Weed Technology

www.cambridge.org/wet

Research Article

Cite this article: Fleming J, Norsworthy JK, Bagavathiannan M, Barber T (2024). Influence of fluazifop timing and rate on johnsongrass (*Sorghum halepense*) control in ACCase-resistant grain sorghum (*Sorghum bicolor*). Weed Technol. **38**(e2), 1–7. doi: 10.1017/wet.2023.47

Received: 8 February 2023
Revised: 1 May 2023
Accepted: 12 July 2023

Associate Editor:
Amit Jhala, University of Nebraska, Lincoln

Nomenclature:
fluazifop-butyl; johnsongrass, *Sorghum halepense* (L.) Pers.; grain sorghum, *Sorghum bicolor* (L.) Moench

Keywords:
TamArk™

Corresponding author:
Jacob Fleming; Email: jaf035@uark.edu

Influence of fluazifop timing and rate on johnsongrass (*Sorghum halepense*) control in ACCase-resistant grain sorghum (*Sorghum bicolor*)

Jacob Fleming[1], Jason K. Norsworthy[2], Muthukumar Bagavathiannan[3] and Tom Barber[4]

[1]Graduate Research Assistant, Department of Crop, Soil, and Environmental Sciences, University of Arkansas, Fayetteville, AR, USA; [2]Distinguished Professor and Elms Farming Chair of Weed Science, Department of Crop, Soil, and Environmental Sciences, University of Arkansas, Fayetteville, AR, USA; [3]Professor of Weed Science, Department of Soil and Crop Sciences, Texas A&M University, College Station, TX, USA and [4]Professor and Extension Weed Scientist, Cooperative Extension Service, Lonoke, AR, USA

Abstract

Genetic similarities between johnsongrass and grain sorghum leave producers with limited herbicide options for postemergence johnsongrass control. TamArk™ grain sorghum with resistance to acetyl-CoA carboxylase-inhibiting herbicides was developed through a collaboration between the University of Arkansas System Division of Agriculture and Texas A&M AgriLife Research. Two field experiments were conducted in 2021 in two locations each: Keiser and Marianna, AR, or Fayetteville and Marianna, AR. The objective of the first was to determine the optimal rate and application timing of fluazifop-butyl for control of natural johnsongrass populations in a noncrop setting, and the objective of the second was to evaluate johnsongrass control and TamArk™ grain sorghum tolerance in response to fluazifop-butyl applied at different timings and rates based on crop growth stage. The highest levels of johnsongrass control occurred when sequential applications of fluazifop-butyl were utilized. All sequential treatments provided at least 80% johnsongrass control at any rate or application timing tested. A single application of fluazifop-butyl provided greater than 90% johnsongrass control when applied at 210 g ai ha^{-1} to johnsongrass with fewer than 6 leaves. Weed size played a role in achieving high levels of johnsongrass control. Greater than 90% control was achieved when johnsongrass had 6 leaves or fewer at the initial application for the sequential application treatments. A single application of fluazifop-butyl at 105 g ai ha^{-1} resulted in no more than 82% johnsongrass mortality at any application timing. TamArk™ grain sorghum injury did not exceed 6% at any application timing or rate. It was therefore considered to be safe even if the initial application was made before the 6-leaf crop stage. Because no unacceptable levels of injury were observed with TamArk™ grain sorghum for fluazifop-butyl, johnsongrass size at the time of application should be the most critical aspect for control with this herbicide.

Introduction

Johnsongrass was first utilized in the United States as a forage crop throughout the Southeast in the 1800s. Although the ability of johnsongrass to produce large quantities of biomass made it an excellent forage species, it also had characteristics of a persistent weed species (Mitch 1987). The inability to contain johnsongrass within forage production fields was first documented during the 1840s in the fertile river bottoms of Alabama (Miller 2014; Mitch 1987). Johnsongrass is a spreading perennial grass known to produce large quantities of biomass and to spread rapidly through both rhizomes and seed production (McWhorter 1971). Rhizome production is one of the main reasons johnsongrass is challenging to control. One johnsongrass plant can produce up to 5,000 rhizomes, potentially leading to new plants, making control of johnsongrass before rhizome production a vital approach (Horowitz 1972; McWhorter 1971). The adaptability of johnsongrass also makes it difficult to control. Johnsongrass can currently be found in almost every state in the United States and in many foreign countries, even though the climate does not fit the warm, dry conditions from which johnsongrass originated (Burt 1974).

