

## Influence of Tillage Method on Management of *Amaranthus* Species in Soybean

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A field study was conducted in 2014 and 2015 in Arkansas, Illinois, Indiana, Ohio, Tennessee, Wisconsin, and Missouri to determine the effects of tillage system and herbicide program on season-long emergence of *Amaranthus* species in glufosinate-resistant soybean. The tillage systems evaluated were deep tillage (fall moldboard plow followed by (fb) one pass with a field cultivator in the spring), conventional tillage (fall chisel plow fb one pass with a field cultivator in the spring), minimum tillage (one pass of a vertical tillage tool in the spring), and no-tillage (PRE application of paraquat). Each tillage system also received one of two herbicide programs; PRE application of flumioxazin (0.09 kg ai ha<sup>-1</sup>) fb a POST application of glufosinate (0.59 kg ai ha<sup>-1</sup>) plus S-metolachlor (1.39 kg ai ha<sup>-1</sup>), or POST-only applications of glufosinate (0.59 kg ha<sup>-1</sup>). The deep tillage system resulted in a 62, 67, and 73% reduction in *Amaranthus* emergence when compared to the conventional, minimum, and no-tillage systems, respectively. The residual herbicide program also resulted in an 87% reduction in *Amaranthus* species emergence compared to the POST-only program. The deep tillage system, combined with the residual program, resulted in a 97% reduction in *Amaranthus* species emergence when compared to the minimum tillage system combined with the POST-only program, which had the highest *Amaranthus* emergence. Soil cores taken prior to planting and herbicide application revealed that only 28% of the *Amaranthus* seed in the deep tillage system was placed within the top 5-cm of the soil profile compared to 79, 81, and 77% in the conventional, minimum, and no-tillage systems. Overall, the use of deep tillage with a residual herbicide program provided the greatest reduction in *Amaranthus* species emergence, thus providing a useful tool in managing herbicide-resistant *Amaranthus* species where appropriate.

**Nomenclature:** Flumioxazin; glufosinate; metolachlor; paraquat; *Amaranthus*; soybean, *Glycine max* (L.) Merr.

**Key words:** moldboard plow, vertical tillage, seedbank, soil-applied residual.

En 2014 y 2015, se realizó un estudio de campo en Arkansas, Illinois, Indiana, Ohio, Tennessee, Wisconsin, y Missouri para determinar los efectos del sistema de labranza y el programa de herbicidas sobre la emergencia de especies de *Amaranthus* a lo largo de la temporada de crecimiento en soja resistente a glufosinate. Los sistemas de labranza evaluados fueron labranza profunda (arado de vertedera en el otoño seguido por (fb) un pase de cultivador de campo en la primavera), labranza convencional (arado de cincel en el otoño seguido de un pase de cultivador de campo en la primavera), labranza mínima (un pase de una herramienta de labranza vertical en la primavera), y cero labranza (aplicación PRE de paraquat). Cada sistema de labranza también recibió uno de dos programas de herbicidas; aplicación PRE de flumioxazin (0.09 kg ai ha<sup>-1</sup>) fb glufosinate POST (0.59 kg ai ha<sup>-1</sup>) más S-metolachlor (1.39 kg ai ha<sup>-1</sup>), o sólo aplicaciones POST de glufosinate (0.59 kg ha<sup>-1</sup>). El sistema de labranza profunda resultó en una reducción de 62, 67, y 73% en la emergencia de *Amaranthus* cuando se comparó con los sistemas de labranza convencional, mínima, y cero, respectivamente. El programa con un herbicida residual también resultó en una reducción de 87% en la emergencia de especies *Amaranthus* al compararse con el programa de sólo herbicidas POST. El sistema de labranza profunda, combinado con el programa residual, resultó en una reducción de 97% en la emergencia de especies de *Amaranthus* cuando se comparó con el sistema de labranza mínima combinado con el programa de sólo herbicidas POST, el cual tuvo la mayor emergencia de *Amaranthus*. Muestras de suelo tomadas antes de la siembra y la aplicación de herbicidas revelaron que en el sistema de labranza profunda solamente 28% de las semillas de *Amaranthus*

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fueron localizadas en los 5 cm de suelo superiores del perfil del suelo comparado con 79, 81, y 77% en los sistemas de labranza convencional, mínima, y cero. En general, el uso de labranza profunda con el programa de herbicida residual brindó la mayor reducción en la emergencia de especies de *Amaranthus*, lo que provee una herramienta útil para el manejo de especies de *Amaranthus* resistentes a herbicidas cuando sea apropiado.

