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Glyphosate-resistant Italian ryegrass (*Lolium perenne* ssp. *multiflorum*) control with preemergence and postemergence herbicide programs

Jason A. Bond[1], Tom W. Allen Jr[2], John W. Seale[3] and Henry M. Edwards[4]

[1]Extension/Research Professor, Department of Plant and Soil Sciences, Mississippi State University, Delta Research and Extension Center, Stoneville, MS, USA; [2]Extension/Research Professor, Department of Biochemistry, Molecular Biology, Entomology and Plant Pathology, Mississippi State University, Delta Research and Extension Center, Stoneville, MS, USA; [3]Former Research Assistant, Department of Plant and Soil Sciences, Mississippi State University, Delta Research and Extension Center, Stoneville, MS, USA and [4]Research Associate II, Department of Plant and Soil Sciences, Mississippi State University, Delta Research and Extension Center, Stoneville, MS, USA

Research Article

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S-metolachlor; clethodim; paraquat; Italian ryegrass; *Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot. LOLMU; *Glycine max* (L.) Merr. GLXMA; *Zea mays* L. ZEAMX.

Keywords:
Fall residual; herbicide resistance; sequential applications; tillage; weed control

Author for correspondence:
Jason A. Bond, Extension/Research Professor, Mississippi State University, Delta Research and Extension Center, P.O. Box 197, Stoneville, MS 38776. Email: jbond@drec.msstate.edu

Abstract

A field study was conducted twice in Elizabeth, MS, at on-farm sites in 2010–11 and 2011–12, and twice in 2012–13 at Mississippi State University's Delta Research and Extension Center in Stoneville, MS, to evaluate glyphosate-resistant (GR) Italian ryegrass control and crop response to fall treatments followed by postemergence herbicide treatments in winter and/or spring. Italian ryegrass was controlled ≥92% and 61% following *S*-metolachlor and tillage 77 d after fall treatments (DA-FT), respectively. *S*-metolachlor fall treatment provided 33% greater control than clethodim winter treatment at 21 d after winter treatments (DA-WT). Tillage fall treatment followed by (fb) clethodim winter treatment fb paraquat spring treatment provided similar control (93%) to treatments containing *S*-metolachlor fall treatment fb a winter or spring herbicide treatment (≥93%) 24 d after spring treatments (DA-ST). Greatest soybean and corn density and yield were also observed following programs containing *S*-metolachlor fall treatment. Sequential postemergence herbicide treatments were not required to increase corn and soybean density and yield when *S*-metolachlor was used as a fall treatment. Growers have the best opportunity to maximize GR Italian ryegrass control when *S*-metolachlor fb a winter or spring herbicide treatment is used.

Introduction

Winter annual weed species that emerge in fall or early spring can interfere with planting and emergence of summer annual crops (Hasty et al. 2004; Monnig and Bradley 2007). The diversity of winter and summer annual weed species presents a challenge for herbicide applications made in no-till soybean and cotton (*Gossypium hirsutum* L.) cropping systems (Owen et al. 2009; Vollmer et al. 2019). Mid-southern U.S. growers rely on herbicide applications to control winter and summer annual weed species prior to planting. In soybean, herbicide applications 1 to 2 wk before planting may provide inadequate control of winter annual weed species (Monnig and Bradley 2007). Therefore, residual herbicides applied in the fall can be an effective weed management strategy for controlling winter annual weed species (Vollmer et al. 2019).

Previous research reported fall residual herbicides controlled more horseweed [*Conyza canadensis* (L.) Cronq.] than fall applications without residual herbicides (Owen et al. 2009). However, fall residual herbicides may not provide adequate control of summer or late-emerging winter annual weed species in the spring. Additional research (Vollmer et al. 2019) reported that fall followed by (fb) spring herbicide applications were required to control the majority of winter annual weed species because fall applications alone were inadequate. Therefore, a two-pass herbicide program consisting of a fall residual fb a spring application or two sequential spring applications was needed to control winter annual weed species. In Delaware, fall residual herbicides applied in December were more beneficial than applications in November for winter annual weed control (Vollmer et al. 2019). However, research in Mississippi reported fall residual herbicides applied in November provided greater control of Italian ryegrass than earlier applications (Bond et al. 2014).