Since its introduction as a forage crop, johnsongrass control has been a significant issue for row crop producers across the Mid-South. Historically, johnsongrass control was achieved by soil incorporating dinitroaniline herbicides in-row cultivation, physical removal, and spot treatments with nonselective postemergence herbicides (McWhorter 1989). In the 1980s, control methods were improved with the commercialization of multiple postemergence herbicides targeting the acetyl-CoA carboxylase (ACCase) and the acetolactate synthase enzymes (Bridges 1989; Camacho et al. 1991; Foy and Witt 1990; McWhorter 1989; Obrigawitch et al. 1990). While these herbicides successfully controlled johnsongrass in corn (*Zea mays* L.)

and soybean [*Glycine max* (L.) Merr.], neither could be used in grain sorghum because of the close genetic similarities, resulting in a lack of selectivity.

Until recently, grain sorghum producers relied on methodologies that are more than 30 yr old to control johnsongrass in grain sorghum (Brown et al. 1988; McWhorter and Hardwig 1965; Smith and Scott 2010). Tillage for johnsongrass control in grain sorghum is one of the first control methods producers utilize. Fall tillage brings rhizomes to the surface and exposes them to harsh winter weather, reducing infestations in the following year by 75% to 85% (McWhorter and Hardwig 1965). In the 1970s, the introduction of glyphosate improved johnsongrass control for grain sorghum producers. Although glyphosate could not be applied postemergence in grain sorghum, producers could utilize the nonselective herbicide prior to crop emergence as a fall or preplant burndown. The addition of glyphosate as a fall burndown paired with a preplant burndown increased johnsongrass control in grain sorghum to greater than 90% (Brown et al. 1988). In more recent years, some producers still utilize a glyphosate prior to planting for johnsongrass control in grain sorghum (Smith and Scott 2010).

The introduction of a fluxofenim (Concep®, Syngenta, Greensboro, NC, USA) seed treatment allowed chloroacetamide herbicides like *S*-metolachlor to be applied preemergence for grass control, significantly advancing weed control in grain sorghum. *S*-metolachlor provides greater than 90% control of seedling johnsongrass while causing less than 5% injury to grain sorghum hybrids treated with fluxofenim (Ghosheh and Chandler 1998; Wright et al. 1992). Although glyphosate and *S*-metolachlor have been successful for johnsongrass control in grain sorghum for many years, current herbicide resistance trends threaten the sustainability of these herbicides (Brabham et al. 2019; Johnson et al. 2014a, 2014b; Meyer et al. 2015). Quinclorac and bromoxynil are postemergence herbicides labeled for postemergence grass control in grain sorghum, but neither provides effective johnsongrass control (Corbett et al. 2004; Kering et al. 2013). Paraquat is also labeled for in-season grass control in grain sorghum but must be applied postdirected, under hoods, to prevent significant crop injury. With the increasing number of herbicide-resistant weed populations and a lack of effective control options for johnsongrass and other grasses, grain sorghum producers need new tools that aid weed control.

Herbicide-resistant lines of grain sorghum have been researched and commercialized, adding new options for grass control in this crop (Pinkerton 2020). Specifically, the University of Arkansas System Division of Agriculture and Texas A&M AgriLife Research have worked collaboratively to develop a new line of grain sorghum, TamArk™, with known resistance to the ACCase inhibitor fluazifop. TamArk™ grain sorghum is also resistant to some other herbicides within the aryloxyphenoxypropionate family of ACCase inhibitors, including quizalofop (Piveta et al. 2020). TamArk™ is currently patented, and the trait is being crossed into different grain sorghum lines to possibly be available soon. Quizalofop is expected to be labeled for use on TamArk™ grain sorghum because the research has already been conducted on its effects; however, a label for fluazifop may also be in the future owing to the level of tolerance seen. ACCase inhibitors have been utilized for more than 30 yr to successfully control grass weeds in crops like cotton (*Gossypium hirsutum* L.) and soybean (Camacho et al. 1991; Meyer et al. 2015; Minton et al. 1989).

Grain sorghum producers will benefit from the TamArk™ grain sorghum line by adding a new option to their toolbox to control problematic grasses. However, a knowledge gap exists on optimal application characteristics of fluazifop-butyl for achieving effective johnsongrass control. Therefore research was conducted to determine the rate, timing, and number of applications necessary to effectively control johnsongrass using fluazifop-butyl (Experiment I) and to determine the effect of application timing and rate on johnsongrass control in TamArk™ grain sorghum (Experiment II).

