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Integrating Cereals and Deep Tillage with Herbicide Programs in Glyphosate- and Glufosinate-Resistant Soybean for Glyphosate-Resistant Palmer Amaranth Management

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A field experiment was conducted at Marianna, AR in 2012 and 2013 to test various combinations of (1) soybean production systems: full-season tillage (rye plus deep tillage using a moldboard plow), full season (no rye plus no tillage), late-season tillage (wheat plus deep tillage), and late season (no wheat plus no tillage); (2) soybean cultivars: glufosinate or glyphosate resistant; and (3) four herbicide programs for management of glyphosate-resistant Palmer amaranth. At soybean harvest, Palmer amaranth control was 95 to 100% when flumioxazin plus pyroxasulfone was applied PRE. In both years full-season tillage and late-season tillage systems in combination with flumioxazin plus pyroxasulfone applied PRE increased Palmer amaranth control over the same systems in the absence of flumioxazin plus pyroxasulfone applied PRE. The addition of deep tillage in the form of a moldboard plow to the full-season and late-season systems reduced Palmer amaranth densities at harvest. Similarly, Palmer amaranth seed production was often lower in the full-season tillage and late-season tillage systems compared with the full-season and late-season no-tillage systems, regardless of soybean cultivar and herbicide programs. Overall, the use of deep tillage in the full-season or late-season systems in combination with a PRE application of flumioxazin plus pyroxasulfone provided greater control of Palmer amaranth, decreasing both density and seed production and increasing soybean grain yields.

Nomenclature: Palmer amaranth, *Amaranthus palmeri* S. Wats; soybean, *Glycine max* (L.) Merr.; rye, *Secale cereale* L.

Key words: Cover crop, soil-applied residual, weed control, weed seed production.

Un experimento de campo fue realizado en Marianna, Arkansas en 2012 y 2013, para evaluar varias combinaciones de (1) sistemas de producción de soja: temporada completa y labranza (centeno más labranza profunda), temporada completa (sin centeno y sin labranza), temporada tardía y labranza (trigo más labranza profunda), temporada tardía (sin trigo y sin labranza); (2) cultivares de soja: resistentes a glyphosate o a glufosinate; y (3) cuatro programas de herbicidas para el manejo de *Amaranthus palmeri* resistente a glyphosate. Al momento de la cosecha de la soja, el control de *A. palmeri* fue 95 a 100% cuando se aplicó flumioxazin más pyroxasulfone PRE. En ambos años los sistemas de temporada completa más labranza y temporada tardía más labranza en combinación con flumioxazin más pyroxasulfone aplicados PRE aumentaron el control de *A. palmeri* en comparación con los mismos sistemas en ausencia de flumioxazin más pyroxasulfone aplicados PRE. La adición de labranza profunda en forma de arado de vertedera a los sistemas de temporada completa y temporada tardía redujo las densidades de *A. palmeri* al momento de la cosecha. Similarmente, la producción de semilla de *A. palmeri* fue frecuentemente menor en los sistemas de temporada completa más labranza y temporada tardía más labranza al compararse con los sistemas de temporada completa y tardía sin labranza, sin importar el cultivar de soja ni el programa de herbicidas. En general, el uso de labranza profunda en sistemas de temporada completa y temporada tardía en combinación con la aplicación de flumioxazin más pyroxasulfone PRE brindaron un mayor control de *A. palmeri*, disminuyendo tanto su densidad como la producción de semilla e incrementando así el rendimiento de grano de soja.

Glyphosate-resistant soybean were commercially released in 1996 (Duke and Powles 2008; Sammons et al. 2007). Adoption of transgenic glyphosate-resistant crops has been unprecedented (James 2007). In 2009, > 90% of soybean acreage in the United States was planted in glyphosate-resistant soybean and adoption in Argentina was almost 90% within the first 4 yr of introduction (Duke and

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Powles 2009; Green 2009; Powles 2008). Greater than 80% of the 120 million ha of transgenic crops grown worldwide are glyphosate resistant (Dukes and Powles 2009).

Glufosinate-resistant soybean were first available in 1999 (Wiesbrook et al. 2001). With the widespread occurrence of glyphosate-resistant Palmer amaranth in the Mid-South by 2012, growers began to adopt glufosinate-resistant soybean as an option for control of this weed and other difficult-to-control weeds of soybean (Riar et al. 2013). Biological factors such as rapid growth rate, extended emergence period, and prolific seed production contribute to the ability of Palmer amaranth to compete with crops (DeVore et al. 2013; Horak and Loughlin 2000; Jha and Norsworthy 2009; Scott and Smith 2011).

Winter annual cover crops may be used in agronomic systems. Winter wheat (*Triticum aestivum* L.) and cereal rye suppress growth of many annual weeds by acting as a physical mulch and by releasing allelochemicals (Weston 1996). Moore et al. (1994) reported that cereal rye and triticale (× *Triticosecale* Wittmack 'OAC Wintri') cover crops reduced the emergence of common lambsquarters (*Chenopodium album* L.) and redroot pigweed (*Amaranthus retroflexus* L.) by 78% when compared with the absence of a cover crop.

Including a herbicide program with a cover-crop system can reduce weed emergence (DeVore et al. 2013). Reddy et al. (2003) reported that PRE and POST herbicide programs combined with crimson clover [*Trifolium incarnatum* (L.) Dixie] or rye cover crops in soybean controlled barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.], broadleaf signalgrass [*Urochloa platyphylla* (Griseb.) Nash], entireleaf morningglory [*Ipomoea hederacea* (L.) Jacq.], and hyssop spurge (*Euphorbia hyssopifolia* L.) 92% or more. Additionally, cereal crops incorporated into a conservation-tillage, glyphosate-resistant cotton (*Gossypium hirsutum* L.) production system can reduce the selection pressure of glyphosate by aiding in early-season weed management (Norsworthy et al. 2011).