The adoption of conservation-tillage practices and glyphosate-resistant (GR) crops over the last several decades has led to an increased reliance on herbicides as one of the primary methods of weed control (Culpepper et al. 2000; DeVore et al. 2013; Krausz et al. 1993; Young 2006). Glyphosate-resistant crops have been rapidly adopted since their release in 1996 and have enabled producers to simplify weed management by providing control of a broad spectrum of common weeds with little or no injury to the crop (Fernandez-Cornejo and McBride 2002). In 1997, only 17% of US soybean hectares were planted with herbicide-resistant varieties (Fernandez-Cornejo and Wechsler 2015). By 2015, 94% of soybean hectares were planted with herbicide-resistant varieties, with the vast majority of those being GR (Fernandez-Cornejo and Wechsler 2015). The continuous use of glyphosate on millions of hectares has led to the selection of GR weed biotypes around the world (Heap 2016). The United States currently has 14 GR weed species, including 3 *Amaranthus* species: Palmer amaranth (*Amaranthus palmeri* S. Wats.), spiny amaranth (*Amaranthus spinosus* L.) and waterhemp (*Amaranthus rudis* Sauer). Among the 14 GR weeds, waterhemp and Palmer amaranth are consistently ranked as two of the most common and persistent weeds in southern and midwestern United States crops, especially in soybean (Beckie 2006; Bradley 2013; Heap 2016; Legleiter and Johnson 2013; Schultz et al. 2015b; Webster and Nichols 2012). The evolution of glyphosate resistance in weeds like Palmer amaranth and waterhemp has increased production costs in soybean and complicated weed management dramatically (Legleiter et al. 2009; Mueller et al. 2005).

Soybean yield losses of 43% have been reported after 10 wk of interference by waterhemp at densities of 89 to 362 plants  $m^{-2}$  (Hager et al. 2002). Palmer amaranth at a density of 8 plants per meter of row that emerged with soybean reduced yields by 79% (Bensch et al. 2003). Currently, Palmer amaranth populations with resistance to six different herbicide modes of action have been confirmed: 5-enolpyruvyl-shikimate-3-phosphate (EPSP) synthase-inhibitors, microtubule-inhibitors, photosystem II-inhibitors, acetolactate

synthase (ALS)-inhibitors, protoporphyrinogen oxidase (PPO)-inhibitors, and 4-hydroxyphenylpyruvate dioxxygenase (HPPD)-inhibitors (Heap 2016). In addition, waterhemp with resistance to six different herbicide modes of action has been reported in the United States: synthetic auxins and EPSP-, ALS-, photosystem II-, PPO-, and HPPD-inhibitors (Heap 2016).

The increase in the occurrence of multiple-herbicide resistance in *Amaranthus* species and other weeds illustrates the need for producers to diversify their weed management practices (Bradley 2013; Norsworthy et al. 2012). Cultural control practices such as tillage can significantly impact weed populations (Norsworthy et al. 2012). Tillage has a large impact on the vertical distribution of weed seed in the soil profile and on weed emergence (Cousens and Moss 1990; Roberts 1963; Starica et al. 1990). Tillage implements that provide deep inversion of the soil place weed seed low enough in the soil profile to prevent successful germination and emergence (DeVore et al. 2013). Shaw et al. (2012) defined inversion tillage as tillage that flips over a layer of soil (often 15 to 30 cm), burying surface residues in the process. Moldboard plowing, a type of inversion tillage, not only kills plants but also can bury >95% of weed seeds at a depth from which most cannot emerge (Douglas and Peltzer 2004; Morris et al. 2010). Swanton et al. (2000) found that moldboard plowing resulted in 63% of weed seeds being concentrated at a depth of 10 to 15 cm. In contrast, Clements et al. (1996) and Pareja et al. (1985) both found that no-tillage systems result in the largest concentration of weed seed being contained in the uppermost layers of soil. However, soil type has also been shown to affect the vertical distribution of weed seed caused by tillage (Swanton et al. 2000). Diversified integrated weed management strategies, including the incorporation of cultural practices such as tillage, narrow row spacing, and increased seeding densities, are among the best management practices currently recommended for the prevention, mitigation, and management of herbicide-resistant weed species (Beckie 2006; Norsworthy et al. 2012; Schultz et al. 2015a).