Materials and Methods

Experiment I: Effect of Fluazifop-butyl Rate, Timing, and Number of Applications on Johnsongrass

Experimental Setup

A trial was conducted in summer 2021 at the Lon Mann Cotton Research Station in Marianna, AR, on a Convent silt loam (coarse-silty, mixed, superactive, thermic Fluvaquentic Endoaquepts) consisting of 9% sand, 11% clay, and 80% silt, with an organic matter content of 1.9% and a pH of 6.3, and at the Northeast Research and Extension Center in Keiser, AR, on a Sharkey silty clay (very fine, smectitic, thermic Chromic Epiaquerts) consisting of 31% sand, 26% silt, and 43% clay, with an organic matter content of 1.9% and a pH of 6.7. These fields contained a natural infestation of johnsongrass, comprising both seedling and rhizomatous plants. These trials were conducted in the absence of a crop in plots 1.9 m wide × 4.8 m long. A single application of dicamba at 560 g ae ha^{-1} and hand weeding were used to control broadleaf weeds in the test. The trial did not receive any fertilization because no crop was present.

The experiment was set up as a three-factor, randomized complete block design with 13 treatments, including a nontreated control. Each treatment was replicated four times. Factors included johnsongrass size at the time of application (three levels: 2- to 3-leaf, 5- to 6-leaf, and 8- to 9-leaf or heading), fluazifop-butyl (Fusilade®, Syngenta) rates (two levels: 105 and 210 g ai ha^{-1}), and number of applications (two levels: single and sequential [a total of two] applications). Plots receiving sequential applications were treated with the same rate, with 21 d between applications. Herbicides were applied using a CO_2-pressurized backpack sprayer and a four-nozzle boom calibrated to deliver 140 L ha^{-1} at 6.4 kmph. Air induction extended range (AIXR) 110015 nozzles (TeeJet® Technologies, Springfield, IL, USA) were used for all applications. Boom height was 46 cm above the johnsongrass canopy.

Visible johnsongrass control was evaluated weekly after the initial herbicide application and continued for 4 wk after the final application. Evaluations were made on a scale of 0 to 100, where 0 represented no johnsongrass control and 100 represented complete johnsongrass control (Frans and Talbert 1986). Two 0.5-m^2 quadrats were established in each plot, and initial johnsongrass densities were recorded. Twenty-eight days after final application (DAFA), the total number of live johnsongrass plants in each quadrat was recorded, and percentage mortality was calculated using the equation

$$\frac{\text{Initial johnsongrass density} - \text{Final johsongrass density}}{\text{Initial johsongrass density}} \times 100$$

Data Analysis

Data were analyzed using JMP® Pro 16.1 (SAS Institute Inc., Cary, NC, USA). A general regression with factorial to degree was utilized to determine the level of significance, with fixed factors being the rate, timing, and number of applications for 21 and 28

DAFA and percentage mortality. A factorial to degree was used to allow two-way interactions to be evaluated and to determine if the initial johnsongrass count as a covariate was significant. A covariate of initial count with the variable of percentage mortality was not significant ($P = 0.79$) and therefore was not considered in the analysis. Block was considered random to account for variance among replications. Visible control and percentage mortality were assumed to follow a beta distribution (Gbur et al. 2012). A three-factor factorial was constructed with the main effects of rate, timing, and application with their respective interactions in the PROC GLIMMIX model in SAS 9.4 (SAS Institute Inc.). Location was also considered a random effect. Means were separated using Fisher's protected least significant difference (LSD) at $\alpha = 0.05$ when four or fewer treatments were compared. When comparing treatments resulting from a three-way interaction, a Tukey's honestly significant difference was used to separate means at $\alpha = 0.05$.

Experiment II: Johnsongrass Control in TamArk™ Grain Sorghum Using Fluazifop-p-butyl

Experimental Setup

Field trials were also conducted in 2021 at the Lon Mann Cotton Research Station in Marianna, AR, on a Convent silt loam (coarse-silty, mixed, superactive, thermic Fluvaquentic Endoaquepts) consisting of 9% sand, 11% clay, and 80% silt, with an organic matter content of 1.9% and a pH of 6.3, and at the Arkansas Agricultural Research and Extension Center in Fayetteville, AR, on a Leaf silt loam (fine, mixed, active, thermic Typic Albaquults) with 20% sand, 58% silt, and 22% clay and a pH of 6.2. Each location consisted of a naturally occurring johnsongrass population with a mixture of seedling and rhizomatous plants.

TamArk™ grain sorghum was planted at both locations using a conventional John Deere planter with Almaco cone attachments, 1.2 cm deep, in conventionally tilled and raised beds at 154,000 seeds ha^{-1}. Plots were 4.8 m long × 3.8 m wide with row spacing of 91 cm in Fayetteville and 4.8 m long × 3.9 m wide with row spacing of 96 cm in Marianna. A single application of dicamba at 560 g ae ha^{-1} and hand weeding were used to control broadleaf weeds in the test. In addition, the trial received split nitrogen applications, the first incorporated before planting and the second at the boot stage. In-furrow irrigation was provided on an as-need basis. All management practices, including fertilizer rates, followed the Arkansas grain sorghum production handbook (Espinoza 2015).

