were conducted under dryland conditions, but in 2012, experiments were irrigated as needed by the co-operator with a center-pivot irrigation system. In all years, soybean was grown commercially in the field where the experimental site existed; hence, irrigation in 2012 was at the discretion of the co-operator.

All treatments were applied with a CO_2-pressurized backpack sprayer consisting of a handheld boom that contained four 110015 flat-fan nozzles (Teejet Technologies, Springfield, IL 62703) on 48-cm spacing and was calibrated to deliver 140 L ha^{-1} at 276 kPA. Johnsongrass was 15 to 25 cm tall at the time of the first POST application 3 WAE and 45 to 70 cm at the time of the second POST application 6 WAE. Visual estimates of johnsongrass control on a scale of 0 (no control) to 100% (complete plant mortality) were taken at 3 and 6 WAE and again 4 wk after the final application. Immediately after the final weed control evaluation, the entire test area was oversprayed with clethodim at 136 g ai ha^{-1} to prevent seed production and further spread of the glyphosate-resistant biotype. The seven innermost rows of each plot were harvested with a small-plot combine at soybean maturity. Soybean was then adjusted to 13% moisture, and yields were calculated.

Effect of Glufosinate Rate and Application Sequence on Glyphosate-Resistant Johnsongrass Control. Treatments were arranged in a randomized complete block (RCB) design, with each treatment replicated four times. The experiment consisted of multiple rates of glufosinate applied in sequential applications at 3 and 6 WAE with and without a residual herbicide at planting vs. a single application 6 WAE following a PRE-applied residual herbicide. Treatments evaluated were (1) flumioxazin at 71 g ha^{-1} PRE followed by (fb) glufosinate at 450 g ai ha^{-1} 6 WAE, (2) flumioxazin at 71 g ha^{-1} PRE fb glufosinate at 450 g ha^{-1} 3 WAE fb glufosinate at 450 g ha^{-1} 6 WAE, (3) flumioxazin at 71 g ha^{-1} PRE fb glufosinate at 590 g ha^{-1} 6 WAE, (4) flumioxazin at 71 g ha^{-1} PRE fb glufosinate at 590 g ha^{-1} 3 WAE fb glufosinate at 590 g ha^{-1} 6 WAE, (5) flumioxazin at 71 g ha^{-1} PRE fb glufosinate at 740 g ha^{-1} 6 WAE, (6) flumioxazin at 71 g ha^{-1} PRE fb glufosinate at 590 g ha^{-1} 3 WAE fb glufosinate at 590 g ha^{-1} 6 WAE, (7) glufosinate at 450 g ha^{-1} 3 WAE fb glufosinate at 450 g ha^{-1} 6 WAE, (8) glufosinate at 590 g ha^{-1} 3 WAE fb glufosinate at 590 g ha^{-1} 6 WAE, (9) glufosinate at 740 g ha^{-1} 3 WAE fb glufosinate at 740 g ha^{-1} 6 WAE, and (10) a nontreated control.

Single vs. Sequential Applications of Clethodim in Combination with Glufosinate. Treatments were arranged in a RCB design with four replications. The experiment consisted of sequential applications of glufosinate at 450 g ha^{-1} applied alone or in combination with one of three rates of clethodim at 3 or 6 WAE or sequentially. The following treatments were evaluated: (1) glufosinate 3 WAE fb glufosinate 6 WAE, (2) glufosinate + clethodim at 68 g ha^{-1} 3 WAE fb glufosinate 6 WAE, (3) glufosinate + clethodim at 102 g ha^{-1} 3 WAE fb glufosinate 6 WAE, (4) glufosinate + clethodim at 136 g ha^{-1} 3 WAE fb glufosinate 6 WAE, (5) glufosinate 3 WAE fb glufosinate + clethodim at 68 g ha^{-1} 6 WAE, (6) glufosinate 3 WAE fb glufosinate + clethodim at 102 g ha^{-1} 6 WAE, (7) glufosinate 3 WAE fb glufosinate + clethodim at 136 g ha^{-1} 6 WAE, (8) glufosinate + clethodim at 68 g ha^{-1} 3 WAE fb glufosinate + clethodim at 68 g ha^{-1} 6 WAE, (9) glufosinate + clethodim at 102 g ha^{-1} 3 WAE fb glufosinate + clethodim at 102 g ha^{-1} 6 WAE, (10) glufosinate + clethodim at 136 g ha^{-1} 3 WAE fb glufosinate + clethodim at 136 g ha^{-1} 6 WAE, and (11) a nontreated control. Applications of clethodim in combination with glufosinate contained 1% (v/v) of a crop oil concentrate.