The initial effectiveness and simplicity of the GR cropping system led many producers to rely solely on POST herbicide applications for weed control in soybean (Powles 2008; Young 2006). As a result, Palmer amaranth and waterhemp have evolved resistance to herbicides that act at many different sites of action, but, at the current time, neither of these species has evolved resistance to glufosinate (Heap 2016). If used appropriately, glufosinate remains an effective POST option for the control of *Amaranthus* species in glufosinate-resistant soybean (Heap 2016; Norsworthy et al. 2008). However, it has been shown that repeated POST-only herbicide applications can lead to the selection of herbicide-resistant weed biotypes (Bradley 2013; Powles 2008). The use of residual herbicide applications, PRE and POST, has been shown to reduce weed densities while also reducing the likelihood of herbicide resistance (Beckie 2006; Bradley 2013; Legleiter et al. 2009; Schultz et al. 2015a).

The effect of tillage systems and residual herbicide programs on the control of GR *Amaranthus* species in glufosinate-resistant soybean has not been researched extensively over a broad range of geographies and soil types. The objectives of this research were to 1) determine the effect of four tillage systems (deep tillage, conventional tillage, minimum tillage, and no tillage), with and without a residual herbicide program, on season-long emergence of *Amaranthus* species in glufosinate-resistant soybean, and to 2) determine the effect of these four tillage systems on the vertical distribution of *Amaranthus* seed in the soil profile.

## Materials and Methods

A field study was conducted in 2014 and 2015 at sites in Randolph County, Missouri; Boone County, Missouri; Washington County, Arkansas; St. Claire County, Illinois; Tippecanoe County, Indiana; Clark County, Ohio; Madison County, Tennessee; and Columbia County, Wisconsin (Table 1). Glufosinate-resistant soybean varieties of an appropriate maturity group were seeded at 321,000 to 432,000 seeds  $\text{ha}^{-1}$  in rows spaced 76 to 91 cm apart, depending upon location. Specific site information, such as previous crop production history, crop information, and soil type, is provided in Table 1. Monthly rainfall totals are presented in Table 2.

Treatments were arranged as a split-plot design with four replications, where tillage system was the

main plot and herbicide program was the subplot, arranged in a randomized complete block design. Four tillage regimes were evaluated: 1) a fall tillage pass of a moldboard plow followed by a pass with a field cultivator in the spring, referred to as the deep-tillage treatment; 2) a fall pass with a chisel plow followed by a pass with a field cultivator in the spring, referred to as the conventional-tillage treatment; 3) a single pass of a vertical tillage tool in the spring, referred to as the minimum-tillage treatment; and 4) a no-tillage treatment that received a burndown herbicide treatment of paraquat ( $0.84 \text{ kg ha}^{-1}$ ) near the time of the spring tillage treatments. Dates of major field operations for each site are provided in Table 1. Each tillage treatment received one of two herbicide programs: 1) a PRE application of flumioxazin ( $0.09 \text{ kg ha}^{-1}$ ) followed by a POST application of glufosinate ( $0.59 \text{ kg ha}^{-1}$ ) plus S-metolachlor ( $1.39 \text{ kg ha}^{-1}$ ), referred to as the residual herbicide program, or 2) POST-only applications of glufosinate ( $0.59 \text{ kg ha}^{-1}$ ), referred to as the POST-only herbicide program. The specific herbicide formulations utilized are listed in Table 3. All herbicide treatments were applied with a  $\text{CO}_2$ -pressurized backpack sprayer calibrated to deliver  $140 \text{ L ha}^{-1}$ . Treatments were applied at a constant speed of  $5 \text{ km hr}^{-1}$ . PRE treatments were applied at or just prior to planting. POST application for the residual herbicide program was applied 21 d after planting, and the first POST application for the POST-only herbicide program was applied approximately 14 d after planting.

**Field Densities.** *Amaranthus* species emergence was monitored every 14 d from planting up to the R6 soybean stage or senescence by counting all plants within two  $1\text{-m}^2$  quadrats between the center two rows of soybean. The location of each quadrat was permanently marked to ensure counts occurred in the same area for the duration of the experiment. Immediately after each weed count was completed, the entire area was treated with glufosinate ( $0.59 \text{ kg ha}^{-1}$ ) and then monitored for surviving weeds.

