Weed Technology 2015 29:390–404

Effect of Row Spacing, Seeding Rate, and Herbicide Program in Glufosinate-Resistant Soybean on Palmer Amaranth Management

Holden D. Bell, Jason K. Norsworthy, Robert C. Scott, and Michael Popp*

A field experiment was conducted in Fayetteville, AR, in 2012 and 2013 to determine the influence of soybean row spacing, seeding rate, and herbicide program in glufosinate-resistant soybean on Palmer amaranth control, survival, and seed production; soybean groundcover and grain yield; and economic returns. Soybean groundcover was > 80% by 85 d after soybean planting (DAP) for all row spacing and seeding rates in 2012 and in 2013 all soybean row spacings and soybean seeding rates had achieved > 90% groundcover by 50 DAP. Difference in groundcover between years was due to lack of precipitation in 2012. Palmer amaranth control at 21 DAP was 99 to 100% for both years when a PRE application of *S*-metolachlor plus metribuzin was made at planting. At 42 DAP, Palmer amaranth control following PRE-applied *S*-metolachlor plus metribuzin was ≥ 98 and ≥ 88% in 2012 and 2013, respectively. When relying on a POST-only herbicide program initiated at 21 DAP, Palmer amaranth control ranged from 52 to 84% across row spacings at 42 DAP. At soybean harvest, Palmer amaranth control was ≥ 95% in 2012 and ≥ 86% in 2013 regardless of row spacing or seeding rate when *S*-metolachlor plus metribuzin was applied at planting. Conversely, total-POST programs had no more than 50 and 85% Palmer amaranth control in 2012 and 2013, respectively. In both years, Palmer amaranth density and seed production at soybean harvest were generally lower in the PRE herbicide programs compared to POST-only programs. Use of a PRE herbicide at planting also improved soybean grain yield and economic returns over programs that relied on a POST-only program. Overall, the impacst of soybean row spacing and seeding rate on Palmer amaranth control, density, or seed production were less apparent than the influence of herbicide programs.

Nomenclature: Metribuzin; *S*-metolachlor; Palmer amaranth, *Amaranthus palmeri* S. Wats. AMAPA; soybean, *Glycine max* (L.) Merr.

Key words: Glufosinate-resistant, postemergence-only, preemergence, residual, row spacing, seeding rate.

Se realizó un experimento en Fayetteville, Arkansas, en 2012 y 2013, para determinar la influencia de la distancia entre hileras de siembra de la soja y el programa de herbicidas en soja resistente a glufosinate sobre el control, la supervivencia, y la producción de semilla de *Amaranthus palmeri*, la cobertura del suelo y el rendimiento de grano de la soja, y la rentabilidad económica. La cobertura del suelo de la soja fue > 80% a 85 d después de la siembra (DAP) para todas las distancias entre hileras y densidades de siembra en 2012, y en 2013, todas las distancias entre hileras y densidades de siembra de la soja habían alcanzado > 90% de cobertura del suelo a 50 DAP. La diferencia en cobertura de suelo entre los años se debió a falta de lluvia en 2012. El control de *A. palmeri* a 21 DAP fue 99 a 100% para ambos años cuando se realizó una aplicación PRE de *S*-metolachlor más metribuzin al momento de la siembra. A 42 DAP, el control de *A. palmeri* después de aplicaciones PRE de *S*-metolachlor más metribuzin fue ≥ 98 y ≥ 88% en 2012 y 2013, respectivamente. Cuando se dependió de programas de herbicidas con solamente aplicaciones POST iniciadas 21 DAP, el control de *A. palmeri* varió de 52 a 84% en las diferentes distancias entre hileras a 42 DAP. Al momento de la cosecha de la soja, el control de *A. palmeri* fue ≥ 95% en 2012 y ≥ 86% en 2013 sin importar la distancia entre hileras o la densidad de siembra cuando se aplicó *S*-metolachlor más metribuzin al momento de la siembra. En cambio, los programas totalmente POST no tuvieron más de 50 y 85% de control de *A. palmeri*, en 2012 y 2013, respectivamente. En ambos años, la densidad y producción de semilla de *A. palmeri* al momento de la cosecha de la soja, fueron generalmente menores en los programas con herbicidas PRE, al compararse con los programas con sólo herbicidas POST. El uso de herbicidas PRE al momento de la siembra también mejoró los rendimientos de grano de la soja y la rentabilidad económica por encima de los programas con sólo herbicidas POST. En general, el impacto de la distancia entre hileras y la densidad de siembra de la soja sobre el control, densidad, o producción de semilla de *A. palmeri* fue menos aparente que la influencia del programa de herbicidas.

DOI: 10.1614/WT-D-14-00156.1

* First and second authors: Former Graduate Research Assistant 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, P.O. Box 357, Lonoke, AR 72086; fourth author: Professor, Department of Agricultural Economics and Agribusiness, AGRI217, Fayetteville, AR 72701. Corresponding author's E-mail: holdendbell@gmail.com

One of the most important glyphosate-resistant (GR) weed species through much of the southern United States cropping region is Palmer amaranth. Palmer amaranth was first confirmed resistant to glyphosate in Georgia in 2005, followed by Arkansas in 2006, and currently is reported in 23 states in the United States (Heap 2014). Palmer amaranth's prolific seed production ($\geq$ 250,000 seed per female plant [Keeley et al. 1987; Scott and Smith 2011; Sellers et al. 2003]), extended emergence period (early April until the first killing frost [DeVore et al. 2013; Jha and Norsworthy 2009]), and rapid erect growth (Klingaman and Oliver 1994; Monks and Oliver 1988; Norsworthy et al. 2008b) make it one of the most troublesome weeds in crop production.

Palmer amaranth can be viewed as a chief example of what happens when the efficacy of a herbicide is no longer effective due to herbicide resistance. In just 14 yr, Palmer amaranth went from being the 23rd most troublesome weed in soybean to the second most troublesome weed in the southern states of Alabama, Arkansas, Florida, Georgia, Kentucky, Missouri, North Carolina, Oklahoma, South Carolina, and Virginia (Webster and Nichols 2012). More recently, a survey conducted by Riar et al. (2013) reported that Palmer amaranth was the most problematic weed of soybean in Arkansas, Louisiana, Mississippi, and Tennessee.

Soybean growers in the Midsouth have limited effective POST herbicide options for Palmer amaranth control because of the evolution of herbicide resistance (glyphosate and acetolactate synthase [ALS]-inhibiting herbicides) (Riar et al. 2013). Current options for POST control of Palmer amaranth in soybean include several protoporphyrinogen oxidase (PPO)-inhibiting herbicides and glufosinate in glufosinate-resistant (LibertyLink®, Bayer CropScience) soybean (Scott et al. 2014). Hectares planted to glufosinate-resistant soybean in the Midsouth are more numerous than in other areas of the United States partially as a result of the effectiveness of glufosinate on Palmer amaranth resistant to glyphosate and ALS-inhibiting herbicides (Barnett et al. 2013; Norsworthy et al. 2008a). However, for glufosinate to provide consistent, effective control of Palmer amaranth, it must be applied when the plants are small, generally $\leq$ 10 cm in height (Anonymous 2014a; Norsworthy et al. 2012; Riar et al. 2013). Because of environmental conditions, applicator scheduling, and timing of on-farm operations, it is difficult for producers to effectively time glufosinate applications and whenever Palmer amaranth escapes control because of its large size at application, producers have to hand-weed portions of fields, costing as much as \$371 ha^{-1} for dense infestations of Palmer amaranth (Riar et al. 2013).

The introduction of GR crops enabled producers to use one effective herbicide (i.e., glyphosate) mechanism of action (MOA) for broad-spectrum weed control, resulting in primarily a glyphosate monoculture weed control program (Young 2006). Relying on repeated applications of effective herbicides with the same MOA increases the risk of herbicide-resistant weeds evolving (Norsworthy et al. 2012; Powles et al. 1997). Therefore, multiple herbicides with different MOAs are needed throughout the growing season and in subsequent seasons (i.e., using crop rotations, trait rotations, etc.) to delay the evolution of herbicide resistance in weed species.