Herbicide Programs in Glufosinate-Resistant Soybean. The experiment was conducted in a RCB design with four replications. The experiment consisted of sequential applications of glufosinate at 450 g ha^{-1} applied alone or in combination with additional MOAs. The following herbicide treatments were evaluated with and without a PRE application of *S*-metolachlor at 1,215 g ha^{-1} + fomesafen at 266 g ha^{-1}. POST herbicide applications consisted of (1) glufosinate 3 WAE fb glufosinate 6 WAE, (2) glufosinate + imazamox at 44 g ha^{-1} 3 WAE fb glufosinate + clethodim at 136 g ha^{-1} 6 WAE, (3) glufosinate + clethodim at 136 g ha^{-1} 3 WAE fb glufosinate + imazamox at 44 g ha^{-1} 6 WAE, (4) glufosinate + imazethapyr at 70 g ha^{-1} 3 WAE fb glufosinate + clethodim at 136 g ha^{-1} 6 WAE, (5) glufosinate + clethodim at 136 g ha^{-1} 3 WAE fb glufosinate + imazethapyr at 70 g ha^{-1} 6 WAE, and (6) glufosinate + clethodim at 68 g ha^{-1} 3 WAE fb glufosinate + clethodim at 68 g ha^{-1} 6 WAE. A nontreated control was included for comparison. Applications including clethodim, imazamox, or imazethapyr contained either 1% (v/v) of a crop oil concentrate or 0.25% (v/v) of a nonionic surfactant.

Statistical Analyses. Data were analyzed using ANOVA with the MIXED procedure in JMP (JMP, Version 10; SAS Institute Inc., Cary, NC) with herbicide treatment as a fixed effect and year as a random effect. Year, replication (nested within year), and any interactions containing either variable were considered random effects. This approach has previously been successful in allowing inferences to be made about the behavior of treatments over multiple environmental conditions (Bond et al. 2005; Hager et al. 2003; Stephenson et al. 2004; Zhang et al. 2005). Means were separated using Tukey's honestly significant difference (HSD) test at a 5% level of significance. Additionally, to determine the effect of different herbicide treatments on johnsongrass control and soybean yield, the mixed procedure in JMP was used to test a preplanned single degree of freedom contrast. Preplanned contrasts were conducted to compare programs with a PRE vs. total POST programs, programs containing clethodim vs. programs without clethodim, clethodim at 3 WAE vs. clethodim at 6 WAE, and one vs. two applications of clethodim in glufosinate-based programs.

Results and Discussion

Effect of Glufosinate Rate in Single and Sequential Applications for Glyphosate-Resistant Johnsongrass Control. Johnsongrass density in the nontreated control averaged 55 shoots m^{-2} for 2010 and 2012. No treatment caused more than 5% injury to soybean at any evaluation (data not shown). At 6 WAE, only the PRE and initial POST treatments (V3 soybean) had been applied. Flumioxazin PRE did not provide effective johnsongrass control at 6 WAE; however, control improved to 75% when flumioxazin was followed by glufosinate in the first POST application at 3 WAE. Glufosinate at 450 g ha^{-1} was less effective than the two higher rates evaluated in sequential applications, and a single application of glufosinate was less effective than multiple applications, regardless of application rate (Table 1). Consistent with the results of this experiment, Steckel et al. (1997) found that the efficacy of glufosinate on several annual weed species was influenced by rate as well as weed height at the time of application. It should be noted that at the initiation of this research, the labeled rate of glufosinate in soybean was 450 g ha^{-1}; however, the label has since been changed to allow growers to apply sequential applications of glufosinate at 590 g ha^{-1} in glufosinate-resistant soybean (Anonymous 2013).