In Mississippi, Italian ryegrass has been one of the most difficult weeds to control over the last 15 yr (Bond 2018). Italian ryegrass is an annual or biennial bunchgrass that grows rapidly throughout the winter and spring and reaches 30 to 90 cm in height (Bond et al. 2014; Davies 1928). In addition to being a general roadside weed, Italian ryegrass can impact economically important row crops. Research reported corn yield losses up to 49% from an Italian ryegrass density of four plants per meter (Nandula 2014). Reduced crop stand and yield loss attributed to Italian ryegrass interference requires the adoption of effective weed control strategies. Justice et al. (1994) reported that Italian ryegrass may be controlled with cultural practices such as reduced row spacing, increased tillage, delayed planting, crop rotation, and increased seeding rate for winter wheat production; however, those practices were less effective than herbicides.

Herbicide applications have been the most common management strategy to control Italian ryegrass in wheat (Bond et al. 2014; Kuk et al. 2008). Diclofop, an acetyl CoA carboxylase (ACCase)-inhibiting herbicide, was historically the most widely used chemical option for Italian ryegrass control in wheat (Crooks et al. 2003; Ellis et al. 2008). However, repeated applications of this herbicide selected for diclofop-resistant (DR) biotypes in some production fields (Grey and Bridges 2003; Rauch et al. 2010). The first DR Italian ryegrass population was documented in Oregon in 1987 (Betts et al. 1992), and 12 U.S. states have documented Italian ryegrass resistance to diclofop since that time (Heap 2021). Herbicides such as glyphosate, imazamox, mesosulfuron, and pinoxaden have been used for postemergence (POST) control of Italian ryegrass in wheat as well as additional economically important row crops throughout the United States (Bond et al. 2005; Ellis et al. 2008; Jordan et al. 2001; Kuk and Burgos 2007); however, resistance to these herbicides has been documented in Mississippi (Bond et al. 2014; Bond 2018; Heap 2021; Nandula et al. 2019). Therefore, POST herbicides are limited to clethodim and/or paraquat for herbicide-resistant Italian ryegrass control in Mississippi (Bond et al. 2005; Bond 2018; Eubank et al. 2012).

Clethodim is an ACCase-inhibiting herbicide that has been used throughout Mississippi for glyphosate-resistant (GR) Italian ryegrass control (Bond 2018). Clethodim applied in November or January provided greater Italian ryegrass control than when it was applied in March (Bond et al. 2011). Additionally, clethodim was more effective for Italian ryegrass control than other ACCase-inhibiting herbicides, and potential resistance to this herbicide was the rarest among 12 herbicides evaluated (Rauch et al. 2010). However, repetitive use of this herbicide has resulted in clethodim-resistant Italian ryegrass biotypes in seven Mississippi counties (Nandula et al. 2019). The loss of clethodim in recent years has left some Mississippi producers with paraquat as the only POST herbicide for Italian ryegrass control (Bond 2018; Nandula et al. 2019).

Paraquat is a nonselective contact herbicide that is used to control grass and broadleaf weed species in spring burndown applications for many agronomic, vegetable, and fruit crops (Eubank et al. 2008; Grillo et al. 2014; Jordan et al. 2001; Tharp and Kells 2001). Italian ryegrass is controlled by paraquat, but control is influenced by weed size and foliar coverage (Jordan et al. 2001). During spring preplant burndown applications, Italian ryegrass may be larger in size (30 to 60 cm) and often requires two paraquat applications spaced 10 to 14 d apart (Bond 2018). Therefore, paraquat should be applied when Italian ryegrass plants are small, and roots are not well established (Nandula et al. 2019). To date, paraquat-resistant Italian ryegrass has been confirmed only in California in the United States (Heap 2021; Tehranchian et al. 2019).