The use of soil-residual herbicides not only can increase the number of MOAs used in a herbicide program, but can also offer extended weed control compared to POST herbicides (i.e., glyphosate or glufosinate) that lack residual activity (Taylor-Lovell et al. 2002; Wiesbrook et al. 2001). The efficacy of soil-residual herbicides is highly dependent on either rainfall or irrigation shortly after application, which places the herbicide molecules into soil solution where they can be taken up as weeds germinate and emerge (Krausz et al. 2001; Stewart et al. 2010). The incorporation of a soil-residual herbicide into herbicide programs has been reported to effectively control Palmer amaranth (Riar et al. 2011). In soybean planted on 38-cm-wide rows and at a rate of 295,000 seed ha^{-1}, *S*-metolachlor in combination with flumioxazin, fomesafen, or metribuzin plus chlorimuron applied PRE followed by (fb) a POST application of fomesafen controlled GR Palmer amaranth $\geq$ 94% 30 d after the POST herbicide application (Whitaker et al. 2010). Similar results were observed by Norsworthy (2004) where the combination of *S*-metolachlor and flumetsulam, flumioxazin, chlorimuron plus sulfentrazone, or metribuzin applied PRE controlled Palmer amaranth $\geq$ 99% for 5 wk after planting soybean at rates of 306,000 and 432,000 seed ha^{-1} on 19- and 97-cm row widths.

Herbicides are the principal tool and foundation of most effective weed control programs (Harker and O'Donovan 2013; Norsworthy et al. 2012). Since the occurrence of herbicide-resistant weeds, there has been a need for research on the effectiveness of nonherbicidal management practices that could potentially increase weed control, as evidenced by consultants describing their top priority of weed management research being that of cultural weed control practices (Riar et al. 2013). Examples of cultural management practices that could impact weed control include tillage intensity, crop row widths and seeding rates, herbicide trait selection, and crop rotations, as well as others.

The positive benefits of a narrow soybean row spacing and increased seeding rate on weed control are numerous (Nice et al. 2001; Place et al. 2009; Rich and Renner 2007). Harder et al. (2007) reported less weed emergence in 19-cm-wide than in 76-cm-wide soybean rows and also weed biomass was greater at a soybean density of 124,000 plants ha^{-1} compared to 445,000 plants ha^{-1}. End-of-season weed biomass decreased (Hock et al. 2006), weed control increased (Young et al. 2001), and weed survival decreased (Norsworthy et al. 2007) in narrow-row (19 cm) versus wide-row ($\geq$ 76 cm) soybean. A soybean density of at least 478,000 plants ha^{-1} in combination with narrow rows ($\leq$ 38 cm) increased mid- and late-season control of sicklepod [*Senna obtusifolia* (L.) Irwin and Barneby] compared to a density of 269,000 plants ha^{-1} and a 76-cm row spacing (Buehring et al. 2002). Increasing soybean population from 217,000 plants ha^{-1} to 521,000 plants ha^{-1} reduced pitted morningglory (*Ipomoea lacunosa* L.) seed production by 41% (Norsworthy and Oliver 2002). Although there are numerous reports on how soybean row spacing and seeding rate influence control of various weeds, there is minimal research on how soybean row spacing and seeding rate affect Palmer amaranth (Jha et al. 2008).

The objective of this research was to determine the effect of soybean row spacing, seeding rate, and herbicide program on Palmer amaranth emergence, survival, and seed production, as well as soybean grain yield and economic returns given differences in cost of production as a function of varying weed control practices.

Materials and Methods

Field experiments were conducted at the University of Arkansas–Agriculture Research and Extension Center, Fayetteville, AR during the summers of 2012 and 2013. The soil type was a Leaf silt loam (Fine, mixed, active, thermic Typic Albaquults) with 34% sand, 53% silt, 13% clay, 1.5% organic matter, and a pH of 6.9.

The experiment consisted of plots that were 2 to 4 m wide (depending on row spacing) by 9 m in length and organized as a split-split plot design replicated four times. The main plot factor was row spacing (19, 45, and 90 cm), the subplot factor was soybean seeding rate (247,000 and 432,000 seed ha^{-1}), and the sub-subplot factor was herbicide program. Herbicide programs consisted of the following: (1) nontreated control; (2) a premix of *S*-metolachlor at 1,545 g ai ha^{-1} plus metribuzin at 368 g ai ha^{-1} (Boundary® 6.5 EC, Syngenta Crop Protection, Greensboro, NC 27419) applied PRE; (3) *S*-metolachlor at 1,545 g ha^{-1} plus metribuzin at 368 g ha^{-1} applied PRE fb glufosinate (Liberty® 280 SL, Bayer CropScience LP, Research Triangle Park, NC 27709) at 595 g ai ha^{-1} plus a premix of *S*-metolachlor at 1217 g ha^{-1} plus fomesafen at 266 g ai ha^{-1} (Prefix®, Syngenta Crop Protection) applied at 21 d after soybean planting (DAP); (4) *S*-metolachlor at 1,545 g ha^{-1} plus metribuzin at 368 g ha^{-1} applied PRE fb glufosinate at 595 g ha^{-1} plus *S*-metolachlor at 1,217 g ha^{-1} plus fomesafen at 266 g ha^{-1} applied 21 DAP fb glufosinate at 738 g ha^{-1} plus acetochlor at 1,260 g ai ha^{-1} (Warrant®, Monsanto Company, St. Louis, MO 63167) applied 42 DAP; (5) *S*-metolachlor at 1,545 g ha^{-1} plus metribuzin at 368 g ha^{-1} applied PRE fb glufosinate at 738 g ha^{-1} plus acetochlor at 1,260 g ha^{-1} applied 42 DAP; and (6) glufosinate at 595 g ha^{-1} plus *S*-metolachlor at 1,217 g ha^{-1} plus fomesafen at 266 g ha^{-1} applied 21 DAP fb glufosinate at 738 g ha^{-1} plus acetochlor at 1,260 g ha^{-1} applied 42 DAP (POST only). 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 calibrated to deliver 140 L ha^{-1} at 276 kPa.

Soybean seed were counted with a Seedburo 801 Count-A-Pak® (Seedburo Equipment Co., Des Plaines, IL 60018) for each seeding rate to determine the correct number of seed to be planted

https://doi.org/10.1614/WT-D-14-00156.1 Published online by Cambridge University Press

Table 1. Nonlinear regression models for determining the number of days after planting for 95% soybean groundcover at Fayetteville, AR, in 2012 and 2013.[a]

Row spacing	Seeding rate	Nonlinear regression groundcover model 2012 Model	R^2	2013 Model	R^2
cm	1,000 seed ha^{-1}	$y = y0 + ax + bx^2 + cx^3$		$y = a/\{1 + e^{[(x0-x)/b]}\}$	
19	247	$y = -6.005 + 2.929x - 0.0432x^2 + 0.0003x^3$	0.9633	$y = 100/\{1 + e^{[(29.21-x)/5.71]}\}$	0.9882
45	247	$y = -12.73 + 3.652x - 0.0606x^2 + 0.0004x^3$	0.9937	$y = 100/\{1 + e^{[(31.54-x)/4.108]}\}$	0.9704
90	247	$y = -3.352 + 2.667x - 0.0477x^2 + 0.0003x^3$	0.9891	$y = 100/\{1 + e^{[(30.17-x)/5.327]}\}$	0.9095
19	432	$y = -19.48 + 4.042x - 0.0654x^2 + 0.0004x^3$	0.9572	$y = 100/\{1 + e^{[(21.9-x)/5.918]}\}$	0.9952
45	432	$y = -11.19 + 3.279x - 0.0473x^2 + 0.0003x^3$	0.9935	$y = 100/\{1 + e^{[(25.48-x)/4.27]}\}$	0.9721
90	432	$y = 1.082 + 2.409x - 0.0327x^2 + 0.0002x^3$	0.9794	$y = 100/\{1 + e^{[(23.05-x)/7.91]}\}$	0.9964