On the basis of contrasts, johnsongrass control at 10 WAE after a PRE herbicide application was greater with sequential compared with single applications of glufosinate (Table 1). The addition of a PRE herbicide application before sequential glufosinate applications did not improve control over applications that did not follow a PRE herbicide. At 10 WAE, johnsongrass control with flumioxazin PRE fb glufosinate at 6 WAE was less than 68%, regardless of the glufosinate rate. Conversely, sequential applications of glufosinate at 3 and 6 WAE after a PRE application of flumioxazin provided up to 97% control, with the highest rates providing the most effective control. Kelly et al. (2005) and Stephenson et al. (2011) also reported that a single application of glufosinate generally does not provide effective control of johnsongrass.

No differences were found in soybean yield among herbicide programs, with yields ranging from 2,620 to 3,300 kg ha^{-1} (Table 1). Conversely, soybean in the nontreated control yielded only

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Table 1. Effect of glufosinate rate and application sequence after PRE herbicide or total POST programs on glyphosate-resistant johnsongrass control and glufosinate-resistant soybean yield at West Memphis, AR, averaged over 2010 and 2012.[a]

Herbicide	Timing	Rate	Control[b] 6 WAE	10 WAE	Yield
		g ai ha^{-1}	%		kg ha^{-1}
Flumioxazin fb	PRE	71	24 c	64 c	2,760 a
glufosinate	6 WAE	450			
Flumioxazin fb	PRE	71	75 b	84 b	2,760 a
glufosinate fb	3 WAE	450			
glufosinate	6 WAE	450			
Flumioxazin fb	PRE	71	24 c	64 c	2,760 a
glufosinate	6 WAE	590			
Flumioxazin fb	PRE	71	94 a	96 a	3,030 a
glufosinate fb	3 WAE	590			
glufosinate	6 WAE	590			
Flumioxazin fb	PRE	71	26 c	67 c	2,760 a
glufosinate	6 WAE	740			
Flumioxazin fb	PRE	71	96 a	97 a	3,030 a
glufosinate fb	3 WAE	740			
glufosinate	6 WAE	740			
Glufosinate fb	3 WAE	450	74 b	80 b	2,620 a
glufosinate	6 WAE	450			
Glufosinate fb	3 WAE	590	94 a	95 a	2,960 a
glufosinate	6 WAE	590			
Glufosinate fb	3 WAE	740	97 a	97 a	3,300 a
glufosinate	6 WAE	740			
Nontreated	—	—	—	—	1,330 b
Contrasts					
PRE fb glufosinate 6 WAE vs. PRE fb sequential glufosinate			—	$P < 0.0001$	NS
PRE fb sequential glufosinate vs. sequential glufosinate total POST			—	NS	NS
PRE fb glufosinate 6 WAE vs. sequential glufosinate total POST			—	$P < 0.0001$	NS

[a] Abbreviation: fb, followed by; HSD, honestly significant difference; NS, not significant; WAE, weeks after soybean emergence.

[b] Means within a column with the same lowercase letters are not significantly different according to Tukey's HSD (0.05).

1,330 kg ha^{-1}, an indication of the competiveness of johnsongrass with soybean. Results of this experiment are similar to those of previous experiments in which johnsongrass competition with soybean resulted in 23 to 88% reduction of crop yield (McWhorter and Hartwig 1968; Williams and Hayes 1984).