Tillage may also be used to control weeds. Three main types of tillage practiced in the United States are conservation, reduced, and conventional tillage. Conservation tillage is measured immediately after crop planting and is defined as 30% or more of the soil covered by previous residues; reduced tillage is defined as 15 to 30% of the soil being covered by residue; and conventional tillage is defined as any set of practices that leaves less than 15% of the soil covered by crop residues after planting (Horowitz et al. 2010).

Tillage has an effect on weed diversity and changes in tillage practices select for different weed species. Leon and Owen (2006) determined that when using a moldboard plow a fourfold reduction in common waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer] emergence occurred, compared with a no-till system. Conversely, no till reduced common cocklebur (*Xanthium strumarium* L.) emergence by 59 to 69% when compared with conventional tillage (Norsworthy and Oliveira 2007). Reddy (2005) reported that redvine [*Brunnichia ovata* (Walt.) Shinners] density was reduced 88 to 97% with deep tillage (45 cm) compared with shallow tillage (15 cm). Barnes and Oliver (2003) determined that conventional tillage provided greater sicklepod [*Senna obtusifolia* (L.) Irwin and Barnaby] control than in no till; however, soybean yields were greater in no-till compared with conventional tillage. DeVore et al. (2013) reported that when soybean had either a rye or wheat cover crop in combination with a one-time moldboard plow, Palmer amaranth emergence in soybean was reduced as much as 98%.

The introduction of glyphosate-resistant crops allowed a rapid reduction of tillage (Duke and Powles 2008, 2009; Powles 2008) because weeds that had been controlled with tillage could now be controlled with the broad-spectrum glyphosate. Producers discovered many advantages of reduced tillage, such as time savings and savings on equipment and fuel costs (Lithourgidis et al. 2006). Furthermore, reduced tillage is beneficial to the environment by reducing soil erosion and reduced tillage can also aid soil moisture retention, allowing more water to be available to plants (DeFelice et al. 2006; Lithourgidis et al. 2005). Herbicide-resistant weeds could be a threat to conservation-tillage systems in that tillage would have to be used to control resistant weeds if effective herbicides are not available.

The objective of this study was to determine how various production systems in combination with either a glufosinate- or glyphosate-resistant soybean cultivar and multiple herbicide programs affect

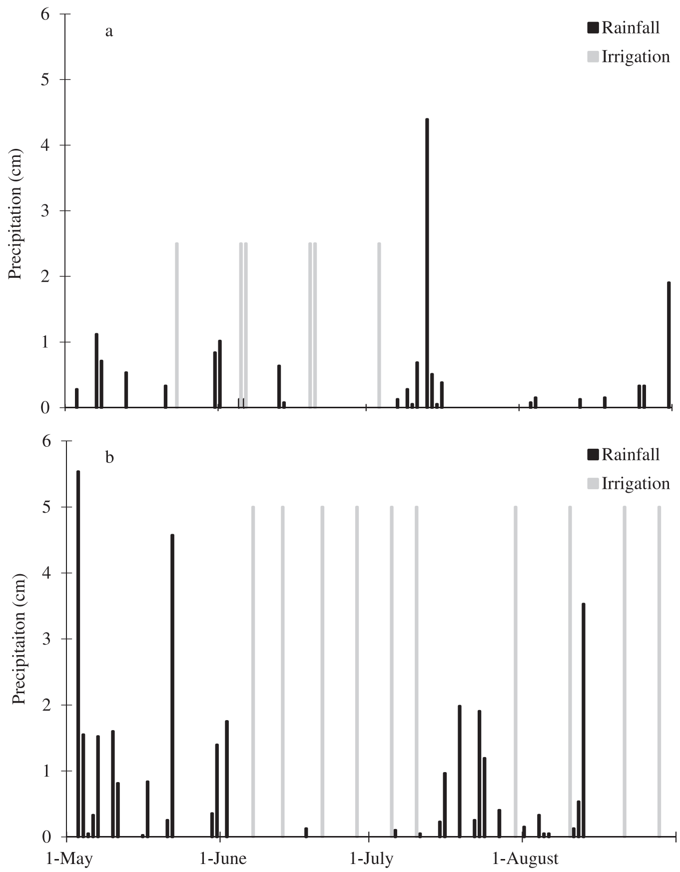

Figure 1. Rainfall and irrigation distribution at Marianna, AR in 2012 (a) and in 2013 (b).

Palmer amaranth control, density, and seed production as well as soybean grain yield.

Materials and Methods

The experiment was conducted at the Lon Mann Cotton Research Station in Marianna, AR during 2012 and 2013. The soil series was a Convent silt loam (Coarse-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts) with 9% sand, 80% silt, 11% clay, 1.8% organic matter, and a soil pH of 6.6. The experiment in 2012 was conducted under dryland conditions; however, a sprinkler irrigator, calibrated to deliver 2.5 cm of water per irrigation event, was used at each application timing to ensure that the residual herbicides were activated (Figure 1a). In 2013, polypipe, with holes spaced every 1 m, was located on the high end of the graded field so that the test site could be border irrigated throughout the growing season (Figure 1b). The experiment was organized in a split-split plot design with four replications. The main plot factors were four soybean production systems: (1) rye plus tillage (full-season tillage), (2) wheat plus tillage (late-season tillage), (3) no rye plus no tillage (full season), and (4) no wheat plus no tillage (late season). Tillage refers specifically to deep tillage with a moldboard plow at an approximate 25-cm depth and tillage will be referring to deep tillage with a moldboard plow throughout the remainder of this paper. Immediately after tillage on November 9, 2011 and October 25, 2012, the deep-tilled plots were tilled to a 5-cm depth with a field cultivator to allow for a smooth seedbed. The same day 'Wrens Abruzzi' rye and 'Agripro® Coker 9553' (Syngenta Cereals, Berthoud, CO 80513) wheat were drill seeded at 79 kg ha^{-1} and 134 kg ha^{-1}, respectively, using a John Deere grain drill (Deere & Company World Headquarters, Moline, IL 61265).