The experimental design was a two-factor, randomized complete block design with eight treatments, including a nontreated and a weed-free check for comparison, each replicated four times. The factors consisted of TamArk™ grain sorghum size at application (two levels: 2- to 3- leaf or 5- to 6-leaf) and fluazifop-butyl rate (three levels: 140 g ai ha^{-1}, 210 g ai ha^{-1}, and 140 g ai ha^{-1} followed by [fb] 140 g ai ha^{-1} 21 d later). Fluazifop-butyl was applied using CO_2-pressurized backpack sprayers and a four-nozzle boom calibrated to deliver 140 L ha^{-1} at 6.4 kmph. AIXR 110015 nozzles (TeeJet® Technologies) were used for all applications. Boom height was 46 cm above the largest plant in the canopy. Each application was blocked on either side, and only the center two rows of each plot were treated to eliminate overlap and create a running check throughout the trial.

Two 0.5-m^2 quadrats were established in each plot. The number of johnsongrass plants in each was recorded before initial application. At 28 DAFA, the total number of surviving johnsongrass plants was counted and used to calculate percentage mortality. In addition, the total number of johnsongrass panicles per quadrat was recorded, and panicles were removed before harvest. The seed was then harvested and counted to determine percentage seed reduction as influenced by the treatment. Visible crop injury was assessed weekly until 28 DAFA on a scale of 0 to 100, where 0 represented no visible crop injury and 100 represented complete crop death. The date to 50% heading was recorded for each plot and made relative to the nontreated plot within the block. Yield data could not be collected owing to significant yield loss caused by birds after seed development. Visible johnsongrass control was also evaluated on a scale of 0 to 100, where 0 represented no visible johnsongrass control and 100 indicated that none of the johnsongrass plants were alive (Frans and Talbert 1986).

Data Analysis

Because nontreated plots were rated as 0 for visible injury and control, data were made relative, and nontreated plots were excluded from the data analysis. Visible johnsongrass control, percentage mortality, and percentage johnsongrass seed reduction were assumed to follow a beta distribution, and grain sorghum injury was assumed to follow a gamma distribution by assessing the AICc values in the distribution function of JMP® Pro 16.1 (Gbur et al. 2012). The relative heading date was assumed to follow a normal distribution. A two-factor factorial statement was developed with the main effects of application rate and timing, including interactions using the PROC GLIMMIX model in SAS 9.4. Block and location were considered random effects. The treatment means for visible crop injury, johnsongrass control, percentage mortality, percentage seed reduction, and relative heading date were separated using the Fisher's protected LSD ($\alpha = 0.05$).

Results and Discussion

Experiment I: Effect of Fluazifop-butyl Rate, Timing, and Number of Applications on Johnsongrass

Control

Overall, no interactions were observed among the rate, timing, and number of applications when visible johnsongrass control was evaluated at 14, 21, and 28 DAFA (Table 1). Johnsongrass control increased 5 to 7 percentage points when fluazifop-butyl was applied at 210 g ai ha^{-1} compared to 105 g ai ha^{-1}, resulting in at least 94% control at each rating averaged over timing and number of applications (Table 2). Even with an increase in control at the higher rate, it is important to recognize that at 21 and 28 DAFA, fluazifop-butyl at 105 g ai ha^{-1} resulted in greater than 90% johnsongrass control (Table 2). These findings are comparable to those of Rosales-Robles et al. (1999), where approximately 90% johnsongrass control was achieved with fluazifop-butyl at 105 g ai ha^{-1}. For >95% johnsongrass control, a rate of 210 g ai ha^{-1} was needed (Table 2).

Johnsongrass control differed based on the growth stage at the initial application. Johnsongrass control was lower when the initial application was made to plants at the 8- to 9-leaf stage than at the 5- to 6-leaf stage, with a 9 percentage point difference in control between the smallest and largest plants at 28 DAFA (Table 3). Initial applications to 2- to 3-leaf johnsongrass resulted in control levels similar to those of 5- to 6-leaf plants at all evaluation timings, with greater than 90% control achieved. Likewise, Rosales-Robles et al. (1999) observed that fluazifop-butyl applications to johnsongrass at the 5- to 7-leaf stage resulted in greater than 90% control.