Single vs. Sequential Applications of Clethodim in Combination with Glufosinate. Johnsongrass density in the nontreated control plots averaged 49 shoots m^{-2} for 2010 and 2012. Injury to soybean induced by the herbicide treatments was < 5% at all evaluations (data not shown). At 6 WAE, treatments containing clethodim in the first POST application (3 WAE and V3 soybean) in combination with glufosinate resulted in > 90% johnsongrass control, regardless of clethodim rate (Table 2). A single glufosinate application at 450 g ha^{-1} at 3 WAE controlled johnsongrass 69 to 74% at 6 WAE, which was less than the control provided by the same rate of glufosinate in combination with clethodim.

On the basis of contrasts, johnsongrass control at 10 WAE was greater for the herbicide programs that contained clethodim than for those that did not (Table 2). Furthermore, at 10 WAE, a timely application of clethodim applied at 3 WAE provided greater johnsongrass control compared with a first clethodim application at 6 WAE. With the exception of the high rate of clethodim (94% control), sequential clethodim applications were also superior to a single application at 6 WAE. However, a single application of clethodim at 3 WAE was as effective as sequential applications of clethodim regardless of rate (Table 2). At 10 WAE, two applications of glufosinate at 450 g ha^{-1}

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Table 2. Single compared with sequential applications of clethodim in combination with glufosinate on glyphosate-resistant johnsongrass control and glufosinate-resistant soybean yield at West Memphis, AR, averaged over 2010 and 2012.[a]

Herbicide[b]	Timing (WAE)	Rate	Control[c] 6 WAE	Control[c] 10 WAE	Yield
		g ai ha^{-1}	%	%	kg ha^{-1}
Glufosinate fb	3	450	74b	83b	2,560a
glufosinate	6	450			
Glufosinate + clethodim fb	3	450 + 68	95a	94a	2,560a
glufosinate	6	450			
Glufosinate + clethodim fb	3	450 + 102	95a	94a	2,760a
glufosinate	6	450			
Glufosinate + clethodim fb	3	450 + 136	96a	96a	2,690a
glufosinate	6	450			
Glufosinate fb	3	450	74b	82b	2,490a
glufosinate + clethodim	6	450 + 68			
Glufosinate fb	3	450	74b	87b	2,290a
glufosinate + clethodim	6	450 + 102			
Glufosinate fb	3	450	69b	94a	2,620a
glufosinate + clethodim	6	450 + 136			
Glufosinate + clethodim fb	3	450 + 68	91a	97a	2,620a
glufosinate + clethodim	6	450 + 68			
Glufosinate + clethodim fb	3	450 + 102	93a	97a	2,760a
glufosinate + clethodim	6	450 + 102			
Glufosinate + clethodim fb	3	450 + 136	93a	99a	3,160a
glufosinate + clethodim	6	450 + 136			
Nontreated	—	—	—	—	1,540b
Contrasts					
Clethodim vs. no clethodim			—	$P < 0.0001$	NS
Clethodim 3 WAE vs. clethodim 6 WAE			—	$P < 0.0001$	NS
Clethodim 3 or 6 WAE vs. clethodim 3 and 6 WAE			—	$P < 0.0001$	NS

[a] Abbreviations: fb, followed by; HSD, honestly significant difference; WAE, weeks after soybean emergence.
[b] POST applications of clethodim contained 1% (v/v) of a crop oil concentrate as recommended by the manufacturer.
[c] Means within a column with the same lowercase letters are not significantly different according to Tukey's HSD (0.05).

controlled johnsongrass 83% (Table 2). Regardless of clethodim rate, johnsongrass control at 10 WAE ranged from 94 to 99% with treatments that contained clethodim in combination with glufosinate in the first POST or in both POST applications. Results of this experiment are consistent with those of Gardner et al. (2006), who reported at least 94% control of 5- to 15-cm johnsongrass with glufosinate in combination with clethodim. However, clethodim at 136 g ha^{-1} was the only rate that resulted in greater than 90% johnsongrass control when applications were delayed until the last POST treatment, evidence that applications must be timely. The lower clethodim rates were unable to control johnsongrass effectively because the initial glufosinate application provided marginal control, allowing the plants to continue growth, rendering them too large for control by 6 WAE (johnsongrass plants were 45 to 70 cm tall by the 6 WAE application). Unlike previous findings (Burke et al. 2005; Gardner et al. 2006), there was no apparent antagonism from the addition of glufosinate to clethodim for johnsongrass control.