The subplot factor was a glyphosate-resistant soybean cultivar (AG 5232 in 2012; AG 5233 in 2013) and a glufosinate-resistant soybean cultivar (Halomax 494 in 2012 and 2013). Rye cover crops were desiccated with glyphosate at 870 g ae ha^{-1} 2 wk before planting the full-season soybean. Before planting, soybean rye aboveground biomass was measured in four 1-m^2 quadrats. Full-season soybean cultivars were drill seeded using a John Deere no-till drill on May 23, 2012 and May 9, 2013. Wheat was grown to maturity and harvested with a small-plot combine (Massey Ferguson 8xp, AGCO, Duluth, GA 30096). Immediately after wheat harvest, late-season soybean were drill seeded on June 5, 2012 and July 7, 2013. Soybean for both the full-season and late-season production systems were drill seeded on a 19-cm row spacing at a rate of 432,000 seed ha^{-1}.

The sub-subplot factor was four herbicide programs: (1) paraquat at 700 g ai ha^{-1} applied PRE to soybean (control treatment), (2) paraquat at 700 g ha^{-1} applied PRE to soybean followed by (fb) glyphosate at 870 g ae ha^{-1} or glufosinate at 595 g ai ha^{-1} applied 14 d after planting soybean (DAP) fb glyphosate at 870 g ha^{-1} or glufosinate at 595 g ha^{-1} applied 28 DAP, (3) paraquat at 700 g ha^{-1} applied PRE fb glyphosate at 870 g ha^{-1} or glufosinate at 595 g ha^{-1} plus (*S*-metolachlor plus fomesafen at 1,217 g ai ha^{-1} plus 266 g ai ha^{-1}, respectively) applied 14 DAP fb glyphosate at 870 g ha^{-1} or glufosinate at 595 g ai ha^{-1} plus acetochlor

Table 1. Source of herbicides used in the experiment.

Herbicide	Trade name	Formulation[a]	Rate	Manufacturer	Address
			g ai or ae ha^{-1}		
Paraquat	Gramoxone	SL	700	Syngenta Crop Protection	Greensboro, NC
Glyphosate	Roundup PowerMAX	SL	870	Monsanto Company	St. Louis, MO
Glufosinate	Liberty	SL	595	Bayer CropScience	Research Triangle Park, NC
Fomesafen + *S*-metolachlor	Prefix	EC	266 + 1,217	Syngenta Crop Protection	Greensboro, NC
Acetochlor	Warrant	ME	1,260	Monsanto Company	St. Louis, MO
Flumioxazin + pyroxasulfone	Fierce	WDG	700 + 82	Valent U.S.A.	Walnut Creek, CA

[a] Abbreviations: SL, soluble liquid; EC, emulsifiable concentration; ME, microencapsulated; WDG, water dispersible granule.

at 1,260 g ai ha^{-1} applied 28 DAP, (4) paraquat at 700 g ha^{-1} plus (flumioxazin plus pyroxasulfone at 82 g ai ha^{-1} plus 104 g ai ha^{-1}, respectively) applied PRE fb glyphosate at 870 g ha^{-1} or glufosinate at 595 g ha^{-1} plus (*S*-metolachlor plus fomesafen at 1,217 g ha^{-1} plus 266 g ha^{-1}, respectively) applied 14 DAP fb glyphosate at 870 g ha^{-1} or glufosinate at 595 g ha^{-1} plus acetochlor at 1,260 g ha^{-1} applied 28 DAP (Table 1). Each sub-subplot measured 2.25 m by 11 m with a 1.5-m alley.

Herbicide treatments were applied using a CO_2-pressurized backpack sprayer. The sprayer consisted of a handheld boom that contained four 110015 flat-fan nozzles (Teejet Technologies, Springfield, IL 62703) on a 48-cm spacing calibrated to deliver 140 L ha^{-1} at 276 kPa. More than 90% of the weeds present in the plots were Palmer amaranth. Other weeds present at low densities included barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] and goosegrass (*Eleusine indica* L.). Grasses were removed by applying clethodim over the entire test area as needed. Palmer amaranth control estimates were taken at each herbicide application and at harvest relative to the no-cover-crop, no-tillage, and paraquat-applied-PRE treatments (check plots) on a 0 to 100% scale, where 0 was equal to no weed control and 100 was equal to complete weed control. When PRE herbicides were applied, no Palmer amaranth plants were present. When the remaining herbicide applications were made, Palmer amaranth heights varied from 2 to 30 cm.

After soybean planting, two 0.5-m^2 areas were marked with flags (Gempler's, Janesville, WI 53547) in the center of each sub-subplot to provide a uniform and consistent area to determine Palmer amaranth density and seed production. Palmer amaranth plant counts were taken before each herbicide application and before soybean harvest in both quadrats. At soybean harvest, the surviving Palmer amaranth plants were collected from the two 0.5-m^2 areas, threshed, and total biomass was weighed. Seeds were counted in three 0.25-g subsamples per plot, then extrapolated to the total biomass weight to determine the total seed production from the surviving Palmer amaranth. Soybean yield was measured at crop maturity by harvesting each individual sub-subplot with a small-plot combine and correcting grain yield to 13% moisture.