Table 1. Analysis of variance for johnsongrass response to fluazifop-butyl in Marianna and Keiser, AR, in 2021.[a,b]

Independent variable	Control			Mortality
	14 DAFA	21 DAFA	28 DAFA	
	P-value			
Fluazifop-butyl rate	**<0.0001**	**<0.0001**	**0.0002**	**0.0011**
Application timing	**0.0308**	**0.0215**	**<0.0001**	**<0.0001**
No. of applications	**0.0027**	**0.0016**	**<0.0001**	**<0.0001**
Fluazifop-butyl Rate × Application Timing	0.3958	0.1607	0.7526	0.0796
Fluazifop-butyl Rate × No. of Applications	0.4286	0.2323	0.8121	0.8674
Application Timing × No. of Applications	0.3469	0.4003	0.4540	0.0679
Fluazifop-butyl Rate × Application Timing × No. of Applications	0.4084	0.3452	0.0840	**0.0295**

[a]Abbreviation: DAFA, days after final application.
[b]Boldface indicates significant interactions.

Table 2. Visible johnsongrass control by fluazifop-butyl for two rates at 14, 21, and 28 d after final application, averaged over application stage, number of applications, and location.[a,b]

Fluazifop-butyl	14 DAFA	21 DAFA	28 DAFA
g ai ha^{-1}	%		
105	87 b	90 b	92 b
210	94 a	96 a	97 a

[a]Abbreviation: DAFA, days after final application.
[b]Means within a column followed by the same letter are not significantly different based on Fisher's protected least significant difference (α = 0.05).

Table 3. Visible estimates of johnsongrass control as influenced by growth stage at application at 14, 21, and 28 d after final application, averaged over application rate, type, and location.[a,b]

Stage at application	14 DAFA	21 DAFA	28 DAFA
	%		
2- to 3-leaf	90 b	92 b	95 a
5- to 6-leaf	93 a	96 a	97 a
8- to 9-leaf	89 b	90 b	88 b

[a]Abbreviation: DAFA, days after final application.
[b]Means within a column followed by the same letter are not significantly different based on Fisher's protected least significant difference (α = 0.05).

Table 4. Visible estimates of johnsongrass control as influenced by number of applications at 14, 21, and 28 d after final application, averaged over application rate, stage, and location.[a,b]

No. of applications	14 DAFA	21 DAFA	28 DAFA
	%		
Single	88 b	91 b	88 b
Sequential[c]	93 a	95 a	98 a

[a]Abbreviation: DAFA, days after final application.
[b]Means within a column followed by the same letter are not significantly different based on Fisher's protected least significant difference (α = 0.05).
[c]Sequential applications were made 21 d after the initial application.

Sequential applications of fluazifop-butyl, regardless of fluazifop-butyl rate and johnsongrass size at the initial application, resulted in increased control compared to a single application at all three evaluations (Table 4). Sequential applications resulted in a 5, 4, and 10 percentage point increase in johnsongrass control at 14, 21, and 28 DAFA, respectively (Table 4). Winton-Daniels et al. (1990) reported that sequential applications of fluazifop-butyl at 140 g ai ha^{-1} resulted in greater than 85% johnsongrass control over a 3-yr period, which was higher than a single application of 280 g ai ha^{-1}.

Table 5. Percentage mortality of johnsongrass as influenced by application rate, type, and timing of fluazifop at 28 d after the final application, averaged over location.[a,b]

Fluazifop-butyl	No. of applications	Stage at application	Mortality
g ai ha^{-1}			%
105	Single	2- to 3-leaf	87 b
		5- to 6-leaf	70 c
		8- to 9-leaf	58 d
	Sequential[c]	2- to 3-leaf	91 ab
		5- to 6-leaf	99 a
		8- to 9-leaf	83 bc
210	Single	2- to 3-leaf	90 ab
		5- to 6-leaf	95 ab
		8- to 9-leaf	66 d
	Sequential	2- to 3-leaf	99 a
		5- to 6-leaf	99 a
		8- to 9-leaf	87 b

[a]Abbreviation: DAFA, days after final application.
[b]Means within a column followed by the same letter are not significantly different based on Fisher's protected least significant difference (α = 0.05).
[c]Sequential applications were made 21 d after the initial application.

Mortality

A significant three-way interaction of fluazifop-butyl rate by number of applications by johnsongrass size at initial application was observed for johnsongrass mortality 28 DAFA ($P = 0.029$) (Table 1). Three treatment combinations resulted in 99% johnsongrass mortality, with those being fluazifop-butyl at 105 g ai ha^{-1} applied sequentially beginning on 5- to 6-leaf johnsongrass and fluazifop-butyl at 210 g ai ha^{-1} applied sequentially beginning on 2- to 3-leaf or 5- to 6-leaf johnsongrass (Table 5). Single applications did provide greater than 95% johnsongrass mortality, but fluazifop-butyl at 210 g ai ha^{-1} applied once to 2- to 3-leaf or 5- to 6-leaf johnsongrass was not different from the three sequential treatments that reached 99% mortality (Table 5). The lowest levels of johnsongrass mortality resulted when a single application of fluazifop-butyl at 105 or 210 g ai ha^{-1} was made to 8- to 9-leaf johnsongrass, which did not result in greater than 66% mortality. Likewise, Bridges and Chandler (1987) observed reductions in fluazifop-butyl efficacy when applied to johnsongrass greater than 6-leaf. The authors have also evaluated sequential applications of fluazifop-butyl at 140 g ai ha^{-1} and reported 93% to 95% johnsongrass control when applications were made to plants having fewer than 6 leaves.