Currently, weed management strategies in Mississippi suggest implementing a fall residual herbicide prior to GR Italian ryegrass emergence. Based on research conducted by Hasty et al. (2004), Owen et al. (2009), and Vollmer et al. (2019), a two-pass herbicide program consisting of a fall residual fb a spring POST application was required to maximize control of winter annual weed species. Additionally, Bond et al. (2014) concluded that fall residual herbicides controlled GR Italian ryegrass, but a spring POST herbicide would be required to control escapes. Because paraquat is one of the only reliable POST preplant burndown options for Italian ryegrass control in Mississippi, fall residual herbicides must be used to mitigate the potential development of paraquat resistance. Therefore, research was conducted to evaluate GR Italian ryegrass management programs including fall treatments fb POST herbicide treatments in winter and/or spring.

Materials and Methods

A study was conducted from 2010–11 to 2012–13 to evaluate preemergence followed by POST herbicide programs for control of GR Italian ryegrass. The study was conducted twice in 2010–11 (2010–11A and 2010–11B) and 2011–12 (2011–12A and 2011–12B) at on-farm sites near Elizabeth, MS, known to be infested with GR Italian ryegrass (Nandula et al. 2007). The study was repeated twice in 2012–13 (2012–13A and 2012–13B) at the Mississippi State University Delta Research and Extension Center in Stoneville, MS. Coordinates, soil series, soil description, soil pH, and soil organic matter for each site year are presented in Table 1. Sites were fallow the previous year and tilled in midsummer prior to plot establishment. GR Italian ryegrass was surface-seeded immediately preceding summer tillage at individual sites in 2012–13 to ensure uniform infestation.

The study was designed as a randomized complete block with treatments arranged as a factorial of three fall, two winter, and two spring treatments with four replications. Fall treatments included no fall treatment, tillage, and *S*-metolachlor (Dual Magnum; Syngenta Crop Protection LLC, Greensboro, NC) at 1.42 kg ai ha^{-1} plus paraquat (Gramoxone SL; Syngenta Crop Protection LLC) at 0.84 kg ai ha^{-1} plus crop oil concentrate (COC; Agri-Dex; Helena Chemical Co., Memphis, TN) at 1% (vol/vol). The tillage treatment consisted of two passes in opposite directions with a tandem disk set to operate at 7.6 cm. Winter treatments included no winter treatment and clethodim (Select Max; Valent U.S.A. LLC, Walnut Creek, CA) at 0.11 kg ai ha^{-1} plus glyphosate (Roundup Powermax; Bayer CropScience LP, St. Louis, MO) at 0.84 kg ae ha^{-1} plus a nonionic surfactant (Induce, a 90% nonionic surfactant, Helena Chemical Co.) at 0.25% (vol/vol). Spring treatments included no spring treatment and paraquat at 1.12 kg ha^{-1} plus COC at 1% (vol/vol). Herbicide rates were identified from previous research in Mississippi (Bond et al. 2011, 2014). Treatments were applied with a tractor-mounted sprayer calibrated to deliver 140 L ha^{-1} at 276 kPa, fitted with extended range flat-fan (XR10002; TeeJet, Wheaton, IL) nozzles. Dates of treatment application for individual site years and dates of first measurable rainfall after fall treatment application are presented in Table 2.

Two site years were used in 2011–12 and 2012–13 to facilitate planting and evaluation of corn and soybean response to GR Italian ryegrass control programs. Corn and soybean were planted 1 and 28 d, respectively, following the spring treatment application in the second and third year of the research. 'Pioneer 31G71' (Pioneer, Johnston, IA) corn hybrid was sowed with a John Deere small-plot air planter (John Deere 1730; Deere and Company, Moline, IL) at 64,200 seed ha^{-1}. 'Pioneer 94Y80' maturity group IV soybean was sowed at 370,600 seed ha^{-1}. Each plot contained four rows spaced 1 m apart and 9 m in length. Plots were separated by a 3-m weed-free, fallow alley. Corn and soybean were managed throughout the growing season to optimize yield.