[a] y is the percentage of soybean groundcover, e is the constant 2.718, x is days after soybean planting, and $y0$, a, b, and c are parameter estimates.

in each sub-subplot. Prior to planting, the seedbed was prepared by disking the field and using a field cultivator (Kongskilde Industries Inc., Hudson, IL 61748) to obtain a uniform seedbed. 'Halomax 494', a late-maturity group IV glufosinate-resistant soybean cultivar, was either drill-seeded with a 10-row Almaco (ALMACO, Nevada, IA 50201) cone-type drill on a 19-cm row spacing or seeded with a four-row John Deere 6403 (Deere and Company, Moline, IL 61265) planter set to either a 45- or 90-cm row spacing. Soybean were planted on May 16 in 2012 and on June 14 in 2013 and irrigated with an overhead sprinkler.

After soybean planting, two 0.5-m^2 areas were marked with flags (Gempler's, Janesville, WI 53547) in the center of each plot to provide an area to assess Palmer amaranth emergence, survival, and seed production as well as soybean densities (recorded at 21 DAP). Palmer amaranth density and weed control (visually estimated on a 0 to 100% scale, where 0 was equal to no control and 100 was complete control) were recorded at the 21 and 42 DAP applications and at soybean harvest, and Palmer amaranth survival and seed production were recorded prior to soybean harvest in the two quadrats in each sub-subplot. Palmer amaranth seed production was measured by harvesting all plants within each quadrat. Biomass was recorded, then ground, and seed were counted from subsamples of the ground biomass, then extrapolated to determine the number of seed.

A digital camera (Sony Cyber-shot®, Sony Electronics, San Diego, CA 92127) was mounted on a 5-cm-diam pipe at a height of 1.5 m and at a 70° downward-facing angle. Weekly photographs were taken from a marked position in the center of each sub-subplot, starting when soybean reached cotyledon stage. Photographs were taken throughout the growing season and then transferred to a computer, sorted, and individually analyzed by SigmaScan® Pro 5.0 (Systat Software, Inc., San Jose, CA 95110) to determine the soybean canopy formation in DAP using the procedures described by Purcell (2000). The output values from SigmaScan were exported, entered, and fit to a nonlinear regression in SigmaPlot® 12.5 (Systat Software, Inc., San Jose, CA 95110) and tested for normality by Shapiro-Wilk's test (Table 1).

Partial returns were used to compare production alternatives where only the revenue and cost items that change across production alternatives were tracked. Hence, the alternative with the greatest partial returns would be most profitable (Kay et al. 2008). Average chemical and seed costs were obtained from two distributors in Arkansas (Helena Chemical Co., Hughes, AR 72348; Crop Production Services Inc., Crawfordsville, AR 72327) (Table 2). Chemical application costs were taken from the University of Arkansas Division of Agriculture Research and Extension 2014 Crop Enterprise Budgets (Anonymous 2014b) and soybean market price (Anonymous 2014c) was used to determine the value associated with soybean grain yield. Further, a sensitivity analysis on soybean market prices ranging between 10-yr low and high soybean prices as reported by the National Agricultural Statistics Service (Anonymous 2014d), holding all else constant, was conducted to

Table 2. Costs associated with chemical, soybean seed, application, and market price for calculating partial returns in 2012 and 2013.

	Partial return costs	
	Unit	$ unit^{-1}
Chemical[a]		
Boundary (*S*-metolachlor + metribuzin)	L	20.69
Prefix (*S*-metolachlor + fomesafen)	L	13.22
Warrant (acetochlor)	L	8.52
Liberty (glufosinate)	L	20.84
Soybean seed[a]		
Glufosinate-resistant	140,000	57.75
Custom chemical application[b]		
Ground application	ha	14.82
Market price[c]		
Soybean	kg	0.43

[a] Chemical and seed costs were averaged from prices given by Helena Chemical Co. (Hughes, AR 72348) and Crop Production Services Inc. (Crawfordsville, AR 72327) during the summer of 2014.

[b] Application cost was determined from the University of Arkansas Division of Agriculture Research and Extension's 2014 Crop Enterprise Budgets (Anonymous 2014b).

[c] Soybean market price was based off the August 2014 price accessed from the Arkansas Soybean Promotion Board (Anonymous 2014c).

determine whether the most profitable production alternative would switch among alternatives analyzed.

Due to the different environmental conditions between 2012 and 2013, years were analyzed separately. Data were analyzed using ANOVA with the MIXED procedure in JMP (JMP, Version 11; SAS Institute Inc., Cary, NC) to test the significance of main effects and interactions. Soybean row spacing, soybean density, herbicide program, and any interactions containing these effects were fixed effects and replication and its interactions were random effects. Fisher's protected LSD values were calculated and used to separate means when *F* values were statistically significant ($\alpha \leq 0.05$).

Results and Discussion

Soybean Density and Canopy Formation. In 2012, for the soybean seeding rate of 247,000 seed ha^{-1}, observed soybean densities at 21 DAP were 18, 21, and 22 plants m^{-2} for row spacings of 19, 45, and 90 cm, respectively, and for the seeding rate of 432,000 seed ha^{-1} densities at 21 DAP were 25, 38, and 41 plants m^{-2} for row spacings of 19, 45, and 90 cm, respectively. In 2013, for the seeding rate of 247,000 seed ha^{-1}, soybean densities at 21 DAP averaged 23, 19, and 22 plants m^{-2} for the row spacings of 19, 45, and 90 cm, respectively, and for the seeding rate of 432,000 seed ha^{-1} densities at 21 DAP were 38, 32, and 39 plants m^{-2} for the row spacings of 19, 45, and 90 cm, respectively. There was no apparent effect of row spacing except for a slightly higher survival in 2012 with widest row spacing.

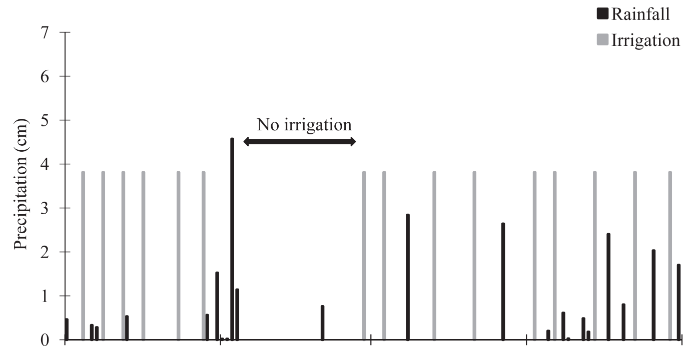

Figure 1. Rainfall and irrigation distribution at Fayetteville, AR, in (a) 2012 and (b) 2013.

Growing conditions differed between the 2012 and 2013 seasons. The growing season of 2012 was characterized as a dry, hot year, having less rainfall compared to the growing season of 2013 (Figures 1a and 1b). Although the experiment was positioned where overhead sprinkler irrigation was accessible, the irrigation system malfunctioned in 2012 during the month of June, resulting in no irrigation for this period. The lack of rainfall or irrigation in June of 2012 hampered soybean growth and resulted in drought stress to the Palmer amaranth, which lowered herbicide efficacy. Additionally, the lack of soybean growth during June may have contributed to low efficacy as a result of slow soybean canopy formation and less interference of soybean with Palmer amaranth compared to 2013. Furthermore, there was little residual activity from the *S*-metolachlor plus fomesafen applied at 21 DAP due to the lack of precipitation following application.