Table 6. Analysis of variance for TamArk™ grain sorghum injury and johnsongrass control, mortality, and seed reduction in Fayetteville and Marianna, AR, in 2021.[a,b]

	Crop injury			Control				
Independent variable	14 DAFA	21 DAFA	28 DAFA	14 DAFA	21 DAFA	28 DAFA	Mortality	Seed reduction
	P-value							
Fluazifop-butyl rate	0.3490	0.7070	0.2639	**0.0125**	**0.0071**	**0.0093**	**0.0087**	0.9452
Application stage	**0.0467**	0.9705	0.2180	**0.0342**	**0.0169**	0.0592	0.1922	0.9776
Fluazifop-butyl Rate × Application Stage	0.9005	0.9237	0.7315	0.0957	0.1094	0.2679	0.0862	0.9857

[a]Abbreviation: DAFA, days after final application.
[b]Boldface indicates signicant interactions.

Table 7. Visible estimates of johnsongrass control from fluazifop-butyl initially applied to 2- to 3-leaf and 5- to 6-leaf TamArk™ grain sorghum and rated 14, 21, and 28 d after final application and johnsongrass mortality and seed production, averaged over application rate and location.[a,b]

	Control				
Application stage	14 DAFA	21 DAFA	28 DAFA	Mortality	Seed reduction[c]
	%				
2- to 3-leaf	97 a	98 a	98 a	94	99
5- to 6-leaf	90 b	92 b	93 b	90	99

[a]Abbreviation: DAFA, days after final application.
[b]Means within a column followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).
[c]Seed reduction is calculated relative to the nontreated.

Experiment II: Johnsongrass Control Programs in TamArk™ Grain Sorghum

Johnsongrass Control and Mortality

No significant interactions between rate and application timing across all evaluation timings were observed (Table 6). The main effect of application timing was significant across all visible johnsongrass control ratings but was not significant for johnsongrass mortality ($P = 0.1922$). Fluazifop-butyl rate was significant for both visible johnsongrass control and mortality evaluations.

The application timings of 2- to 3-leaf and 5- to 6-leaf TamArk™ grain sorghum resulted in johnsongrass control and mortality greater than 90% when averaged across rate and location. A 5 to 7 percentage point increase in johnsongrass mortality occurred when fluazifop-butyl applications were made at the 2- to 3-leaf stage of grain sorghum compared to applications made at the 5- to 6-leaf stage (Table 7). Because application timings were based on grain sorghum growth stage, increased control was seen at earlier sorghum growth stages when johnsongrass was smaller. At the 2- to 3-leaf applications, johnsongrass plants within the treated plots ranged from 5 to 20 cm and had 2 to 5 leaves. Conversely, at the 5- to 6-leaf stage of grain sorghum, johnsongrass within the treated plots ranged from 10 to 70 cm with 4 to 9 leaves, which is above the size recommended for effective control (Anonymous 2019).

The main effect of fluazifop-butyl rate was significant across all control ratings and mortality evaluations. A similar trend was seen in the noncrop study, where sequential applications of a lower fluazifop-butyl rate provided similar control levels as using a single application of a higher rate. For the in-crop study, fluazifop-butyl 210 g ai ha^{-1} provided control levels not different from sequential applications of 140 g ai ha^{-1} fb 140 g ai ha^{-1}, except for the 21 DAFA evaluation. Furthermore, both rates controlled johnsongrass greater than 90% across all evaluation timings (Table 8). Single applications of fluazifop-butyl at 140 g ai ha^{-1} resulted in lower johnsongrass control and mortality percentages than did applications of 210 g ai ha^{-1} and 140 g ai ha^{-1} fb 140 g ai ha^{-1} across all evaluation timings and did not result in greater than 84% johnsongrass mortality, averaged over timing and location.

Table 8. Visible estimates of johnsongrass control as influenced by fluazifop-butyl rate at 14, 21, and 28 d after final application and johnsongrass mortality averaged over application timing and location.[a,b]

	Control				
Fluazifop-butyl	14 DAFA	21 DAFA	28 DAFA	Mortality	Seed reduction[c]
g ai ha^{-1}	%				
140	84 b	91 c	92 b	84 b	99
210	92 a	95 b	95 a	92 a	99
140 fb 140[d]	96 a	98 a	98 a	96 a	99

[a]Abbreviations: DAFA, days after final application; fb, followed by.
[b]Means within a column followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).
[c]Seed reduction is calculated relative to the nontreated.
[d]Initial application followed by a second application 21 d later.