**Vertical Seed Distribution.** Vertical distribution of *Amaranthus* seed in the soil profile was determined by taking six 2.5 by 25 cm soil cores randomly from each plot utilizing 2.9-cm diameter soil recovery probes (AMS Inc., American Falls, ID). Soil probes were fitted with 2.5 by 30.5 cm acetate sleeves

Table 1. Site characteristics for field trials conducted in 2014 and 2015.<sup>a</sup>

Test site	Year	Soil properties				Tillage dates		Soybean variety	Plant population	Planting date
		Texture	OM	pH	CEC	Fall <sup>b</sup>	Spring			
			%						seeds ha <sup>-1</sup>	
AR <sup>c</sup>	2014	silt loam	1.8	5.8	11.7	10/18/13	6/4/14	Pioneer <sup>®</sup> 95L01	388,000	6/4/14
	2015	silt loam	1.8	5.8	11.7	9/30/14	6/26/15	Credenz <sup>®</sup> LL4748	321,000	5/26/15
IL <sup>d</sup>	2014	silt loam	3.0	6.1	12.0	10/28/13	5/28/14	Pioneer <sup>®</sup> P43T41L	346,000	5/28/14
	2015	silt loam	3.4	5.9	13.0	10/27/14	5/22/15	Pioneer <sup>®</sup> P43T41L	346,000	5/22/15
IN <sup>e</sup>	2014	silt loam	2.3	6.5	14.3	12/9/13	5/6/14	Beck's 298NL	345,000	5/8/14
	2015	silt loam	2.3	6.5	14.3	3/24/15	5/14/15	Beck's 298NL	345,000	5/14/15
MO 1 <sup>f</sup>	2014	silt loam	2.1	6.4	11.0	10/28/13	5/6/14	MorSoy LL3759N	432,000	5/7/14
	2015	silt loam	2.0	6.3	10.5	4/1/15	6/11/15	MorSoy LL3759N	432,000	6/12/15
MO 2 <sup>g</sup>	2014	silt loam	1.9	6.3	9.80	10/27/13	5/6/14	MorSoy LL3759N	432,000	5/21/14
	2015	silt loam	1.6	5.9	9.10	4/17/15	5/12/15	MorSoy LL3759N	432,000	5/13/15
OH <sup>h</sup>	2014	silty clay loam	2.8	5.9	17.4	11/13/13	5/29/14	Pioneer <sup>®</sup> 34T35L	408,000	5/29/14
	2015	silty clay loam	3.4	6.4	22.5	10/27/14	5/14/15	Pioneer <sup>®</sup> 34T35L	370,000	5/14/15
TN <sup>i</sup>	2014	silt loam	-	-	-	10/15/13	5/2/14	Hornbeck 4950	346,000	5/6/14
	2015	silt loam	-	-	-	10/23/14	5/4/15	Hornbeck 4950	346,000	5/5/15
WI <sup>j</sup>	2014	silt loam	2.9	7.1	-	-	-	Tracy's 2513 LL	346,000	5/22/14
	2015	silt loam	3.1	7.1	-	-	-	Tracy's 2513 LL	346,000	5/21/15

<sup>a</sup> Abbreviations: CEC, cation exchange capacity (meq per 100 g soil); OM, organic matter.

<sup>b</sup> Due to excessive soil moisture at and following harvest, some fall-tillage operations were not able to be completed until the following spring.

<sup>c</sup> Fayetteville, Arkansas. Arkansas Agriculture Research and Extension Center, University of Arkansas (36.092996°N, 94.173423°W). Site has been in small-plot research with conventional tillage for the past 50 yr.

<sup>d</sup> Belleville, Illinois. Belleville Research Center, Southern Illinois University (38.521476°N, 89.845294°W). Small-plot research for more than 7 yr. No deep tillage for at least 30 yr.

<sup>e</sup> Lafayette, Indiana. Throckmorton Purdue Agricultural Center, Purdue University (40.271114°N, 86.881163°W). Research plots with conventional tillage for at least 9 yr.

<sup>f</sup> Columbia, Missouri. Bradford Research and Extension Center, University of Missouri (38.898432°N, 92.216371°W). Small-plot research for 50 yr. Conservation agriculture at least 12 yr.

<sup>g</sup> Moberly, Missouri. Resistant Waterhemp Research Site, University of Missouri (39.302782°N, 92.369678°W). Continuous soybean production for at least 12 yr. Conservation agriculture the past 15 years. Confirmed presence of waterhemp populations resistant to glyphosate and protoporphyrinogen oxidase- and acetolactate synthase-inhibiting herbicides.