Due to the dry environment, the narrow-row soybean (19-cm spacing) needed 85 DAP to achieve 90% groundcover whereas the 90-cm spacing never achieved 90% groundcover in 2012 (Figure 2). Conversely in 2013, soybean plants had adequate

https://doi.org/10.1614/WT-D-14-00156.1 Published online by Cambridge University Press

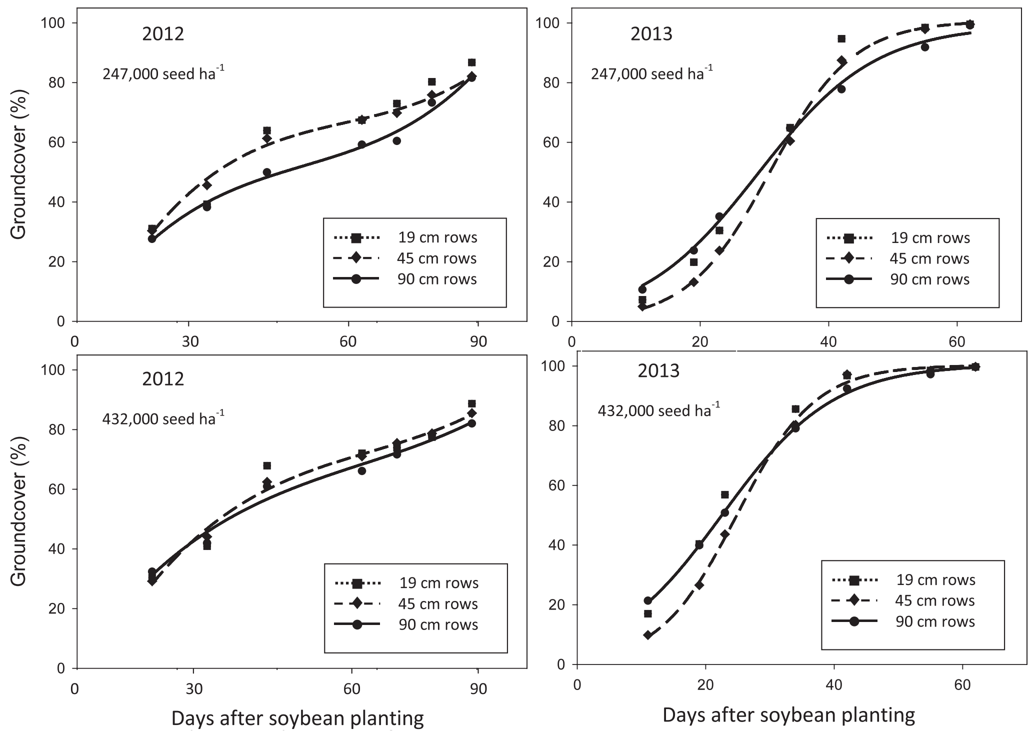

Figure 2. Effect of soybean row spacing on soybean groundcover at two different seeding rates at Fayetteville, AR, in 2012 and 2013.

moisture and plant growth was not hindered. In 2013, the 19-cm row spacing achieved > 90% groundcover by 40 DAP, regardless of soybean seeding rate, and all soybean row spacings achieved > 90% groundcover by 50 DAP, regardless of soybean seeding rate. The benefit of the narrow row spacing or increased seeding rate on soybean groundcover was not as apparent in 2012 compared to 2013 due to the dry conditions.

Palmer Amaranth Control. Immediately following soybean planting, sufficient irrigation was provided to activate the PRE herbicide in both years. As a result, all PRE herbicide treatments provided ≥ 99% Palmer amaranth control through 21 DAP for both years (data not shown). In 2012, a row spacing by herbicide program interaction occurred at 42 DAP and at soybean harvest.

At 42 DAP, treatments including a PRE herbicide had ≥ 98% Palmer amaranth control, regardless of row spacing or seeding rate in 2012. However, Palmer amaranth control for the POST-only program ranged from 52 to 69% over row spacings (Table 3). The low control in the POST-only treatments was because Palmer amaranth heights (≥ 15 cm) at treatment were in excess of the maximum size (≤ 10 cm) for effective control with glufosinate and fomesafen. Furthermore, the lack of rainfall and irrigation prevented activation of the residual herbicides that were applied at 21 DAP.

Palmer amaranth control in all treatments that contained a PRE herbicide in 2012 was ≥ 95%, regardless of row spacing and seeding rate, at soybean harvest (Table 3). Similarly, in other research improved control of *Amaranthus* spp. was reported when glufosinate was applied POST following a PRE residual herbicide (Gardner et al. 2006). When *S*-metolachlor plus metribuzin were applied PRE, no differences were noted in Palmer amaranth control among row spacings at harvest. Conversely, Palmer amaranth control with the POST-only treatments was 26, 50, and 18% for the 19-, 45-, and 90-cm row spacings due to Palmer amaranth being > 10 cm at the time of application, further evidence for the need for PRE herbicides in glufosinate-resistant soybean.

In 2013, all treatments containing a PRE herbicide had ≥ 98% control at 42 DAP, except for the 19-cm row spacing that did not receive a POST treatment until 42 DAP (Table 3). Tank-mixing glufosinate with residual herbicides has been shown to provide effective control of *Amaranthus*

https://doi.org/10.1614/WT-D-14-00156.1 Published online by Cambridge University Press

Table 3. Palmer amaranth control at 42 d after soybean planting (DAP) and at soybean harvest as influenced by soybean row spacing and herbicide program, averaged over soybean seeding rate at Fayetteville, AR, in 2012 and 2013.

			Control											
			2012						2013					
			42 DAP			Harvest			42 DAP			Harvest		
			Row spacing											
Herbicide program	Rate	Application timing	19 cm	45 cm	90 cm	19 cm	45 cm	90 cm	19 cm	45 cm	90 cm	19 cm	45 cm	90 cm
	g ai ha^{-1}		%											
S-metolachlor	1,545	PRE	99 aA[a]	99 aA	100 aA	98 aA	97 aA	97 aA	98 abA	99 aA	96 aA	98 abA	99 aA	96 aA
+ metribuzin	368	PRE												
S-metolachlor	1,545	PRE	99 aA	100 aA	99 aA	96 aA	99 aA	96 aA	99 abA	99 aA	100 aA	99 abA	99 aA	100 aA
+ metribuzin	368	PRE												
Glufosinate	595	21 DAP												
+ *S*-metolachlor	1,217	21 DAP												
+ fomesafen	266	21 DAP												
S-metolachlor	1,545	PRE	100 aA	98 aA	99 aA	98 aA	96 aA	96 aA	100 aA	100 aA	99 aA	100 aA	100 aA	100 aA
+ metribuzin	368	PRE												
Glufosinate	595	21 DAP												
+ *S*-metolachlor	1,217	21 DAP												
+ fomesafen	266	21 DAP												
Glufosinate	738	42 DAP												
+ acetochlor	1,260	42 DAP												
S-metolachlor	1,545	PRE	100 aA	100 aA	99 aA	98 aA	98 aA	95 aB	88 abA	98 aA	96 aA	86 abA	99 aA	98 aA
+ metribuzin	368	PRE												
Glufosinate	738	42 DAP												
+ acetochlor	1,260	42 DAP												
Glufosinate	595	21 DAP	63 bA	69 bA	52 bA	26 bA	50 bA	18 bA	84 bA	68 bAB	55 bB	85 bA	68 bAB	53 bB
+ *S*-metolachlor	1,217	21 DAP												
+ fomesafen	266	21 DAP												
Glufosinate	738	42 DAP												
+ acetochlor	1,260	42 DAP												

[a] Lowercase letters are used to compare herbicide programs within a soybean row spacing and uppercase letters are used to compare soybean row spacing within an herbicide program for each year. Means followed by the same letter, either lowercase or uppercase, are not different according to Fisher's protected LSD test at $\alpha \leq 0.05$.

spp. (Hamill et al. 2000) and use of residual herbicides when nonresidual POST herbicides are applied is recommended for managing against evolution of resistant weeds (Norsworthy et al. 2012). The POST-only treatments at 42 DAP with a 45- or 90-cm row spacing had less Palmer amaranth control than the 19-cm row spacing, likely because of increased competitiveness and earlier canopy formation in the narrow row spacing.