Data were analyzed in JMP using ANOVA with the MIXED procedure. Years were initially analyzed and found to be different; hence, years were analyzed separately because of differences in environmental conditions. Production system, soybean cultivar, herbicide program, and any interactions containing these effects were considered fixed effects. Replication and any interaction containing replication were considered random effects. Means for significant main effects and their interactions were separated by Fisher's protected LSD test at the 0.05 significance level.

Results and Discussion

Palmer Amaranth Control, Density, and Seed Production. At 14 DAP, flumioxazin plus pyroxasulfone applied PRE in combination with full-season tillage or late-season tillage provided > 98% Palmer amaranth control in both years (data not shown). Flumioxazin plus pyroxasulfone applied PRE reduced Palmer amaranth emergence 87 to 100%, regardless of production system and cultivar (Table 2).

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Table 2. Palmer amaranth density at 14 d after soybean planting as influenced by production system and herbicide program, averaged over soybean cultivar at Marianna, AR in 2012 and 2013.

			Density							
			2012				2013			
			Production system							
Herbicide program	Rate	Application timing[a]	Full season[b]	Full-season tillage[c]	Late season[d]	Late-season tillage[e]	Full season	Full-season tillage	Late season	Late-season tillage
	g ai or ae[f] ha^{-1}		plants m^{-2}							
Paraquat	700	PRE	97.9 aA[h]	5.5 aBC	29.6 aB	1.6 aC	33.6 aA	4.3 aB	10.6 abB	2.9 aB
Paraquat	700	PRE	87.5 aA	4.8 aB	18.5 aB	3.4 aB	42.4 aA	2.3 aB	11.1 abB	3.6 aB
Glufosinate[g]/	595	14 DAP								
glyphosate[f]	870	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP								
Paraquat	700	PRE	73.6 aA	0.6 aC	24.3 aB	0.4 aC	47.1 aA	2.8 aB	18.5 aB	3.3 aB
Glufosinate/	595	14 DAP								
glyphosate	870	14 DAP								
+ *S*-metolachlor	1,217	14 DAP								
+ fomesafen	266	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP								
+ acetochlor	1,260	28 DAP								
Paraquat	700	PRE	0.0 bA	0.0 aA	0.0 bA	0.0 aA	0.0 bB	0.0 aB	1.4 bA	0.0 aB
+ flumioxazin	82	PRE								
+ pyroxasulfone	104	PRE								
Glufosinate/	595	14 DAP								
glyphosate	870	14 DAP								
+ *S*-metolachlor	1,217	14 DAP								
+ fomesafen	266	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP								
+ acetochlor	1,260	28 DAP								

[a] Abbreviation: DAP, days after soybean planting.
[b] Full season represents no rye and no tillage.
[c] Full-season tillage represents rye in combination with deep tillage using a moldboard plow.
[d] Late season represents no wheat and no tillage.
[e] Late-season tillage represents wheat in combination with deep tillage using a moldboard plow.
[f] Glyphosate rate is acid equivalent.
[g] Glufosinate used for the glufosinate-resistant soybean cultivar and glyphosate used for the glyphosate-resistant soybean cultivar.
[h] Lowercase letters are used to compare herbicide programs within a production system and uppercase letters are used to compare a production system within a 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 $\alpha \leq 0.05$.

Tillage alone at 14 DAP in the paraquat-only herbicide program reduced Palmer amaranth densities by 94 to 95% in 2012 and 73 to 87% in 2013 (Table 2). The cause for differences in the effectiveness of deep tillage between years is not completely known but differences may be due to more Palmer amaranth seed being present near the soil surface before deep tillage for the 2012 experiment; hence, burial during deep tillage would place the seed at a depth less suitable for successful germination and emergence, whereas buried seed would be brought to the surface during the tillage event.

Palmer amaranth control at 28 DAP in 2012 was influenced by the interaction of production system, soybean cultivar, and herbicide program (Table 3).

Table 3. Palmer amaranth control at 28 d after soybean planting as influenced by production system, soybean cultivar, and herbicide program at Marianna, AR in 2012.

			Control							
			Production system							
			Full season[b]		Full-season tillage[c]		Late season[d]		Late-season tillage[e]	
			Soybean cultivar							
Herbicide program	Rate	Application timing[a]	Glufosinate resistant	Glyphosate resistant	Glufosinate resistant	Glyphosate resistant	Glufosinate resistant	Glyphosate resistant	Glufosinate resistant	Glyphosate resistant
	g ai or ae[f] ha^{-1}		%							
Paraquat	700	PRE	84 bB[h]	69 bC	95 bAB	92 aAB	88 abAB	53 bD	99 aA	99 aA
Glufosinate[g]/	595	14 DAP								
glyphosate[f]	870	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP								
Paraquat	700	PRE	83 bBC	75 bC	93 bAB	91 aAB	73 bC	71 bC	100 aA	98 aA
Glufosinate/	595	14 DAP								
glyphosate	870	14 DAP								
+ *S*-metolachlor	1,217	14 DAP								
+ fomesafen	266	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP								
+ acetochlor	1,260	28 DAP								
Paraquat	700	PRE	100 aA	100 aA	100 aA	99 aA	100 aA	100 aA	100 aA	100 aA
+ flumioxazin	82	PRE								
+ pyroxasulfone	104	PRE								
Glufosinate/	595	14 DAP								
glyphosate	870	14 DAP								
+ *S*-metolachlor	1,217	14 DAP								
+ fomesafen	266	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP								
+ acetochlor	1,260	28 DAP								

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

[b] Full season represents no rye and no tillage.