GR Italian ryegrass control was visibly estimated at 30 and 77 d after fall treatment (DA-FT), 21 d after winter treatment

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Table 1. Study location data.[a]

Site year	Coordinates	Soil series	Description	pH	Organic matter
				1:2(vol:vol)	%
2010–11A	33.42096667°N, 90.88500000°W	Commerce very fine sandy loam	Fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts	6.3	1.0
2010–11B	33.41893333°N, 90.88500000°W	Commerce very fine sandy loam	Fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts	6.5	1.2
2011–12A	33.42276944°N, 90.88166667°W	Boskett very fine sandy loam	Fine-loamy, mixed, active, thermic Mollic Hapludalfs	6.1	0.9
2011–12B	33.42035000°N 90.88388889°W	Commerce very fine sandy loam	Fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts	6.3	1.3
2012–13A	33.42034167°N, 90.90333333°W	Tunica clay	Clayey over loamy, smectitic over mixed, superactive, nonacid, thermic Vertic Epiaquepts	6.8	2.0
2012–13B	33.41904167°N, 90.90333333°W	Tunica clay	Clayey over loamy, smectitic over mixed, superactive, nonacid, thermic Vertic Epiaquepts	6.9	2.1

[a]The study, carried out from 2010–11 to 2012–13, at locations near Elizabeth and Stoneville, MS, was designed to evaluate preemergence and postemergence herbicide programs to control glyphosate-resistant Italian ryegrass.

Table 2. Dates of treatment application and first rainfall after fall treatment.

Site year	Fall treatment	Winter treatment	Spring treatment	First rainfall
2010–11A	October 24, 2010	February 5, 2011	February 23, 2011	October 25, 2010
2010–11B	November 1, 2010	February 8, 2011	February 23, 2011	November 2, 2010
2011–12A	October 26, 2011	February 2, 2012	March 6, 2012	October 28, 2011
2011–12B	November 7, 2011	February 3, 2012	March 6, 2012	November 9, 2011
2012–13A	October 17, 2012	February 5, 2013	March 7, 2013	October 18, 2012
2012–13B	November 4, 2012	February 5, 2013	March 7, 2013	November 12, 2012

(DA-WT), and 14 and 24 d after spring treatment (DA-ST) on a scale of 0% (no control) to 100% (complete control). Following the 24 d after spring treatment evaluation, aboveground shoot biomass of GR Italian ryegrass was collected from a 1-square-meter quadrat in each plot. Plants were cut at soil level, placed in paper bags, allowed to dry under greenhouse conditions for 14 d, and dry weights of each sample were recorded. Corn and soybean seedling densities were determined by counting all plants in two 1-square-meter quadrats from rows 2 and 3 in each plot 14 d after emergence (DAE) and calculating the mean. Corn and soybean were harvested with a small-plot combine (Kincaid Equipment, Haven, KS), grain weights and moisture contents were recorded, and corn and soybean yields were adjusted to uniform moisture concentrations of 15.5% and 13%, respectively, for statistical analysis.

All data were subjected to ANOVA using the MIXED procedure in SAS (Statistical Analysis Software v9.4; SAS Institute, Cary, NC) with site year and replication (nested within site year) as random effect parameters (Blouin et al. 2011). Type III statistics were used to test all possible main effects or interactions among the fixed effects. The square roots of visible control data were arcsine transformed. Arcsine transformation did not improve homogeneity of variance; therefore, nontransformed data were used in analyses. Least-square means were calculated, and mean separation ($P \leq 0.05$) was produced using PDMIX800 in SAS, which is a macro for converting mean separation output letter groupings (Saxton 1998).

Results and Discussion

Glyphosate-Resistant Italian Ryegrass Control

A fall treatment main effect was detected for GR Italian ryegrass control at 30 and 77 DA-FT (Table 3). Tillage provided 61% and 50% GR Italian ryegrass control at 30 and 77 DA-FT, respectively (Table 4). *S*-metolachlor controlled more GR Italian ryegrass than tillage at 30 and 77 DA-FT, and control was ≥92%. According to Justice et al. (1994), herbicides were more effective than increased tillage for Italian ryegrass control. Furthermore, results herein complement those reported by Vollmer et al. (2019), who concluded that fall residual herbicides were the most effective strategy for managing winter annual weed species.