Similar to the 42 DAP ratings, Palmer amaranth control at harvest in 2013 was generally greatest when a PRE herbicide had been applied. In the absence of a soil-residual herbicide, several glufosinate applications may be needed for effective weed management (Beyers et al. 2002). The POST-only herbicide treatments once again had less control of Palmer amaranth compared to the herbicide programs that included a PRE application. The POST-only applications for the 19-cm row spacing had comparable control to most PRE herbicide treatments; however, the wider row spacings of 45 and 90 cm had less control than the narrow spacing. The main factor contributing to the control of Palmer amaranth was a PRE herbicide application and/or multiple herbicide applications. Coetzer et al. (2002) reported multiple applications of glufosinate provided greater control of Palmer amaranth than a single application.

In both years, there were minimal differences, if any, among the soybean row spacings for Palmer amaranth control when *S*-metolachlor plus metribuzin was applied PRE. It should be noted that the PRE application was activated via rainfall or irrigation in both years; hence, the high level of control. If rainfall or irrigation did not occur soon after application, most of the weed control would be supplied by the POST herbicide, similar to the POST-only program that was evaluated in this research. In such instances where PRE herbicides fail or are not applied, value of the 19-cm row spacing over wider row spacings became evident.

Approximately 80% of the soybean fields in Arkansas are irrigated (J Ross, personal communication); however, furrow or flood irrigation is the most common means of irrigating soybean, and these types of irrigation are often not initiated until several weeks after crop emergence. Therefore, PRE herbicides applied in most soybean fields would be solely dependent upon rainfall for activation. By planting glufosinate-resistant soybean in fields containing glyphosate- and ALS-resistant Palmer amaranth both glufosinate and PPO-inhibiting herbicides such as fomesafen can be applied to provide multiple effective mechanisms of action for POST control of Palmer amaranth—a strategy that is recommended for reducing the risk of herbicide resistance evolving (Norsworthy et al. 2012). Differences among row spacings that had a PRE herbicide were minimal. However, in the instances when a PRE herbicide was not included (i.e., not activated), the benefit of a narrow row spacing (19 cm) would be evident as a result of some Palmer amaranth control being provided by earlier soybean canopy formation, which may allow a Palmer amaranth–infested field to be salvaged.

Palmer Amaranth Density. Palmer amaranth densities were solely influenced by herbicide programs at 21 and 42 DAP for both years and at soybean harvest in 2012 (Table 4). At soybean harvest in 2013, interactions between soybean row spacing and herbicide program and between soybean seeding rate and herbicide program occurred. At 21 DAP, herbicide programs that included a PRE herbicide had less Palmer amaranth in both years than the nontreated control and the POST-only herbicide program for which no treatment had yet been applied (Table 4).

At 42 DAP, no more than 3.6 plants m^{-2} in 2012 and 3.9 plants m^{-2} in 2013 were observed for the treatments containing a PRE application of *S*-metolachlor plus metribuzin whereas the nontreated control had 437 plants m^{-2} in 2012 and 38 plants m^{-2} in 2013 (Table 4). Palmer amaranth densities in the POST-only program in 2012 and 2013 were comparable to the nontreated control at 42 DAP.

At soybean harvest in 2012, Palmer amaranth densities were $\leq$ 1.9 plants m^{-2} with the inclusion of *S*-metolachlor plus metribuzin PRE (Table 4). In comparison, Palmer amaranth densities were 270 plants m^{-2} in the POST-only treatment, and 516 plants m^{-2} in the nontreated control. No differences between Palmer amaranth densities occurred at soybean harvest in 2013 in the presence of herbicides, either PRE or POST. Furthermore in 2013, when *S*-metolachlor plus metribuzin were applied PRE fb a POST application at 21 DAP, no Palmer amaranth was found in quadrats regardless of row spacing or soybean density.

Although the POST-only treatment had less Palmer amaranth than the nontreated control at

Table 4. Palmer amaranth density at 21 and 42 d after soybean planting (DAP) and at soybean harvest influenced by herbicide program, averaged over soybean row spacing and seeding rate at Fayetteville, AR, in 2012, and Palmer amaranth density at 21 and 42 DAP as influenced by herbicide program, averaged over soybean row spacing and seeding rate and at soybean harvest as influenced by soybean row spacing and herbicide program, averaged over seeding rate and as influenced by soybean seeding rate and herbicide program, averaged over row spacing at Fayetteville, AR, in 2013.

			Density									
			Observation timing									
			2012			2013						
								Harvest				
								Row spacing			Seed rate	
Herbicide program	Rate	Application timing	21 DAP	42 DAP	Harvest	21 DAP	42 DAP	19 cm	45 cm	90 cm	247,000	432,000
	g ai ha^{-1}		plants m^{-2}									
Nontreated	—	—	438 a[a]	437 a	516 a	59 a	38 a	19 aB[b]	26 aB	41 aA	36 aA	22 aB
S-metolachlor	1,545	PRE[a]	0 b	3.6 c	1.9 c	0 b	0.4 c	0 bA	0.1 bA	0 bA	0.1 bA	0 bA
+ metribuzin	368	PRE										
S-metolachlor	1,545	PRE	0 b	0.5 c	0.5 c	0 b	0.2 c	0 bA	0 bA	0 bA	0 bA	0 bA
+ metribuzin	368	PRE										
Glufosinate	595	21 DAP[a]										
+ *S*-metolachlor	1,217	21 DAP										
+ fomesafen	266	21 DAP										
S-metolachlor	1,545	PRE	0 b	0 c	0 c	0 b	0.2 c	0 bA	0 bA	0 bA	0 bA	0 bA
+ metribuzin	368	PRE										
Glufosinate	595	21 DAP										
+ *S*-metolachlor	1,217	21 DAP										
+ fomesafen	266	21 DAP										
Glufosinate	738	42 DAP										
+ acetochlor	1,260	42 DAP										
S-metolachlor	1,545	PRE	0 b	0.8 c	0.1 c	1.8 b	3.9 c	2.1 bA	0 bA	0 bA	1.4 bA	0 bA
+ metribuzin	368	PRE										
Glufosinate	738	42 DAP										
+ acetochlor	1,260	42 DAP										
Glufosinate	595	21 DAP	478 a	329 b	270 b	59 a	23 b	4.8 bA	3.5 bA	2.6 bA	4.4 bA	2.8 bA
+ *S*-metolachlor	1,217	21 DAP										
+ fomesafen	266	21 DAP										
Glufosinate	738	42 DAP										
+ acetochlor	1,260	42 DAP										

[a] Lowercase letters are used to compare herbicide programs within a soybean row spacing and uppercase letters are used to compare soybean row spacing within an herbicide program for each year. Means followed by the same letter, either lowercase or uppercase, are not different according to Fisher's protected LSD test at $\alpha \leq 0.05$.

harvest for both years, this should not be considered an effective herbicide program because of the large amounts of Palmer amaranth present at harvest. Increasing Palmer amaranth densities have been reported to decrease yield in cotton (*Gossypium hirsutum* L.), grain sorghum (*Sorgum bicolor* L.), corn (*Zea mays* L.), peanut (*Arachis hypogaea* L.), and soybean (Bensch et al. 2003; Burke et al. 2007; Morgan et al. 2001), especially as a result of early-season interference.

Palmer Amaranth Seed Production. Reductions in the soil seedbank have become a central focus of herbicide resistance management in recent years

Table 5. Palmer amaranth seed production at soybean harvest as influenced by herbicide program, averaged over soybean row spacing and soybean seeding rate at Fayetteville, AR, in 2012 and 2013.