[c] Full-season tillage represents rye in combination with deep tillage using a moldboard plow.

[d] Late season represents no wheat and no tillage.

[e] Late-season tillage represents wheat in combination with deep tillage using a moldboard plow.

[f] Glyphosate rate is acid equivalent.

[g] Glufosinate used for the glufosinate-resistant soybean cultivar and glyphosate used for the glyphosate-resistant soybean cultivar.

[h] Lowercase letters are used to compare herbicide programs within soybean cultivar within a production system and uppercase letters are used to compare soybean cultivars within a production system with a herbicide program. Means followed by the same letter, either lowercase or uppercase, are not different according to Fisher's protected LSD test at $\alpha \leq 0.05$. Overall model LSD for the interaction of production system × soybean cultivar × herbicide program = 12.

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Table 4. Palmer amaranth control at 28 d after soybean planting as influenced by production system and herbicide program, averaged over soybean cultivar at Marianna, AR in 2013.

Herbicide program	Rate	Application timing[a]	Control: Production system: Full season[b]	Full-season tillage[c]	Late season[d]	Late-season tillage[e]
	g ai or ae[f] ha^{-1}		—%—			
Paraquat	700	PRE	92 bB[h]	99 aA	95 bAB	98 aA
Glufosinate[g]/	595	14 DAP				
glyphosate[f]	870	14 DAP				
Glufosinate/	595	28 DAP				
glyphosate	870	28 DAP				
Paraquat	700	PRE	100 aA	100 aA	96 abC	98 aB
Glufosinate/	595	14 DAP				
glyphosate	870	14 DAP				
+ *S*-metolachlor	1,217	14 DAP				
+ fomesafen	266	14 DAP				
Glufosinate/	595	28 DAP				
glyphosate	870	28 DAP				
+ acetochlor	1,260	28 DAP				
Paraquat	700	PRE	99 aA	100 aA	98 aB	98 aB
+ flumioxazin	82	PRE				
+ pyroxasulfone	104	PRE				
Glufosinate/	595	14 DAP				
glyphosate	870	14 DAP				
+ *S*-metolachlor	1,217	14 DAP				
+ fomesafen	266	14 DAP				
Glufosinate/	595	28 DAP				
glyphosate	870	28 DAP				
+ acetochlor	1,260	28 DAP				

[a] Abbreviation: DAP, days after soybean planting.
[b] Full season represents no rye and no tillage.
[c] Full-season tillage represents rye in combination with deep tillage using a moldboard plow.
[d] Late season represents no wheat and no tillage.
[e] Late-season tillage represents wheat in combination with deep tillage using a moldboard plow.
[f] Glyphosate rate is acid equivalent.
[g] Glufosinate used for the glufosinate-resistant soybean cultivar and glyphosate used for the glyphosate-resistant soybean cultivar.
[h] Lowercase letters are used to compare herbicide programs within a production system and uppercase letters are used to compare production systems within a herbicide program. Means followed by the same letter, either lowercase or uppercase, are not different according to Fisher's protected LSD test at $\alpha \leq 0.05$.

Flumioxazin plus pyroxasulfone applied PRE provided ≥ 99% control of Palmer amaranth across all production systems and soybean cultivars. In the absence of flumioxazin plus pyroxasulfone in the full-season and late-season systems, Palmer amaranth control ranged from 53 to 88%. The addition of tillage to these systems improved Palmer amaranth control to 91 to 100%, across cultivars and herbicide programs. The benefit of the deep tillage is that fewer Palmer amaranth plants were present when applying the POST herbicides; hence the improved control. In 2013, there were fewer differences in PRE fb POST and POST-only programs. For example, Palmer amaranth control was ≥ 96% in the PRE fb POST residual herbicide programs at 28 DAP compared with ≥ 92% in the POST-only herbicide program, across production systems (Table 4). Timely rainfall and greater irrigation amounts in 2013 compared with 2012 likely contributed to improved activation of residual herbicides as well as POST activity of the various treatments.

Table 5. Palmer amaranth control at soybean harvest as influenced by production system and herbicide program, averaged over soybean cultivar at Marianna, AR in 2012.

Herbicide program	Rate	Application timing[a]	Control: Production system: Full season[b]	Full-season tillage[c]	Late season[d]	Late-season tillage[e]
	g ai or ae[f] ha^{-1}		%			
Paraquat	700	PRE	29 bB[h]	72 bA	75 bA	86 bA
Glufosinate[g]/	595	14 DAP				
glyphosate[f]	870	14 DAP				
Glufosinate/	595	28 DAP				
glyphosate	870	28 DAP				
Paraquat	700	PRE	34 bC	67 bB	54 cB	85 bA
Glufosinate/	595	14 DAP				
glyphosate	870	14 DAP				
+ *S*-metolachlor	1,217	14 DAP				
+ fomesafen	266	14 DAP				
Glufosinate/	595	28 DAP				
glyphosate	870	28 DAP				
+ acetochlor	1,260	28 DAP				
Paraquat	700	PRE	98 aA	98 aA	98 aA	99 aA
+ flumioxazin	82	PRE				
+ pyroxasulfone	104	PRE				
Glufosinate/	595	14 DAP				
glyphosate	870	14 DAP				
+ *S*-metolachlor	1,217	14 DAP				
+ fomesafen	266	14 DAP				
Glufosinate/	595	28 DAP				
glyphosate	870	28 DAP				
+ acetochlor	1,260	28 DAP				

[a] Abbreviations: DAP, days after soybean planting.
[b] Full season represents no rye and no tillage.
[c] Full-season tillage represents rye in combination with deep tillage using a moldboard plow.
[d] Late season represents no wheat and no tillage.
[e] Late-season tillage represents wheat in combination with deep tillage using a moldboard plow.
[f] Glyphosate rate is acid equivalent.
[g] Glufosinate used for the glufosinate-resistant soybean cultivar and glyphosate used for the glyphosate-resistant soybean cultivar.
[h] Lowercase letters are used to compare herbicide programs within a production system and uppercase letters are used to compare a production system within a 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 $\alpha \leq 0.05$.