Despite differences in johnsongrass control among treatments, soybean yields were similar among all herbicide programs, ranging from 2,290 to 3,160 kg ha^{-1} (Table 2). Soybean in the nontreated control yielded only 1,540 kg ha^{-1} as a result of johnsongrass interference. Results of this experiment are consistent with that of previous experiments in which up to 88% reduction in soybean yield has been reported (McWhorter and Hartwig 1968; Williams and Hayes 1984).

Multiple MOA Programs in Glufosinate-Resistant Soybean. Johnsongrass shoot density averaged over 2010 and 2012 was 37 shoots m^{-2}. No

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Table 3. Glyphosate-resistant johnsongrass control and soybean yield in glufosinate-based programs containing multiple modes of action at West Memphis, AR, averaged over 2010 and 2012.

Herbicide program[c]	Timing	Rate	Control[b] 6 WAE	10 WAE	Yield
		g ai ha^{-1}	——%——		kg ha^{-1}
S-metolachlor + fomesafen fb	PRE	1,215 + 266	82 bc	81 c	2,960 a
glufosinate fb	3 WAE	450			
glufosinate	6 WAE	450			
S-metolachlor + fomesafen fb	PRE	1,215 + 266	86 b	98 ab	2,890 a
glufosinate + imazamox fb	3 WAE	450 + 44			
glufosinate +clethodim	6 WAE	450 + 136			
S-metolachlor + fomesafen fb	PRE	1,215 + 266	98 a	98 ab	3,160 a
glufosinate + clethodim fb	3 WAE	450 + 136			
glufosinate + imazamox	6 WAE	450 + 44			
S-metolachlor + fomesafen fb	PRE	1,215 + 266	86 b	98 ab	3,030 a
glufosinate + imazethapyr fb	3 WAE	450 + 70			
glufosinate +clethodim	6 WAE	450 + 136			
S-metolachlor + fomesafen fb	PRE	1,215 + 266	98 a	98 ab	2,890 a
glufosinate + clethodim fb	3 WAE	450 + 136			
glufosinate + imazethapyr	6 WAE	450 + 70			
S-metolachlor + fomesafen fb	PRE	1,215 + 266	97 a	99 a	2,960 a
glufosinate + clethodim fb	3 WAE	450 + 68			
glufosinate + clethodim	6 WAE	450 + 68			
Glufosinate fb	3 WAE	450	75 c	83 c	2,690 a
glufosinate	6 WAE	450			
Glufosinate + imazamox fb	3 WAE	450 + 44	85 b	95 b	2,890 a
glufosinate +clethodim	6 WAE	450 + 136			
Glufosinate + clethodim fb	3 WAE	450 + 136	98 a	98 ab	2,890 a
glufosinate + imazamox	6 WAE	450 + 44			
Glufosinate + imazethapyr fb	3 WAE	450 + 70	85 b	94 b	2,890 a
glufosinate + clethodim	6 WAE	450 + 136			
Glufosinate + clethodim fb	3 WAE	450 + 136	99 a	98 ab	2,760 a
glufosinate + imazethapyr	6 WAE	450 + 70			
Glufosinate + clethodim fb	3 WAE	450 + 68	97 a	98 ab	3,100 a
glufosinate + clethodim	6 WAE	450 + 68			
Nontreated	—	—	—	—	1,680 b
Contrasts					
PRE vs. total POST			—	NS	NS
Clethodim vs. no clethodim			—	$P < 0.0001$	NS
Clethodim 3 WAE vs. clethodim 6 WAE			—	NS	NS
Clethodim 3 or 6 WAE vs. clethodim 3 and 6 WAE			—	$P = 0.0069$	NS

[a] Abbreviations: fb, followed by; HSD, honestly significant difference; WAE, weeks after soybean emergence.