A two-way interaction of fall fb winter treatment was detected for GR Italian ryegrass control at 21 DA-WT (Table 3). Herbicide programs that did not include *S*-metolachlor as a fall treatment controlled GR Italian ryegrass by ≤71% at 21 DA-WT (Table 4). However, control with *S*-metolachlor fb no winter treatment or clethodim was 89% and 92%, respectively, 21 DA-WT. Visible observations 21 DA-WT indicated a winter treatment of clethodim following *S*-metolachlor as a fall treatment did not increase GR Italian ryegrass control compared with *S*-metolachlor alone. Vollmer et al. (2019) reported a two-pass herbicide program consisting of a fall residual herbicide fb a spring herbicide application was required to control winter annual weed species because a fall residual herbicide application alone was inadequate. Furthermore, *S*-metolachlor alone controlled 33% more GR Italian ryegrass than clethodim alone by 21 DA-WT (Table 4). Therefore, a clethodim winter treatment following *S*-metolachlor was not required to improve GR Italian ryegrass control compared with fall-applied *S*-metolachlor alone.

A three-way interaction of fall, winter, and spring treatments was detected for GR Italian ryegrass control at 14 and 24 DA-ST (Table 3). *S*-metolachlor fb a clethodim winter treatment and/or a paraquat spring treatment provided ≥93% GR Italian ryegrass control at 14 and 24 DA-ST (Table 5). However, GR Italian ryegrass control at 14 and 24 DA-ST was also 93% with tillage fb clethodim fb paraquat. Control was similar with programs

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Table 3. Significance of the main effects of fall, winter, and spring treatments and interactions among the main effects for glyphosate-resistant Italian ryegrass control.

	Evaluation interval for control of GR Italian ryegrass control[a,b]									
Effect	1[c]	2[c]	3[d]	4	5	GR Italian ryegrass dry weight	Corn density	Corn yield	Soybean density	Soybean yield
	P-value									
Fall	0.0001	0.0001	0.0001	0.0001	0.0001	0.0319	0.0271	0.0514	0.0001	0.0006
Winter	0.2837	0.6289	0.0001	0.0001	0.0001	0.0001	0.0732	0.0306	0.0001	0.0001
Spring	0.3958	0.2575	0.1661	0.0001	0.0001	0.0001	0.1487	0.2799	0.0089	0.0284
Fall*Winter	0.3876	0.9104	0.0001	0.0001	0.0001	0.0001	0.0110	0.0149	0.0030	0.0001
Fall*Spring	0.5686	0.4891	0.1035	0.0001	0.0001	0.0027	0.9911	0.0994	0.0011	0.1599
Winter*Spring	0.5314	0.6421	0.8169	0.0001	0.0001	0.0001	0.3661	0.3695	0.0089	0.7519
Fall*Winter*Spring	0.8026	0.2220	0.9478	0.0001	0.0001	0.0001	0.6377	0.8936	0.0049	0.8674

[a]Evaluations were carried out 30 and 77 d after fall treatment (Evaluations 1 and 2, respectively), 21 d after winter treatment (Evaluation 3), and 14 and 24 d after spring treatment (Evaluations 4 and 5, respectively).
[b]Abbreviation: GR, glyphosate-resistant.
[c]Winter and spring treatments had not been applied prior to evaluation.
[d]Spring treatments had not been applied prior to evaluation.

Table 4. Glyphosate-resistant Italian ryegrass control 30 and 77 d following fall treatments and 21 d following winter treatment.[a]

			21 d after winter treatment[d]	
Fall treatment	30 d after fall treatment[c]	77 d after fall treatment[c]	No winter treatment	Clethodim[c]
	%			
No fall treatment	0 c	0 c	0 d	56 c
Tandem disk	61 b	50 b	43 c	71 b
S-metolachlor[b]	94 a	92 a	89 a	92 a

[a]Data averaged across six site years. Means followed by same letter for each evaluation interval are not different at P ≤ 0.05.
[b]*S*-metolachlor was applied at 1.40 kg ai ha^{-1}, and applications included paraquat at 0.84 kg ai ha^{-1} plus crop oil concentrate at 1% (vol/vol).
[c]Data averaged across two winter and two spring treatments and six site years; however, winter and spring treatments had not been applied prior to evaluation.
[d]Data averaged across two spring treatments and six site years; however, spring treatments had not been applied prior to evaluation.

consisting of tillage fb clethodim winter treatment fb no spring treatment, *S*-metolachlor fb no winter or spring treatments, and no fall treatment fb clethodim fb paraquat, ranging from 83% to 86% 14 and 24 DA-ST. Remaining programs that did not include *S*-metolachlor fall treatment and resulted in ≤74% and ≤76% GR Italian ryegrass control at 14 and 24 DA-ST, respectively.