When pooled over soybean cultivars, there were no Palmer amaranth plants at 28 DAP when flumioxazin plus pyroxasulfone was applied PRE compared with as many as 170 plants m^{-2} in the absence of a PRE residual herbicide in 2012 (data not shown). Similarly in 2013, PRE-applied flumioxazin plus pyroxasulfone was effective in reducing the density of Palmer amaranth plants at 28 DAP (data not shown).

At soybean harvest, Palmer amaranth control in 2012 was influenced by the interaction of production system and herbicide program (Table 5). Palmer amaranth control at harvest when flumioxazin plus pyroxasulfone were applied PRE was $\geq$ 98%, regardless of production system. Late-season tillage systems without a PRE provided 85 to 86% control of Palmer amaranth, whereas other production systems provided poor to fair control. The combination of deep tillage and use of a cover crop in the late-season tillage system caused a reduction in Palmer amaranth emergence similar to that observed in other research (DeVore et al.

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Table 6. Palmer amaranth control at soybean harvest as influenced by production system, soybean cultivar, and herbicide program at Marianna, AR in 2013.

			Control							
			Production system							
			Full season[b]		Full-season tillage[c]		Late season[d]		Late-season tillage[e]	
			Soybean cultivar							
Herbicide program	Rate	Application timing[a]	Glufosinate resistant	Glyphosate resistant	Glufosinate resistant	Glyphosate resistant	Glufosinate resistant	Glyphosate resistant	Glufosinate resistant	Glyphosate resistant
	g ai or ae[f] ha^{-1}		%							
Paraquat	700	PRE	97 aA[h]	83 bB	94 aA	94 bA	97 aA	83 bB	98 bA	98 bA
Glufosinate[g]/	595	14 DAP								
glyphosate[f]	870	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP								
Paraquat	700	PRE	98 aA	92 abB	97 aA	97 abA	99 aA	97 aA	100 aA	100 aA
Glufosinate/	595	14 DAP								
glyphosate	870	14 DAP								
+ *S*-metolachlor	1,217	14 DAP								
+ fomesafen	266	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP								
+ acetochlor	1,260	28 DAP								
Paraquat	700	PRE	95 aA	98 aA	100 aA	100 aA	100 aA	100 aA	100 aA	100 aA
+ flumioxazin	82	PRE								
+ pyroxasulfone	104	PRE								
Glufosinate/	595	14 DAP								
glyphosate	870	14 DAP								
+ *S*-metolachlor	1,217	14 DAP								
+ fomesafen	266	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP								
+ acetochlor	1,260	28 DAP								

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

[b] Full season represents no rye and no tillage.

[c] Full-season tillage represents rye in combination with deep tillage using a moldboard plow.

[d] Late season represents no wheat and no tillage.

[e] Late-season tillage represents wheat in combination with deep tillage using a moldboard plow.

[f] Glyphosate rate is acid equivalent.

[g] Glufosinate used for the glufosinate-resistant soybean cultivar and glyphosate used for the glyphosate-resistant soybean cultivar.

[h] Lowercase letters are used to compare herbicide programs within soybean cultivar within a production system and uppercase letters are used to compare soybean cultivars within a production system with a herbicide program. Means followed by the same letter, either lowercase or uppercase, are not different according to Fisher's protected LSD test at $\alpha \leq 0.05$. Overall model LSD for the interaction of production system × soybean cultivar × herbicide program = 6.

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Table 7. Palmer amaranth density at soybean harvest as influenced by herbicide program and production system, averaged over soybean cultivar at Marianna, AR in 2012 and 2013.

			Density							
			2012				2013			
			Production system							
Herbicide program	Rate	Application timing[a]	Full season[b]	Full-season tillage[c]	Late season[d]	Late-season tillage[e]	Full season	Full-season tillage	Late season	Late-season tillage
	g ai or ae[f] ha^{-1}		plants m^{-2}							
Paraquat	700	PRE	35.5 aA[h]	5.6 aB	8.5 aB	1.3 aB	0.5 aA	0.3 aA	1.5 aA	1.1 aA
Paraquat	700	PRE	21.5 bA	1.0 bB	12.4 aAB	3.0 aB	0.4 aA	0.0 aA	0.9 abA	0.0 bA
Glufosinate[g]/	595	14 DAP								
glyphosate[f]	870	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP								
Paraquat	700	PRE	21.4 bA	0.3 bB	2.8 aB	0.3 aB	0.0 aA	0.0 aA	0.1 bA	0.0 bA
Glufosinate/	595	14 DAP								
glyphosate	870	14 DAP								
+ *S*-metolachlor	1,217	14 DAP								
+ fomesafen	266	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP								
+ acetochlor	1,260	28 DAP								
Paraquat	700	PRE	0.0 cA	0.0 bA	0.0 aA	0.0 aA	0.0 aA	0.0 aA	0.0 bA	0.0 bA
+ flumioxazin	82	PRE								
+ pyroxasulfone	104	PRE								
Glufosinate/	595	14 DAP								
glyphosate	870	14 DAP								
+ *S*-metolachlor	1,217	14 DAP								
+ fomesafen	266	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP								
+ acetochlor	1,260	28 DAP								