[b] Means within a column with the same lowercase letters are not significantly different according to Tukey's HSD (0.05).

[c] POST applications of clethodim and imazamox contained 1% (v/v) of a crop oil concentrate, and imazethapyr contained 0.25% (v/v) of a nonionic surfactant.

soybean injury was observed throughout the growing season (data not shown).

Three weeks after the initial POST application, control of johnsongrass with glufosinate alone was no more than 75% (Table 3). When clethodim was applied in combination with glufosinate, johnsongrass control was at least 97% by 6 WAE, which was greater than the control levels observed with imazethapyr or imazamox in combination with glufosinate.

Two applications of glufosinate alone or after a PRE application of *S*-metolachlor plus fomesafen controlled johnsongrass no more than 83% at 10 WAE, which was the lowest level of control following any herbicide treatment (Table 3). On the basis of contrasts, there was no improvement in

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johnsongrass control from the addition of a PRE herbicide to the evaluated programs. However, it should be noted that the PRE herbicides evaluated in this research, particularly *S*-metolachlor plus fomesafen, are quite effective on other weeds, especially Palmer amaranth, one of the most troublesome weeds of midsouthern soybean (Riar et al. 2013).

Clethodim in combination with glufosinate applied 6 WAE improved johnsongrass control with herbicide programs containing imazamox or imazethapyr in the first POST application from 85 and 86% at 6 WAE to at least 94% by 10 WAE (Table 3). Control remained high (98% control) through 10 WAE when clethodim was applied at 6 WAE. On the basis of contrasts, herbicide programs with clethodim had a higher level of johnsongrass control than those that did not, and sequential applications of clethodim further improved control over herbicide programs that contained only a single clethodim application.

Johnsongrass control did not influence soybean yield of treated plots, with yields ranging from 2,690 to 3,160 kg ha^{-1} across herbicide treatments. Yields were reduced up to 47% by johnsongrass in the nontreated control. It should be noted again that the entire test area was oversprayed with clethodim at 10 WAE, and it is possible that yield losses from johnsongrass could have been greater if clethodim had not been applied late in the growing season. In South Carolina, a johnsongrass density of 3.6 plants m^{-2} reduced soybean yields by 14 to 43% when grown in 0.97-m-wide rows (Toler et al. 1996). Furthermore, Bendixen (1988) concluded that soybean grown at 25-cm spacing was more competitive with johnsongrass than soybean grown in 76-cm spacing. Therefore, johnsongrass may require more intensive management in wide-row soybean production systems.

Upon evaluation of herbicide programs and soybean yield, results of this research present soybean producers with herbicide programs in glufosinate-resistant soybean that will effectively control glyphosate-resistant johnsongrass. Furthermore, this research demonstrates that effective control of glyphosate-resistant johnsongrass can be achieved using multiple MOAs without placing sole reliance upon a single MOA. With well-documented resistance to ACCase-inhibiting herbicides, it is crucial that herbicide programs containing multiple effective MOAs be used for control of johnsongrass. Use of diversified herbicide programs containing more than one MOA is an excellent strategy for protecting the existing effective herbicide MOAs that are currently available, while also managing herbicide-resistant weeds (Norsworthy et al. 2012).

Despite previous confirmations of herbicide-resistant weeds and the recent influx of glyphosate-resistant species in the past decade, growers remain hesitant to adopt and implement weed control programs that employ multiple effective MOAs on the most difficult to control weeds that are the most likely suspects to evolve resistance (Frisvold et al. 2009). Reluctance of growers to adopt proactive resistance management practices stems from the increase in current production costs associated with such a practice and the uncertainty of the benefits it will provide. In assessing the increased production cost of herbicide resistance to growers, Mueller et al. (2005) and Orson (1999) concluded that the cost of proactive measures to prevent herbicide resistance are often less than the cost of the reactive management practices required once resistance has evolved. Furthermore, herbicides are seldom again effective once herbicide resistance has evolved, even when the herbicide is removed from the weed control program for several years. Hence, implementing proactive resistance management programs using multiple effective MOAs as shown in this research are recommended for johnsongrass as well as other resistance-prone weeds.