At 14 and 24 DA-ST, a three-pass program consisting of tillage fb clethodim fb paraquat was required to control GR Italian ryegrass, which was similar to two- or three-pass herbicide programs that used *S*-metolachlor fb a herbicide treatment in winter and/or spring. However, a three-pass herbicide program consisting of winter and spring herbicide treatments following a *S*-metolachlor fall treatment did not improve GR Italian ryegrass control compared with a two-pass herbicide program that used a fall-applied *S*-metolachlor treatment fb a winter or spring herbicide treatment.

A three-way interaction of fall, winter, and spring treatments was detected for GR Italian ryegrass dry weight (Table 3). Dry weight of GR Italian ryegrass was 379 g m^{-2} with no treatments at any of the three prescribed application timings (Table 6). In plots with imposed control tactics, GR Italian ryegrass dry weights were ≤175 g m^{-2}. The least GR Italian ryegrass dry weights (1 to 47 g m^{-2}) were observed following application of *S*-metolachlor alone or fb winter and/or spring treatment, clethodim alone, and tillage fb winter and/or spring treatment. However, *S*-metolachlor or clethodim alone and tillage fb winter or spring herbicide treatments did not maximize GR Italian ryegrass control 24 DA-ST (Table 5). Therefore, two herbicide applications were required to control GR Italian ryegrass and reduce dry weight. Based on these results, growers should use *S*-metolachlor fall treatment fb a clethodim winter treatment to maximize GR Italian ryegrass control and reduce dry weight.

Results from the current study complement those of Vollmer et al. (2019) who reported that a two-pass herbicide program was required to maximize control of winter annual weed species (Table 5). Their results indicated that a fall residual herbicide fb a spring herbicide application or two sequential spring herbicide applications were required to adequately control winter annual weed species such as cutleaf evening primrose (*Oenothera laciniata* Hill), field pansy (*Viola bicolor* Pursh), henbit (*Lamium amplexicaule* L.), horseweed, and knawel (*Scleranthus annuus* L.). Our results suggest a program that includes two herbicide treatments is required to effectively control GR Italian ryegrass in Mississippi. A winter or spring herbicide treatment must be used following a *S*-metolachlor fall treatment to maximize GR Italian ryegrass control 24 DA-ST. If fall tillage is practiced, a winter fb spring herbicide treatment must be included to control GR Italian ryegrass comparable to two-pass programs that include *S*-metolachlor fb winter or spring herbicide treatment.

Mississippi growers should not use a fall tillage treatment to control GR Italian ryegrass based on results of the current research. Because clethodim-resistant (CR) Italian ryegrass has been confirmed in several Mississippi counties (Bond 2018; Bond et al. 2021; Nandula et al. 2019), a practice of tillage in the fall leaves paraquat as the only POST option to control CR Italian ryegrass in fields containing those populations. According to Bond (2018), two spring paraquat applications spaced 10 to 14 d apart were required to adequately control GR Italian ryegrass. In the current research, a fall tillage treatment fb spring treatment with paraquat controlled GR Italian ryegrass by 70% at 24 DA-ST (Table 5). Additionally, producers who till in the fall would need to follow that with two sequential applications of paraquat in the spring to control CR Italian ryegrass (Bond 2018). Relying on a single herbicide such as paraquat may increase selection pressure for herbicide resistance in targeted weed species including Italian ryegrass (Tehranchian et al. 2019; Vencill et al. 2012). To mitigate

Table 5. Glyphosate-resistant Italian ryegrass control 14 and 24 d after spring treatment as influenced by fall, winter, and spring treatments.[a]