[a] Abbreviation: DAP, days after soybean planting.
[b] Full season represents no rye and no tillage.
[c] Full-season tillage represents rye in combination with deep tillage using a moldboard plow.
[d] Late season represents no wheat and no tillage.
[e] Late-season tillage represents wheat in combination with deep tillage using a moldboard plow.
[f] Glyphosate rate is acid equivalent.
[g] Glufosinate used for the glufosinate-resistant soybean cultivar and glyphosate used for the glyphosate-resistant soybean cultivar.
[h] Lowercase letters are used to compare herbicide programs within a production system and uppercase letters are used to compare a production system within a 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 $\alpha \leq 0.05$.

2013). Likewise, Kelton et al. (2013) reported greater late-season *Amaranthus* spp. control when using a moldboard plow compared with conventional tillage.

Palmer amaranth control at soybean harvest in 2013 was influenced by the interaction of production system, soybean cultivar, and herbicide program (Table 6). Palmer amaranth control at harvest in plots treated with flumioxazin plus pyroxasulfone PRE was 95 to 100%. In both full-season and late-season production systems containing glyphosate-resistant soybean, Palmer amaranth control was only 83% at soybean harvest in the absence of a PRE herbicide; hence the need for a PRE herbicide

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Table 8. Palmer amaranth density at soybean harvest as influenced by production system and soybean cultivar, averaged over herbicide program at Marianna, AR in 2012 and 2013.

	Density			
	2012		2013	
	Soybean cultivar			
Production system	Glufosinate resistant	Glyphosate resistant	Glufosinate resistant	Glyphosate resistant
	plants m^{-2}			
Full season[a]	14.4 aA[e]	24.8 aA	0.1 aA	0.3 bA
Full-season tillage[b]	1.7 bA	1.8 bA	0.1 aA	0.0 bA
Late season[c]	6.2 bA	5.6 bA	0.1 aB	1.1 aA
Late-season tillage[d]	0.3 bA	1.9 bA	0.3 aA	0.3 bA

[a] Full season represents no rye and no tillage.

[b] Full-season tillage represents rye in combination with deep tillage using a moldboard plow.

[c] Late season represents no wheat and no tillage.

[d] Late-season tillage represents wheat in combination with deep tillage using a moldboard plow.

[e] Lowercase letters are used to compare production systems within a soybean cultivar for each year and uppercase letters are used to compare soybean cultivars within a production system for each year. Means followed by the same letter, either lowercase or uppercase, are not different according to Fisher's protected LSD test at $\alpha \leq 0.05$.

Table 9. Palmer amaranth seed production at soybean harvest as influenced by production system, averaged over soybean cultivar and herbicide program and as influenced by soybean cultivar, averaged over production system and herbicide program at Marianna, AR in 2012.[a]

Production system	Seed production
	seed m^{-2}
Full season[b]	19,300 A[f]
Full-season tillage[c]	9,100 B
Late season[d]	24,000 A
Late-season tillage[e]	3,900 B
Soybean cultivar	
Glufosinate resistant	10,300 A
Glyphosate resistant	17,900 B

[a] Herbicide program 4 (refer to Materials and Methods for description) was excluded from the analysis because of the lack of seed production, regardless of production system and soybean cultivar.

[b] Full season represents no rye and no tillage.

[c] Full-season tillage represents rye in combination with deep tillage using a moldboard plow.

[d] Late season represents no wheat and no tillage.

[e] Late-season tillage represents wheat in combination with deep tillage using a moldboard plow.

[f] Means followed by the same letter are not different according to Fisher's protected LSD test at $\alpha \leq 0.05$.

in glyphosate-resistant soybean, especially when glyphosate-resistant Palmer amaranth is present. In the full-season tillage and late-season tillage systems having glyphosate-resistant soybean and no PRE residual herbicide, Palmer amaranth control was 94 to 98%. This improved control is a result of deep tillage, which reduced the number of Palmer amaranth plants needing to be controlled by POST applications. Although the Palmer amaranth population in this field was deemed resistant to glyphosate, it should be noted that the population actually contained a mixture of glyphosate-resistant and -susceptible plants; hence, glyphosate supplied some Palmer amaranth control (personal observation).

Palmer amaranth densities at soybean harvest in 2012 and 2013 were influenced by the interaction of production systems and herbicide programs (Table 7). No Palmer amaranth plants were present in the established quadrats after flumioxazin plus pyroxasulfone applied PRE. An interaction of production systems and soybean cultivars was also significant for Palmer amaranth densities at soybean harvest in 2012 and 2013 (Table 8). In 2012, Palmer amaranth density at soybean harvest was reduced more than 65% when tillage was added to full-season or late-season systems. Palmer amaranth densities in 2013 at soybean harvest were lower than in 2012; therefore, the benefit of deep tillage was

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Table 10. Soybean grain yield as influenced by herbicide program and production system, averaged over soybean cultivar at Marianna, AR in 2012 and 2013.