When evaluating percentage seed reduction, no significant difference was observed with rate or application timing. Seed production per plant was reduced 99% or greater when fluazifop-butyl was applied, regardless of the application timing or rate (Tables 7 and 8).

TamArk™ Grain Sorghum Injury

Low levels of injury, no more than 6%, were observed with applications of fluazifop-butyl to TamArk™ grain sorghum (Table 9). TamArk™ grain sorghum injury was higher when fluazifop-butyl was applied to 5- to 6-leaf compared to 2- to 3-leaf grain sorghum, resulting in 6% and 4% injury, respectively (Table 9). No differences in TamArk™ grain sorghum injury were observed when analyzed by rate and application timing (Table 6). TamArk™ grain sorghum consistently reached the heading stage earlier when treated with fluazifop-butyl compared to nontreated plots. However, the relative heading date was not significantly affected by stage at application or application rate. The earlier

https://doi.org/10.1017/wet.2023.47 Published online by Cambridge University Press

Table 9. Injury to TamArk™ grain sorghum as influenced by stage at initial application at 14, 21, and 28 d after final application and relative heading, averaged over application rate and location.[a,b]

	Injury			
Stage at application	14 DAFA	21 DAFA	28 DAFA	Relative heading[c]
	%			
2- to 3-leaf	4 b	4	4	−2
5- to 6-leaf	6 a	4	4	−2

[a]Abbreviation: DAFA, days after final application.
[b]Means within a column followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).
[c]Negative values represent days before the nontreated, and positive values represent days after the nontreated.

heading in treated plots is attributed to the removal of johnsongrass and the associated stress on the crop caused by this weed.

Practical Implications

Fluazifop-butyl applications to johnsongrass greater than 6-leaf did not result in control greater than 90% regardless of the rate or number of applications. The highest level of johnsongrass control with fluazifop-butyl was achieved when johnsongrass ranged between the 2- and 6-leaf stage with either a single or sequential application. If a single application is utilized, the fluazifop-butyl rate must be 210 g ai ha^{-1}. An application of 105 g ai ha^{-1} will result in sufficient johnsongrass control if followed by another application of 105 g ai ha^{-1} approximately 3 wk later. Regardless of fluazifop-butyl rate or timing, johnsongrass seed production was nearly eliminated. No data were collected on rhizome production. Although the number of seeds entering the soil seed bank will be reduced, johnsongrass plants still have the potential to reproduce if rhizome production is not limited.

No more than 6% injury to TamArk™ grain sorghum was observed at both application timings. Fluazifop-butyl applications before the 6-leaf stage resulted in acceptable injury, making the size of johnsongrass the most critical aspect for application timing. It is important to note that herbicide resistance to ACCase inhibitors is present in some grain sorghum–producing states and could become more problematic if grain TamArk™ sorghum is not correctly managed. Therefore fluazifop-butyl should not be relied upon solely for johnsongrass control in grain sorghum but instead should be used in a program approach with residual herbicides like chloroacetamides or atrazine as well as nonchemical control options to develop an integrated weed management strategy. Utilization of multiple strategies and not sole reliance on a single tactic will help mitigate future johnsongrass resistance to fluazifop-butyl. Fluazifop-butyl could be labeled for johnsongrass control if TamArk™ grain sorghum is commercialized in the future.

Acknowledgments. The authors thank the University of Arkansas Department of Crop, Soil, and Environmental Sciences for giving them the opportunity to conduct this research. The authors also thank the fellow graduate assistants and the program technicians for their help with this research. This research received no specific grant from any funding agency or the commercial or not-for-profit sectors. The authors declare no conflicts of interest.

References

Anonymous (2019) Fusillade® DX herbicide product label. Syngenta Publication Number SCP 1070A-L1K 0819. Greensboro, NC: Syngenta. 38 p

Brabham C, Norsworthy JK, Houston MM, Varanasi VK, Barber T (2019) Confirmation of *S*-metolachlor resistance in Palmer amaranth (*Amaranthus palmeri*). Weed Technol 33:720–726

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

Bridges DC, Chandler JM (1987) Effect of herbicide and weed height on johnsongrass (*Sorghum halepense*) control and cotton (*Gossypium hirsutum*) yield. Weed Technol 1:207–211

Brown SM, Chandler JM, Morrison JE (1988) Glyphosate for johnsongrass control in no-till sorghum. Weed Sci 36:510–513