Herbicide program	Rate	Application timing	Seed production 2012	Seed production 2013
	g ai ha^{-1}		seed m^{-2}	
Nontreated	—	—	247,300 a[b]	96,800 a
S-metolachlor	1,545	PRE	10,800 c	2,700 b
+ metribuzin	368	PRE		
S-metolachlor	1,545	PRE	3,600 c	0 b
+ metribuzin	368	PRE		
Glufosinate	595	21 DAP[a]		
+ *S*-metolachlor	1,217	21 DAP		
+ fomesafen	266	21 DAP		
S-metolachlor	1,545	PRE	0 c	0 b
+ metribuzin	368	PRE		
Glufosinate	595	21 DAP		
+ *S*-metolachlor	1,217	21 DAP		
+ fomesafen	266	21 DAP		
Glufosinate	738	42 DAP		
+ acetochlor	1,260	42 DAP		
S-metolachlor	1,545	PRE	4,100 c	10,700 b
+ metribuzin	368	PRE		
Glufosinate	738	42 DAP		
+ acetochlor	1,260	42 DAP		
Glufosinate	595	21 DAP	167,500 b	7,700 b
+ *S*-metolachlor	1,217	21 DAP		
+ fomesafen	266	21 DAP		
Glufosinate	738	42 DAP		
+ acetochlor	1,260	42 DAP		

[a] Abbreviation: DAP, days after soybean planting.
[b] Means within a column followed by the same lowercase letter are not different according to Fisher's protected LSD test at $\alpha \leq 0.05$.

(Bagavathiannan et al. 2011; Norsworthy et al. 2012; Sosnoskie et al. 2013). For a weed such as Palmer amaranth, a prolific seed producer, it is vital to control the weed before seed can be produced.

Herbicide programs impacted Palmer amaranth seed production in 2012 and 2013. Greater seed production was mainly seen in the dry, drought-like growing season of 2012 (Table 5), partly due to the greater Palmer amaranth densities and the fact that Palmer amaranth thrives in dry conditions at the expense of most crops (Gibson 1998). Treatments containing *S*-metolachlor plus metribuzin applied at planting had less Palmer amaranth seed production in comparison to the nontreated control and POST-only program in 2012 (Table 5); yet, it should be noted that some seed production occurred in at least one of 2 yr for all herbicide programs, except when *S*-metolachlor plus metribuzin were applied PRE and followed with two glufosinate applications, both of which contained residual herbicides.

Soybean Grain Yield. Soybean row spacing and herbicide program in 2012 and seeding rate, row spacing, and herbicide program in 2013 influenced soybean grain yield (Table 6). The inclusion of *S*-metolachlor plus metribuzin applied PRE increased grain yield over the POST-only program in 2012. Furthermore, grain yield was greater for the 45-cm row spacing compared to the 19- and 90-cm row spacings in 2012.

Averaged over row spacing and seeding rates, a PRE application of *S*-metolachlor plus metribuzin increased soybean grain yield at least 1,150 kg ha^{-1} over the nontreated control in 2013 (Table 6). The 45-cm row spacing had greater grain yield (3,070 kg ha^{-1}) than both the 19- and 90-cm spacings (2,100 and 2,120 kg ha^{-1}, respectively). Yield reductions up to 79% from Palmer amaranth have previously been reported (Bensch et al. 2003; Klingaman and Oliver 1994; Monks and Oliver 1988); however, with the occurrence of GR Palmer amaranth, producers have experienced complete crop loss in some fields (personal communication; Arkansas Soybean Producers).

Economic Partial Returns. Partial returns were calculated for both 2012 (Table 7) and 2013 (Table 8). For both 2012 and 2013, the inclusion of *S*-metolachlor plus metribuzin applied PRE generally had greater monetary returns. Partial returns were greater for the 45-cm row spacing, due to the higher grain yields, when compared across individual seeding rates and the other row spacings for both years. The POST-only herbicide program had partial returns comparable to the nontreated control in 2012 (Table 7), due to yield loss from Palmer amaranth interference, and returns were comparable to those in herbicide programs containing PRE herbicides, due to the increased efficacy of the POST herbicides in 2013 (Table 8).

Table 6. Soybean grain yield as influenced by (1) herbicide program, averaged over soybean row spacing and seeding rate; (2) soybean row spacing, averaged over herbicide program and soybean seeding rate; and (3) soybean seeding rate, averaged over herbicide program and soybean row spacing at Fayetteville, AR, in 2012 and 2013.

Treatment	Rate	Application timing	Grain yield 2012	Grain yield 2013
Herbicide program	g ai ha^{-1}		kg ha^{-1}	
Nontreated	—	—	490 c[b]	1,280 c
S-metolachlor	1,545	PRE	2,420 a	2,430 b
+ metribuzin	368	PRE		
S-metolachlor	1,545	PRE	2,490 a	2,790 a
+ metribuzin	368	PRE		
Glufosinate	595	21 DAP[a]		
+ *S*-metolachlor	1,217	21 DAP		
+ fomesafen	266	21 DAP		
S-metolachlor	1,545	PRE	2,310 a	2,850 a
+ metribuzin	368	PRE		
Glufosinate	595	21 DAP		
+ *S*-metolachlor	1,217	21 DAP		
+ fomesafen	266	21 DAP		
Glufosinate	738	42 DAP		
+ acetochlor	1,260	42 DAP		
S-metolachlor	1,545	PRE	2,180 a	2,680 ab
+ metribuzin	368	PRE		
Glufosinate	738	42 DAP		
+ acetochlor	1,260	42 DAP		
Glufosinate	595	21 DAP	1,160 b	2,570 ab
+ *S*-metolachlor	1,217	21 DAP		
+ fomesafen	266	21 DAP		
Glufosinate	738	42 DAP		
+ acetochlor	1,260	42 DAP		
Row spacing			kg ha^{-1}	
19 cm			1,730 b	2,100 b
45 cm			2,240 a	3,070 a
90 cm			1,550 b	2,120 b
Seeding rate[c,d] (seed ha^{-1})			kg ha^{-1}	
247,000			1,740 a	2,260 b
432,000			1,950 a	2,610 a

[a] Abbreviation: DAP, days after soybean planting.

[b] Means within a column for either herbicide program, soybean row spacing, or soybean seeding rate, for both years, followed by the same lowercase letter are not different according to Fisher's protected LSD test at $\alpha \leq 0.05$.

[c] Soybean seeding rate in 2012 was not significant at $\alpha = 0.05$.

[d] Average soybean density in 2012 for the seeding rate of 247,000 seed ha^{-1} was 200,000 plants ha^{-1} (20 plants m^{-2}) and for the seeding rate of 432,000 seed ha^{-1} was 350,000 plants ha^{-1} (35 plants m^{-2}). Average soybean density in 2013 for the seeding rate of 247,000 seed ha^{-1} was 210,000 plants ha^{-1} (21 plants m^{-2}) and for the seeding rate of 432,000 seed ha^{-1} was 360,000 plants ha^{-1} (36 plants m^{-2}). Soybean densities were recorded at 21 DAP for each year.

https://doi.org/10.1614/WT-D-14-00156.1 Published online by Cambridge University Press

Table 7. Partial returns as influenced by soybean row spacing, soybean seeding rate, and herbicide program at Fayetteville, AR, in 2012.