			Soybean grain yield							
			2012				2013			
			Production system							
Herbicide program	Rate	Application timing[a]	Full-season[b]	Full-season tillage[c]	Late season[d]	Late-season tillage[e]	Full season	Full-season tillage	Late season	Late-season tillage
	g ai or aef ha^{-1}		kg ha^{-1}							
Paraquat	700	PRE	210 bA[h]	250 cA	60 bB	70 bB	2230 bA	2540 aA	940 bB	2140 bA
Paraquat	700	PRE	640 bA	1040 bA	430 bA	650 aA	3340 aA	3210 aA	3100 aA	2740 aA
Glufosinate[g]/	595	14 DAP								
glyphosate[f]	870	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP								
Paraquat	700	PRE	380 bA	900 bcA	570 bA	600 aA	4030 aA	3020 aB	3070 aB	2910 aB
Glufosinate/	595	14 DAP								
glyphosate	870	14 DAP								
+ *S*-metolachlor	1,217	14 DAP								
+ fomesafen	266	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP								
+ acetochlor	1,260	28 DAP								
Paraquat	700	PRE	1670 aA	1980 aA	1220 aAB	510 aB	3980 aA	3370 aA	3330 aA	3260 aA
+ flumioxazin	82	PRE								
+ pyroxasulfone	104	PRE								
Glufosinate/	595	14 DAP								
glyphosate	870	14 DAP								
+ *S*-metolachlor	1,217	14 DAP								
+ fomesafen	266	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP								
+ acetochlor	1,260	28 DAP								

[a] Abbreviation: DAP, days after soybean planting.
[b] Full season represents no rye and no tillage.
[c] Full-season tillage represents rye in combination with deep tillage using a moldboard plow.
[d] Late season represents no wheat and no tillage.
[e] Late-season tillage represents wheat in combination with deep tillage using a moldboard plow.
[f] Glyphosate rate is acid equivalent.
[g] Glufosinate used for the glufosinate-resistant soybean cultivar and glyphosate used for the glyphosate-resistant soybean cultivar.
[h] Lowercase letters are used to compare herbicide programs within a production system and uppercase letters are used to compare a production system within a 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 $\alpha \leq 0.05$.

less apparent. The lower Palmer amaranth densities in 2013 than in 2012 are likely due to the soybean achieving a rapid canopy cover in 2013 when ample water was available. Also, early-season Palmer amaranth density in the test site in 2013 was less than that of 2012, which likely contributed to the presence of Palmer amaranth at soybean harvest. Conversely, soybean had limited water in the 2012 growing season. Canopy formation has previously been reported to alter the light environment at the soil surface as well as diurnal temperature fluctuations, both known to influence Palmer amaranth germination (Jha and Norsworthy 2009; Norsworthy 2004).

Palmer amaranth seed production was influenced by the main effects of production system and soybean cultivar in 2012 (Table 9). Full-season tillage and late-season tillage production systems in 2012 had less Palmer amaranth seed production ($\leq$ 9,100 seed m^{-2}) compared with the same production systems without deep tillage ($\geq$ 19,300 seed m^{-2}). Furthermore, Palmer amaranth seed production in 2012 was less for the glufosinate-resistant soybean cultivar (10,300 seed m^{-2}) than for the glyphosate-resistant soybean cultivar (17,900 seed m^{-2}). Jha and Norsworthy (2012) reported that when glufosinate (820 g ha^{-1}) was applied to Palmer amaranth at early reproductive development, seed production was reduced up to 95%.

Palmer amaranth seed production in 2013 was influenced by the interaction of production systems and soybean cultivars. Palmer amaranth seed production in 2013 was 61.3-fold greater in the glyphosate-resistant cultivar compared with the glufosinate-resistant cultivar (data not shown). Palmer amaranth seed production was also greater in the late-season production system (24,500 seed m^{-2}) compared with the remaining production systems ($\leq$ 3,000 seed m^{-2}) for the glyphosate-resistant cultivar. The greater seed production in the late-season production system for the glyphosate-resistant cultivar was due to more Palmer amaranth plants being present at soybean harvest compared with all other production systems for the glyphosate-resistant cultivar (Table 8).

Soybean Grain Yield. A lack of rainfall in 2012 hindered soybean growth and negatively affected soybean grain yield. A two-way interaction between production system and herbicide program, averaged over soybean cultivar, occurred in 2012. Soybean grain yield for all production systems, except the late-season tillage, was at least 90% improved in the presence of PRE-applied flumioxazion plus pyroxasulfone fb POST residual herbicide applications compared with no PRE residual herbicide (Table 10). The low rainfall amounts and competition of Palmer amaranth with soybean for soil moisture is believed to have contributed to the yield limitation in the total POST programs. The importance of early-season weed removal in a year in which soil moisture is limited is of utmost importance in protecting soybean yield potential.

Soybean grain yield in 2013 was influenced by the interaction between production system and herbicide program (Table 10). Unlike 2012, the total POST programs in 2013 resulted in soybean yields equivalent to the PRE residual herbicide program. Although a yield improvement from the PRE residual herbicide was not observed in 2013, PRE residual herbicides provide other benefits in addition to yield protection and are currently recommended for resistance management (Norsworthy et al. 2012).

Rye cover crop fb soybean or wheat double cropped with soybean in combination with moldboard plow tillage can significantly reduce Palmer amaranth densities. When these cultural and mechanical practices are incorporated into a highly efficacious herbicide program like flumioxazin plus pyroxasulfone applied PRE fb POST residual herbicides, Palmer amaranth can be adequately managed with minimal additions to the soil seedbank each fall. Using a diverse system that integrates a multifaceted approach for managing Palmer amaranth and other resistant-prone weeds while focusing on lowering the soil seedbank must be utilized if farmers are to minimize risk of additional weeds evolving herbicide resistance (Norsworthy et al. 2012).

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