<sup>h</sup> South Charleston, Ohio. Western Agricultural Research Station, Ohio State University (39.8593°N, 83.66971°W). Small-plot research more than 20 yr. Conventional tillage annually.

<sup>i</sup> Jackson, Tennessee. West Tennessee AgResearch and Education Center, University of Tennessee (35.624655°N, 88.845096°W). No deep tillage for at least 30 yr. Mostly no-till practices.

<sup>j</sup> Arlington, Wisconsin. Arlington Agricultural Research Station, University of Wisconsin (43.307943°N, 89.350072°W). Agronomy research for more than 10 yr. Chisel plowing (25 cm) occurred once, two years prior to initiation of this study.

(AMS Inc.). Soil cores were taken after the spring tillage operations prior to planting and herbicide application. Soil cores from all sites were packaged with dry ice and shipped overnight to the University of Missouri–Columbia, where they were stored at -9 C until processing.

Each soil core was divided into following segments by soil profile depth, with zero representing the soil surface: 0 to 1 cm, 1 to 5 cm, 5 to 10 cm, 10 to 15 cm, 15 to 20 cm, and 20 to 25 cm. Each segment was placed as a topsoil layer in an individual 8 by

6 by 6 cm insert cell in a 28 by 56 cm greenhouse flat (Hummert International™, Earth City, MO) that had previously been three-quarters filled with commercial potting medium (Premier Tech Horticulture, Quakertown, PA). Plants were maintained in a greenhouse at 25 to 30 C, watered and fertilized as needed, and provided with artificial light from metal halide lamps (600 μmol photon m<sup>-2</sup> s<sup>-1</sup>) simulating a 16-h photoperiod. Seedling emergence was monitored over a 3-mo period. Emerged weed seedlings were counted and identified to species every

Table 2. Monthly rainfall (mm) from April through October in 2014 and 2015 at all trial locations. The 30-yr monthly rainfall averages are provided for comparison.<sup>a</sup>

Site	Year	Monthly rainfall						
		mm						
		Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.
AR <sup>b</sup>	2014	87	137	113	35	66	114	166
	2015	81	169	175	269	68	47	58
	30-yr avg <sup>j</sup>	109	132	121	82	77	116	104
IL <sup>c</sup>	2014	165	45	129	34	176	95	108
	2015	91	211	243	99	108	68	24
	30-yr avg	98	124	108	103	84	83	87
IN <sup>d</sup>	2014	95	111	89	83	112	68	159
	2015	102	109	211	177	45	73	43
	30-yr avg	87	118	116	104	100	71	69
MO1 <sup>e</sup>	2014	210	78	129	37	75	156	259
	2015	84	144	192	213	80	29	27
	30-yr avg	114	138	132	115	114	109	85
MO2 <sup>f</sup>	2014	156	64	141	92	120	64	203
	2015	65	119	299	223	73	20	43
	30-yr avg	104	131	130	122	106	110	84
OH <sup>g</sup>	2014	137	110	165	100	83	32	37
	2015	122	52	223	132	73	35	69
	30-yr avg	91	115	109	104	79	67	71
TN <sup>h</sup>	2014	118	107	278	93	151	185	135
	2015	152	126	136	118	111	90	70
	30-yr avg	120	141	126	122	78	89	101
WI <sup>i</sup>	2014	164	71	238	48	95	45	70
	2015	162	112	80	80	110	145	50
	30-yr avg	88.9	94	119	106	99	90	65

<sup>a</sup> Abbreviations: avg, average.

<sup>b</sup> Fayetteville, Arkansas. Arkansas Agriculture Research and Extension Center, University of Arkansas (36.092996°N, 94.173423°W). Site has been in small-plot research with conventional tillage for the past 50 yr.

<sup>c</sup> Belleville, Illinois. Belleville Research Center, Southern Illinois University (38.521476°N, 89.845294°W). Small-plot research for more than 7 yr. No deep tillage for at least 30 yr.

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<sup>j</sup> Thirty-year averages (1982 to 2011) obtained from the National Climatic Data Center (2016).

14 d, then removed from the flats after counting. After 3 mo of monitoring in the greenhouse, the flats were removed and stored in the dark at -9 C for 3 mo

of cold stratification. After cold treatment, flats were returned to the greenhouse and the soil in each cell was stirred by hand. Flats were monitored for weed

Table 3. Sources of materials used in the experiments.