			Partial returns[a]					
			Row spacing					
			19 cm		45 cm		90 cm	
			Seeding rate (seed ha^{-1})					
Herbicide program	Rate	Application timing	247,000	432,000	247,000	432,000	247,000	432,000
	g ai ha^{-1}		$ ha^{-1}					
Nontreated	—	—	7.5	64.06	−19.55[c]	328.07	37.37	3.14
S-metolachlor	1,545	PRE[b]	881.18	833.98	1,063.61	791.35	727.76	751.75
+ metribuzin	368	PRE						
S-metolachlor	1,545	PRE	834.17	592.42	940.32	950.24	797.6	581.17
+ metribuzin	368	PRE						
Glufosinate	595	21 DAP[b]						
+ *S*-metolachlor	1,217	21 DAP						
+ fomesafen	266	21 DAP						
S-metolachlor	1,545	PRE	410.95	702.3	561.99	945.64	432.59	563.8
+ metribuzin	368	PRE						
Glufosinate	595	21 DAP						
+ *S*-metolachlor	1,217	21 DAP						
+ fomesafen	266	21 DAP						
Glufosinate	738	42 DAP						
+ acetochlor	1,260	42 DAP						
S-metolachlor	1,545	PRE	597.86	546.11	966.06	821.8	548.85	352.54
+ metribuzin	368	PRE						
Glufosinate	738	42 DAP						
+ acetochlor	1,260	42 DAP						
Glufosinate	595	21 DAP	−55.9	221.38	611.58	340.08	−97.67	−0.54
+ *S*-metolachlor	1,217	21 DAP						
+ fomesafen	266	21 DAP						
Glufosinate	738	42 DAP						
+ acetochlor	1,260	42 DAP						

[a] Partial returns = (soybean grain yield × market price) − (chemical cost + application cost + soybean seed cost). Market price was $0.43 kg^{-1}. Chemical cost was determined from the average of two chemical companies (refer to Table 2 for complete description). Application cost was $14.82 ha^{-1} $application^{-1}$. Soybean seed cost was $0.41 per 1,000 seed.

[b] Abbreviation: PRE, preemergence; DAP, days after soybean planting.

[c] Negative value denoted by (–).

Although partial returns were not always greatest for the herbicide program that had a PRE, 21 DAP, and 42 DAP herbicide application, no Palmer amaranth seed production occurred in this treatment either year. Therefore, a producer could possibly benefit more in the long term, in regard to the soil seedbank, by reducing the soil seedbank and in turn the risk of herbicide resistance while sacrificing a minimal loss in partial returns for the short term.

Practical Implications. The use of an herbicide had more impact on Palmer amaranth management than either row spacing or seeding rate for both years. However, the use of a narrow row spacing (19 cm) allows soybean to achieve canopy faster compared to wide rows (90 cm), which can aid in

https://doi.org/10.1614/WT-D-14-00156.1 Published online by Cambridge University Press

Table 8. Partial returns as influenced by soybean row spacing, soybean seeding rate, and herbicide program at Fayetteville, AR, in 2013.

			Partial returns[a]					
			Row spacing					
			19 cm		45 cm		90 cm	
			Seed ha^{-1}					
Herbicide program	Rate	Application timing	247,000	432,000	247,000	432,000	247,000	432,000
	g ai ha^{-1}		$ ha^{-1}					
Nontreated	—	—	401.46	432.48	473.63	665.98	244.14	274.62
S-metolachlor	1,545	PRE	623.45	756.72	1,086.01	1,206.51	848.07	543.78
+ metribuzin	368	PRE						
S-metolachlor	1,545	PRE	690.81	861.19	1,096.77	1,262.94	822.16	729.3
+ metribuzin	368	PRE						
Glufosinate	595	21 DAP[b]						
+ *S*-metolachlor	1,217	21 DAP						
+ fomesafen	266	21 DAP						
S-metolachlor	1,545	PRE	598.24	669.62	886.05	1,371.62	729.49	763.97
+ metribuzin	368	PRE						
Glufosinate	595	21 DAP						
+ *S*-metolachlor	1,217	21 DAP						
+ fomesafen	266	21 DAP						
Glufosinate	738	42 DAP						
+ acetochlor	1,260	42 DAP						
S-metolachlor	1,545	PRE	631.94	688.72	1,191.12	1,261.64	736.9	611.35
+ metribuzin	368	PRE						
Glufosinate	738	42 DAP						
+ acetochlor	1,260	42 DAP						
Glufosinate	595	21 DAP	594.7	606.9	1,008.24	1,102.46	595.68	784.46
+ *S*-metolachlor	1,217	21 DAP						
+ fomesafen	266	21 DAP						
Glufosinate	738	42 DAP						
+ acetochlor	1,260	42 DAP						

[a] Partial returns = (soybean grain yield × market price) − (chemical cost + application cost + soybean seed cost). Market price was $0.43 kg^{-1}. Chemical cost was determined from the average of two chemical companies (refer to Table 2 for complete description). Application cost was $14.82 ha^{-1} application^{-1}. Soybean seed cost was $0.41 per 1,000 seed.

[b] Abbreviation: DAP, days after soybean planting.

suppressing late-season Palmer amaranth emergence and limit biomass and seed production of Palmer amaranth growing in conjunction with the crop (Buehring et al. 2002; Norsworthy et al. 2007). Achieving rapid canopy can be useful when POST residual herbicides are not effective or not activated. Furthermore, greater control of Palmer amaranth occurred when *S*-metolachlor plus metribuzin was applied PRE followed by POST residual herbicides compared to a POST-only program, regardless of seeding rate or row spacing.

In conclusion, Palmer amaranth management in glufosinate-resistant soybean is influenced mainly by herbicide selection, application timing, or both, and to a lesser extent by soybean seeding rate and row spacing. Applications of effective PRE herbicides strongly dictate the success of early-season Palmer amaranth management, thus leading to less selection pressure on POST herbicides. The

https://doi.org/10.1614/WT-D-14-00156.1 Published online by Cambridge University Press

combination of a PRE fb POST residual herbicide program as used in this research increases MOA diversity, which lessens the risk of herbicide resistance or slows the spread of herbicide resistance, or both, due to reduced seed production. Also, greater season-long efficacy often occurred whenever a PRE fb POST (residual) herbicide program was employed. Therefore, producers have more to gain, both in returns and Palmer amaranth management, whenever PRE fb POST (residual) herbicide programs are administered in a timely manner.

Acknowledgment

Support for this research was provided by the Arkansas Soybean Promotion Board.

Literature Cited

Anonymous (2014a) Liberty 280 SL herbicide label. Research Triangle Park, NC: Bayer CropScience. http://www.cdms.net/LDat/IdUA5004.pdf. Accessed April 26, 2014

Anonymous (2014b) University of Arkansas Division of Agriculture Research and Extensions 2014 Crop Enterprise Budgets. http://www.uaex.edu/farm-ranch/economics-marketing/farm-planning/enterprise-budget.aspx

Anonymous (2014c) Arkansas Soybean Promotion Board. http://www.themiraclebean.com/markets. Accessed July 6, 2015

Anonymous (2014d) National Agricultural Statistics Service. http://www.nass.usda.gov/statistics_by_subject/index/php?sector=crops

Bagavathiannan MV, Norsworthy JK, Smith KL, Burgos N (2011) Seedbank size and emergence pattern of barnyardgrass (*Echinochloa crus-galli*) in Arkansas. Weed Sci 59:359–365

Barnett KA, Culpepper AS, York AC, Steckel LE (2013) Palmer amaranth (*Amaranthus palmeri*) control by glufosinate plus fluometuron applied postemergence to WideStrike® cotton. Weed Technol 27:291–297

Bensch CN, Horak MJ, Peterson D (2003) Interference of redroot pigweed (*Amaranthus retroflexus*), Palmer amaranth (*Amaranthus palmeri*), and common waterhemp (*A. rudis*) in soybean. Weed Sci 51:37–43

Beyers JT, Smeda RJ, Johnson WG (2002) Weed management programs in glufosinate-resistant soybean (*Glycine max*). Weed Technol 16:267–273

Buehring NW, Nice GRW, Shaw DR (2002) Sicklepod (*Senna obtusifolia*) control in soybean (*Glycine max*) response to soybean row spacing and population in three weed management systems. Weed Technol 16:131–141