	14 d after final treatment				24 d after final treatment			
	No winter treatment		Clethodim[c]		No winter treatment		Clethodim[c]	
Fall treatment	No spring treatment	Paraquat[d]	No spring treatment	Paraquat[d]	No spring treatment	Paraquat[d]	No spring treatment	Paraquat[d]
	%							
No fall treatment	0 f	63 d	74 c	86 b	0 g	59 e	76 c	86 b
Tandem disk	27 e	73 c	83 b	93 a	21 f	70 d	85 b	93 a
S-metolachlor[b]	85 b	93 a	95 a	97 a	84 b	93 a	97 a	98 a

[a]Data averaged across six site years. Means followed by same letter for each evaluation interval are not different at P ≤ 0.05.
[b]*S*-metolachlor was applied at 1.40 kg ai ha^{-1}, and applications included paraquat at 0.84 kg ai ha^{-1} plus crop oil concentrate at 1% (vol/vol).
[c]Clethodim was applied at 0.11 kg ai ha^{-1}, and applications included glyphosate at 0.84 kg ae ha^{-1} and nonionic surfactant at 0.25% (vol/vol).
[d]Paraquat was applied at 1.12 kg ai ha^{-1}, and applications included crop oil concentrate at 1% (vol/vol).

Table 6. Glyphosate-resistant (GR) Italian ryegrass dry weight 24 d after spring treatment and soybean density.[a,e]

	GR Italian ryegrass dry weight				Soybean density			
	No winter treatment		Clethodim[c]		No winter treatment		Clethodim[c]	
Fall treatment	No spring treatment	Paraquat[d]	No spring treatment	Paraquat[d]	No spring treatment	Paraquat[d]	No spring treatment	Paraquat[d]
	g m^{-2}				plants m^{-2}			
No fall treatment	379 a	137 bc	37 de	86 d	19 f	21 def	22 cde	23 bcd
Tandem disk	175 b	47 de	17 e	1 e	20 ef	24 abc	25 ab	25 ab
S-metolachlor[b]	5 e	8 e	7 e	1 e	26 a	25 ab	26 a	26 a

[a]Data averaged across six and two site years for GR Italian ryegrass dry weight and soybean density, respectively. Means followed by same letter for each parameter are not different at P ≤ 0.05.
[b]*S*-metolachlor was applied at 1.40 kg ai ha^{-1} and applications included paraquat at 0.84 kg ai ha^{-1} plus crop oil concentrate at 1% (vol/vo.).
[c]Clethodim was applied at 0.11 kg ai ha^{-1}, and applications included glyphosate at 0.84 kg ae ha^{-1} and nonionic surfactant at 0.25% (vol/vol).
[d]Paraquat was applied at 1.12 kg ai ha^{-1}, and applications included crop oil concentrate at 1% (vol/vol).
[e]Abbreviation: GR, glyphosate-resistant.

development of paraquat-resistant Italian ryegrass in Mississippi, growers should use a residual herbicide in the fall to control GR Italian ryegrass prior to emergence (Bond et al. 2014). However, results reported here demonstrate that a clethodim winter treatment or paraquat spring treatment is required to maximize GR Italian ryegrass control after a fall residual herbicide treatment and prior to spring crop planting. Therefore, producers should use a *S*-metolachlor fall treatment fb a clethodim winter treatment because this program will allow producers to apply a spring paraquat treatment if needed.

Corn Density and Yield

A two-way interaction of fall and winter treatments was detected for corn density and yield (Table 3). Pooled over spring treatments, *S*-metolachlor fb clethodim or no winter treatment and tillage fb clethodim programs resulted in corn densities of 6.6, 6.4, and 6.3 plants m^{-2}, respectively (Table 7). Corn densities were lower following additional treatment combinations. Based on these results, *S*-metolachlor should be applied in the fall, but winter treatment did not improve corn density. Furthermore, tillage fb clethodim winter treatment resulted in similar corn density to programs that used *S*-metolachlor alone or fb clethodim.

Pooled over spring treatments, corn yield was similar and maximized following *S*-metolachlor fb no winter treatment or clethodim (Table 7). Clethodim winter treatment with no fall treatment and tillage fb clethodim programs led to similar corn yield. However, these corn yields were ≤8,320 kg ha^{-1}, which was lower than yields with programs that included *S*-metolachlor. Programs that included *S*-metolachlor led to greatest corn density and yield, but clethodim following *S*-metolachlor did not improve corn yield compared with *S*-metolachlor used alone.