Burt GW (1974) Adaptation of johnsongrass. Weed Sci 22:59–63

Camacho RF, Moshier LJ, Morishita DW, Devlin DL (1991) Rhizome johnsongrass (*Sorghum halepense*) control in corn (*Zea mays*) with primisulfuron and nicosulfuron. Weed Technol 5:789–794

Corbett JL, Askew SD, Thomas WE, Wilcut JW (2004) Weed efficacy evaluations for bromoxynil, glufosinate, glyphosate, pyrithiobac, and sulfosate. Weed Technol 18:443–453

Espinoza L (2015) Fertilization and liming. Pages 21–24 *in* Arkansas Grain Sorghum Production Handbook MP297. Little Rock, AR: University of Arkansas Cooperative Extension Service

Foy CL, Witt HL (1990) Johnsongrass control with DPX-V9360 and CGA-136872 in corn (*Zea mays*) in Virginia. Weed Technol 4:615–619

Frans R, Talbert R (1986) Experimental Design and Techniques for Measuring and Analyzing Plant Responses to Weed Control Practices. 3rd ed. Champaign, IL: Weed Science Society of America. 17 p

Gbur EE, Stroup WW, McCarther KS, Durham S, Young LJ, Christman M, West M, Kramer M (2012) Analysis of Generalized Linear Mixed Models in the Agricultural and Natural Resources Sciences. Madison, WI: American Society of Agronomy and Soil Science Society of America. 49 p

Ghosheh HZ, Chandler JM (1998) Johnsongrass (*Sorghum halepense*) control systems for field corn (*Zea mays*) utilizing crop rotation and herbicides. Weed Technol 12:623–630

Horowitz M (1972) Early development of johnsongrass. Weed Sci 20: 271–273

Johnson DB, Norsworthy JK, Scott RC (2014a) Distribution of herbicide-resistant johnsongrass (*Sorghum halepense*) in Arkansas. Weed Technol 28:111–121

Johnson DB, Norsworthy JK, Scott RC (2014b) Herbicide programs for controlling glyphosate-resistant johnsongrass (*Sorghum halepense*) in glufosinate-resistant soybean. Weed Technol 28:10–18

Kering MK, Huo C, Interrante SM, Hancock DW, Butler TJ (2013) Effect of various herbicides on warm-season grass weeds and switchgrass establishment. Crop Sci 53:665–673

McWhorter CG (1971) Anatomy of johnsongrass. Weed Sci 19:385–393

McWhorter CG (1989) History, biology, and control of johnsongrass. Rev Weed Sci 4:85–121

McWhorter CG, Hardwig EE (1965) Effectiveness of pre-planting tillage in relation to herbicides in controlling johnsongrass for soybean production. Agron J 57:385–389

Meyer CJ, Norsworthy JK, Stephenson DO, Bararpour MT, Landry RL, Woolam BC (2015) Control of johnsongrass in the absence of glyphosate in Mid-South cotton production systems. Weed Technol 29:730–739

Miller JH (2014) Texas Invasive Species Institute. http://www.tsusinvasives.org/home/database/sorghum-halepense. Accessed: August 21, 2023

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

Mitch LW (1987) Colonel Johnson's grass: johnsongrass. Weed Technol 1:112–113

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

Pinkerton S (2020) Advanced cropping solutions for sorghum coming soon. https://sorghumgrowers.com/magazine/checkoff-newsletter-spring-2020/. Accessed: October 3, 2020

Piveta LB, Norsworthy JK, Bagavathiannan MV (2020) Evaluation of ACCase-resistant grain sorghum to fluazifop at different growth stages. Proc South Weed Sci Soc 73:38

Rosales-Robles E, Chandler JM, Senseman SA, Prostko EP (1999) Influence of growth stage and herbicide rate on postemergence johnsongrass (*Sorghum halepense*) control. Weed Technol 13:525–529

Smith K, Scott B (2010) Weed control in grain sorghum. Pages 47–49 *in* Grain Sorghum Handbook. Little Rock, AR: University of Arkansas Research and Extension

Winton-Daniels K, Frans R, McClelland M (1990) Herbicide systems for johnsongrass (*Sorghum halepense*) control in soybeans (*Glycine max*). Weed Technol 4:115–122

Wright DL, Vanderlip RL, Regehr DL, Moshier LJ, Russ OG (1992) Grain sorghum hybrid response to lasso and dual herbicides, and efficacy of screen, CONCEP II, and CONCEP II/APRON seed safeners. Bulletin 659. Hays, KS: Kansas State University Agricultural Experiment Station. 28 p

https://doi.org/10.1017/wet.2023.47 Published online by Cambridge University Press