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Literature Cited

Anonymous (2013) Liberty 280 SL specimen label. http://www.cdms.net/LDat/IdUA5004.pdf Accessed August 4, 2013

Bendixen LE (1988) Soybean (*Glycine max*) competition helps herbicides control johnsongrass (*Sorghum halepense*). Weed Technol 2:46–48

Bond JA, Walker TW, Bollich PK, Kroger CH, Gerard P (2005) Seeding rates for stale seedbed rice production in the midsouthern United States. Agron J 97:1560–1563

Bridges DC (1989) Adjuvant and pH effects on sethoxydim and clethodim activity on rhizome johnsongrass (*Sorghum halepense*). Weed Technol 3:615–620

Bromilow RH, Chamberlain K, Evans AA (1993) Phloem translocation of strong acids—glyphosate, substituted phos-

https://doi.org/10.1614/WT-D-13-00099.1 Published online by Cambridge University Press

phonic acids and sulfonic acids—in *Ricinus communis*. Pestic Sci 37:33–37
Bruce JA, Kells JJ (1990) Horseweed (*Conyza canadensis*) control in no-tillage soybeans (*Glycine max*) with preplant and preemergence herbicides. Weed Technol 4:642–647
Buchanan GA (1974) Weed survey: southern states. South Weed Sci Soc Res Rep 27:215–249
Burke IC, Askew SD, Corbett JL, Wilcut JW (2005) Glufosinate antagonizes clethodim control of goosegrass (*Eleusine indica*). Weed Technol 19:664–668
Burke IC, Wilcut JW, Crammer J (2006) Cross-resistance of a johnsongrass (*Sorghum halepense*) biotype to aryloxyphenoxypropionate and cyclohexanedione herbicides. Weed Technol 20:571–575
Camacho RF, Moshier LJ, Morishita DW, Devlin DL (1991) Rhizome johnsongrass (*Sorghum halepense*) control in corn (*Zea mays*) with primsulfuron and nicosulfuron. Weed Technol 5:789–794
Coetzer E, Al-Khatib K (2001) Photosynthetic inhibition and ammonium accumulation in Palmer amaranth after glufosinate application. Weed Sci 49:454–459
Corbett JL, Askew SD, Thomas WE, Wilcut JW (2004) Weed efficacy evaluations for bromoxynil, glufosinate, glyphosate, pyrithiobac, and sulfosate. Weed Technol 18:443–453
Culpepper AS, York AC (1999) Weed management and net returns with transgenic, herbicide-resistant, and nontransgenic cotton (*Gossypium hirsutum*). Weed Technol 13:411–420
Culpepper AS, York AC, Jennings KM, Batts RB (2000) Weed management in glufosinate- and glyphosate-resistant soybean (*Glycine max*). Weed Technol 14:77–88
Devine MD, Duke SO, Fedtke C (1993) Inhibition of amino acid biosynthesis. Pages 274–275 *in* Physiology of Herbicide Action. Englewood Cliffs, NJ: Prentice Hall
Elmore CD (1983) Weed survey—southern states. South Weed Sci Soc Res Rep 39:136–158
Foy CL, Witt HL (1990) Johnsongrass control with DPX-V9360 and CGA-136872 in corn (*Zea mays*) in Virginia. Weed Technol 4:615–619
Frisvold GB, Hurley TM, Mitchell PD (2009) Adoption of best management practices to control weed resistance by corn, cotton, and soybean growers. Agbioforum 12:370–381
Gardner AP, York AC, Jordan DL, Monks DW (2006) Glufosinate antagonizes postemergence graminicides applied to annual grasses and johnsongrass. J Cotton Sci 10:319–327
Hager AG, Wax LM, Bollero GA, Stoller EW (2003) Influence of diphenylether herbicide application rate and timing on common waterhemp (*Amaranthus rudis*) control in soybean (*Glycine max*). Weed Technol 17:14–20