Soybean Density and Yield

A three-way interaction of fall, winter, and spring treatment was detected for soybean density (Tables 3 and 6), and a two-way interaction of fall fb winter treatment was detected for soybean yield (Tables 3 and 7). Soybean density was 19 to 26 plants m^{-2} following all programs (Table 6). Programs that included *S*-metolachlor fall treatment or tillage fb winter and/or spring herbicide treatment resulted in greatest soybean densities (24 to 26 plants m^{-2}). Therefore, *S*-metolachlor fall treatment maximized soybean density with no winter and/or spring herbicide treatment.

Pooled over spring treatment, soybean yield was greatest (2,600 to 2,750 kg ha^{-1}) among programs that used a *S*-metolachlor fall treatment or clethodim winter treatment (Table 7). Soybean yield was similar and reduced to 2,100 and 1,890 kg ha^{-1} for programs consisting of tillage fb no winter treatment and no fall treatment fb no winter treatment, respectively. Based on these results, Mississippi producers can use *S*-metolachlor alone, *S*-metolachlor fb clethodim, no fall treatment fb clethodim, or tillage fb clethodim to maximize soybean yield. These data suggest that *S*-metolachlor fall treatment alone maximized soybean density and yield without requiring a clethodim winter treatment.

In conclusion, a two-pass herbicide program that uses *S*-metolachlor fb clethodim winter treatment or paraquat spring treatment will maximize GR Italian ryegrass control. Although some programs that included fall tillage provided comparable GR Italian ryegrass control to that of a two-pass herbicide program, both

Table 7. Corn density and corn yield and soybean yield influenced by fall and winter treatments.[a]

Fall treatment	Corn density		Corn yield		Soybean yield	
	No winter treatment	Clethodim[c]	No winter treatment	Clethodim[c]	No winter treatment	Clethodim[c]
	plants m^{-2}		kg ha^{-1}			
No fall treatment	4.51 b	5.25 b	5520 d	7550 bc	1890 b	2730 a
Tandem disk	4.89 b	6.3 a	6250 cd	8320 b	2100 b	2650 a
S-metolachlor[b]	6.36 a	6.58 a	9790 a	10060 a	2600 a	2750 a

[a]Data averaged across two spring treatments and two site years. Means followed by same letter for each parameter are not different at $P \le 0.05$.
[b]*S*-metolachlor was applied at 1.40 kg ai ha^{-1}, and applications included paraquat at 0.84 kg ai ha^{-1} plus crop oil concentrate at 1% (vol/vol).
[c]Clethodim was applied at 0.11 kg ai ha^{-1}, and applications included glyphosate at 0.84 kg ae ha^{-1} and nonionic surfactant at 0.25% (vol/vol).

winter and spring herbicide treatments are required, which results in a three-pass program. Two-pass programs that use fall tillage fb a winter or spring herbicide treatment reduced GR Italian ryegrass dry weight similar to that of two-pass programs that used *S*-metolachlor fb a winter or spring treatment. However, a fall tillage treatment should not be used because it requires an additional herbicide treatment to achieve the same control as a two-pass herbicide program. Regarding spring crops, *S*-metolachlor alone in the fall led to the greatest corn and soybean densities and yields. Mississippi growers who combat GR Italian ryegrass will optimize soybean and corn density and yield by adopting a two-pass herbicide program consisting of *S*-metolachlor fb clethodim because *S*-metolachlor alone provided reduced GR Italian ryegrass control compared with two- or three-pass programs.

To control GR Italian ryegrass in Mississippi, growers should adopt a treatment protocol of *S*-metolachlor in the fall fb clethodim in winter, so a paraquat spring treatment can still be used if needed. This treatment can also help mitigate development of paraquat-resistant Italian ryegrass by reducing exposure to paraquat (Tehranchian et al. 2019). However, if GR- and CR-Italian ryegrass is present, then a two-pass herbicide program consisting of a fall-applied *S*-metolachlor treatment fb a spring paraquat treatment should be used to maximize control of these Italian ryegrass populations and to reduce density and yield losses in soybean and corn.

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