Burke IC, Schroeder M, Thomas WE, Wilcut JW (2007) Palmer amaranth interference and seed production in peanut. Weed Technol 21:367–371

Coetzer E, Al-Khatib K, Peterson DE (2002) Glufosinate efficacy on *Amaranthus* species in glufosinate-resistant soybean (*Glycine max*). Weed Technol 16:326–331

DeVore JD, Norsworthy JK, Brye KR (2013) Influence of deep tillage, a rye cover crop, and various soybean production systems on Palmer amaranth emergence in soybean. Weed Technol 27:263–270

Gardner AP, York AC, Jordan DL, Monks DW (2006) Management of annual grasses and *Amaranthus* spp. in glufosinate-resistant cotton. J Cotton Sci 10:328–338

Gibson AC (1998) Photosynthetic organs of desert plants. Bioscience 48:914

Hamill AS, Knezevic SZ, Chandler K, Sikkema PH, Tardif FJ, Shrestha A, Swanton CJ (2000) Weed control in glufosinate-resistant corn (*Zea mays*). Weed Technol 14:578–585

Harder DB, Sprague CL, Renner KA (2007) Effect of soybean row width and population on weeds, crop yield, and economic return. Weed Technol 21:744–752

Harker KN, O'Donovan JT (2013) Recent weed control, weed management, and integrated weed management. Weed Technol 27:1–11

Heap I (2014) The Internation Survey of Herbicide Resistant Weeds. http://www.weedscience.org/summary/home.aspx. Accessed April 26, 2014

Hock SM, Knezevic SZ, Martin AR, Lindquist JL (2006) Soybean row spacing and weed emergence time influence weed competitiveness and competitive indices. Weed Sci 54:38–46

Jha P, Norsworthy JK (2009) Soybean canopy and tillage effects on emergence of Palmer amaranth (*Amaranthus palmeri*) from a natural seed bank. Weed Sci 57:644–651

Jha P, Norsworthy JK, Bridges W Jr, Riley MB (2008) Influence of glyphosate timing and row width on Palmer amaranth (*Amaranthus palmeri*) and pusley (*Richardia* spp.) demographics in glyphosate-resistant soybean. Weed Sci 56:408–415

Kay RD, Edwards WM, Duffy PA (2008) Farm Management. 6th edn. New York: McGraw-Hill. Pp 175–185

Keeley PE, Carter CH, Thullen RJ (1987) Influence of planting date on growth of Palmer amaranth (*Amaranthus palmeri*). Weed Sci 35:199–204

Klingaman TE, Oliver LR (1994) Palmer amaranth (*Amaranthus palmeri*) interference in soybeans (*Glycine max*). Weed Sci 42:523–527

Krausz RF, Young BG, Kapusta G, Matthews JL (2001) Influence of weed competition and herbicides on glyphosate-resistant soybean (*Glycine max*). Weed Technol 15:530–534

Monks DW, Oliver LR (1988) Interactions between soybean (*Glycine max*) cultivars and selected weeds. Weed Sci 36:770–774

Morgan GD, Baumann PA, Chandler JM (2001) Competitive impact of Palmer amaranth (*Amaranthus palmeri*) on cotton (*Gossypium hirsutum*) development and yield. Weed Technol 15:408–412

Nice GRW, Buehring NW, Shaw DR (2001) Sicklepod (*Senna obtusifolia*) response to shading, soybean (*Glycine max*) row spacing, and population in three management systems. Weed Technol 15:155–162

Norsworthy JK (2004) Soil-applied herbicide use in wide- and narrow-row glyphosate-resistant soybean (*Glycine max*). Crop Prot 23:1237–1244

Norsworthy JK, Griffith GM, Scott RC, Smith KL, Oliver LR (2008a) Confirmation and control of glyphosate-resistant

Palmer amaranth (*Amaranthus palmeri*) in Arkansas. Weed Technol 22:108–113

Norsworthy JK, Jha P, Bridges W Jr (2007) Sicklepod (*Senna obtusifolia*) survival and fecundity in wide- and narrow-row glyphosate-resistant soybean. Weed Sci 55:252–259

Norsworthy JK, Oliver LR (2002) Pitted morningglory interference in drill-seeded glyphosate-resistant soybean. Weed Sci 50:26–33

Norsworthy JK, Oliveria MJ, Jha P, Malik M, Buckelew JK, Jennings KM, Monks DW (2008b) Palmer amaranth and large crabgrass growth with plasticulture-grown bell pepper. Weed Technol 22:296–302

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

Place GT, Reberg-Horton SC, Dunphy JE, Smith AN (2009) Seeding rate effects on weed control and yield for organic soybean production. Weed Technol 23:497–502

Powles SB, Preston C, Bryan IB, Jutsum AR (1997) Herbicide resistance: impact and management. Adv Agron 58:57–93

Purcell LC (2000) Soybean canopy coverage and light interception measurements using digital imagery. Crop Sci 40:834–837

Riar DS, Norsworthy JK, Griffith GM (2011) Herbicide programs for enhanced glyphosate-resistant and glufosinate-resistant cotton (*Gossypium hirsutum*). Weed Technol 25:526–534

Riar DS, Norsworthy JK, Steckel LE, Stephenson DO IV, Eubank TW, Scott RC (2013) Assessment of weed management practices and problem weeds in the midsouth United States-soybean: a consultant's perspective. Weed Technol 27:612–622

Rich AM, Renner KA (2007) Row spacing and seeding rate effects on eastern black nightshade (*Solanum ptychanthum*) and soybean. Weed Technol 21:124–130

Scott B, Smith K (2011) Prevention and control of glyphosate-resistant pigweed in soybean and cotton. University of Arkansas Cooperative Extension Service Printing Services FSA 2152-PD-3-11RV. 4 p

Scott RC, Barber LT, Boyd JW, Norsworthy JK, Burgos N (2014) Recommended Chemicals for Weed and Brush Control. Little Rock, AR: The University of Arkansas Division of Agriculture Cooperative Extension Service Miscellaneous Publication 44. P 38

Sellers BA, Smeda RJ, Johnson WG, Kendig JA, Ellersieck MR (2003) Comparative growth of six *Amaranthus* species in Missouri. Weed Sci 51:329–333

Sosnoskie LM, Webster TM, Culpepper AS (2013) Glyphosate resistance does not affect Palmer amaranth (*Amaranthus palmeri*) seedbank longevity. Weed Sci 61:283–288

Stewart CL, Nurse RE, Hamill AS, Sikkema PH (2010) Environment and soil conditions influence pre- and post-emergence herbicide efficacy in soybean. Weed Technol 24:234–243

Taylor-Lovell S, Wax LM, Bollero G (2002) Preemergence flumioxazin and pendimethalin and postemergence herbicide systems for soybean (*Glycine max*). Weed Technol 16:502–511

Webster TM, Nichols RL (2012) Changes in the prevalence of weed species in the major agronomic crops of the Southern United States: 1994/1995 to 2008/2009. Weed Sci 60:145–157

Whitaker JR, York AC, Jordan DL, Culpepper AS (2010) Palmer amaranth (*Amaranthus palmeri*) control in soybean with glyphosate and conventional herbicide systems. Weed Technol 24:403–410

Wiesbrook ML, Johnson WG, Hart SE, Bradley PR, Wax LM (2001) Comparison of weed management systems in narrow-row, glyphosate- and glufosinate-resistant soybean (*Glycine max*). Weed Technol 15:122–128

Young BG (2006) Changes in herbicide use patterns and production practices resulting from glyphosate-resistant crops. Weed Technol 20:301–307

Young BG, Young JM, Gonzini LC, Hart SE, Wax LM, Kapusta G (2001) Weed management in narrow- and wide-row glyphosate-resistant soybean (*Glycine max*). Weed Technol 15:112–121

Received December 18, 2014, and approved March 17, 2015.