Heap I (2013)The International Survey of Herbicide-Resistant Weeds. http://www.weedscience.org. Accessed June 7, 2013
Johnson DB, Norsworthy JK (2010) Survey of herbicide-resistant johnsongrass in Arkansas. Proc South Weed Sci Soc 63:81 [Poster]
Kelly ST, Miller DK, Stewart AM (2005) Ignite weed control systems in Liberty Link cotton. Pages 2926–2927 *in* Proceedings of the Beltwide Cotton Conference, New Orleans, LA. Memphis, TN: National Cotton Council of America
Lyon BR (1991) Engineering microbial herbicide detoxification genes in higher plants. Pages 79–108 *in* Dennis ES, Llewellyn DJ, eds. Molecular Approaches to Crop Improvement. Vienna, Austria: Springer-Verlag
McWhorter CG (1989) History, biology, and control of johnsongrass. Rev Weed Sci 4:85–121
McWhorter CG, Hartwig EE (1968) Competition of johnsongrass and cocklebur with six soybean varieties. Weed Sci 20:56–59
Mueller TC, Mitchell PD, Young BG, Culpepper AS (2005) Proactive versus reactive management of glyphosate-resistant or tolerant weeds. Weed Technol 19:924–933
Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the risk of herbicide resistance: best management practices and recommendations. Weed Sci 60 (Special Issue):31–62
Obrigawitch TT, Kenyon WH, Kuratle H (1990) Effect of application timing on rhizome johnsongrass (*Sorghum halepense*) control with DPX-V9360. Weed Sci 38:45–49
Orson JH (1999) The cost to the producer of herbicide resistance. Weed Technol 13:607–611
Riar DS, Norsworthy JK, Johnson DB, Scott RC, Bagavathiannan M (2011) Glyphosate resistance in a johnsongrass (*Sorghum halepense*) biotype from Arkansas. Weed Sci 59:299–304
Riar DS, Norsworthy JK, Steckel LE, Stephenson DO IV, Eubank TW, Scott RC (2013) Assessment of weed management needs in midsouth United States soybean: a consultant's perspective. Weed Technol. 27:612–622
Smeda RJ, Snipes CE, Barrentine WL (1997) Identification of graminicide-resistant johnsongrass (*Sorghum halepense*). Weed Sci 45:132–137
Steckel GJ, Wax LM, Simmons FW, Phillips WH 2nd (1997) Glufosinate efficacy is influenced by rate and growth stage. Weed Technol 11:484–488
Stephenson DO 4th, Bond JA, Walker ER, Bararpour MT, Oliver LR (2004) Evaluation of mesotrione in Mississippi delta corn production. Weed Technol 18:1111–1116
Stephenson DO 4th, Griffin J, Burgos NR (2011) Glyphosate resistant johnsongrass monitoring and management. Proc South Weed Sci Soc 64:228 [Symposium]
Toler JE, GuiceJ JB, Murdock EC (1996) Interference between johnsongrass (*Sorghum halepense*), smooth pigweed (*Amaranthus hybridus*), and soybean (*Glycine max*). Weed Sci 44:331–338
Webster TM, Coble HD (1997) Changes in the weed species composition of the southern United States: 1974 to 1995. Weed Technol 11:308–317
Welch C, Ross MA (1997) Effect of glyphosate, glufosinate, and 2,4-D on Canada thistle and hemp dogbane root systems. Proc North Cent Weed Sci Soc 52:33–35
Williams CS, Hayes RM (1984) Johnsongrass (*Sorghum halepense*) competition in soybeans (*Glycine max*). Weed Sci 32:498–501
Wilson HP, Hines TE, Bellinder RR, Grande JA (1985) Comparisons of HOE-39866, SC-0224, paraquat, and glyphosate in no-till corn (*Zea mays*). Weed Sci 33:531–536
Zhang W, Webster EP, Leon CT (2005) Response of rice cultivars to V-10029. Weed Technol 19:307–311

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