Herbicide	Trade name	Formulation <sup>a</sup>	Rate	Manufacturer	Address
			kg ai ha <sup>-1</sup>		
Paraquat	Gramoxone Inteon <sup>®</sup>	2.0 SL	0.84	Syngenta	Greensboro, NC
Flumioxazin	Valor <sup>®</sup>	51 WDG	0.09	Valent USA	Walnut Creek, CA
S-metolachlor	Dual II Magnum <sup>®</sup>	7.64 EC	1.39	Syngenta	Greensboro, NC
Glufosinate	Liberty <sup>®</sup>	280 SL	0.59	Bayer CropScience	Research Triangle Park, NC
Ammonium sulfate	N-Pak <sup>®</sup> AMS	3.4 L	2.9	Winfield Solutions	St. Paul, MN

<sup>a</sup> Abbreviations: EC, emulsifiable concentrate; L, liquid; SL, soluble (liquid) concentrate; WDG, water-dispersible granule.

emergence for an additional 2 mo using the same photoperiod and temperature as before.

To ensure that the density of *Amaranthus* was adequate to compare treatments, field count data were only included in the statistical analysis if cumulative *Amaranthus* densities were greater than 300 plants per trial (12 of 16 site-years), and vertical distribution data were only included in the statistical analysis if *Amaranthus* densities were greater than 32 plants per trial (5 of 14 site-years; no cores were taken from the Ohio location). *Amaranthus* species density data from the field and vertical distribution data from the soil cores were analyzed separately using the PROC GLIMMIX procedure in SAS<sup>®</sup> version 9.4 (SAS Institute Inc., Cary, NC). Count data were transformed using a negative binomial function to satisfy Pearson's chi-square. Data were back-transformed for presentation. Replicate, tillage system, and herbicide program were considered fixed effects for the field count data. Replicate and tillage system were considered fixed effects for the soil core data. Site-year combinations were analyzed as if they were random samples taken from the same environment, and site-years with adequate weed densities were combined for analysis (Blouin et al. 2011; Carmer et al. 1989). Individual treatment differences were separated using Fisher's protected LSD at  $P \leq 0.05$ . Significant differences were present in the field between tillage systems ( $P < 0.0001$ ; Figure 1), herbicide programs ( $P < 0.0001$ ), and tillage system – herbicide program combinations ( $P = 0.04$ ; Figure 2). Significant differences were also present in the greenhouse studies between tillage system and soil profile depth ( $P < 0.0001$ ; Figure 3). In Indiana, only two tillage systems were evaluated: conventional tillage and no tillage. Data from Indiana were analyzed separately using the same procedure that was used for the other sites. Significant differences were noted in

the field studies in Indiana between tillage systems ( $P < 0.0068$ ) and herbicide programs ( $P < 0.0001$ ), but not between tillage system – herbicide program combinations ( $P = 0.7133$ ; data not shown). No significant differences were found between tillage system and soil profile depth for the soil cores taken from Indiana ( $P = 0.2061$ ; data not shown).

## Results and Discussion

The deep-tillage system resulted in a 62%, 67%, and 73% reduction in *Amaranthus* emergence compared with the conventional-, minimum-, and no-tillage systems, respectively, when averaged over all sites except Indiana (Figure 1). The conventional-tillage system resulted in a 28% reduction in *Amaranthus* species emergence compared with the no-tillage system, but emergence was similar in the minimum- and no-tillage

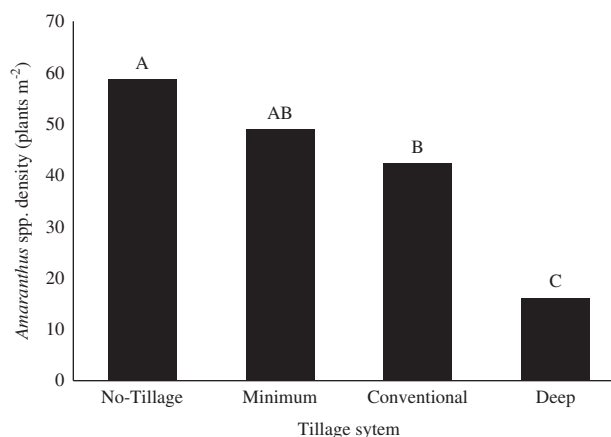


Figure 1. Influence of tillage method on *Amaranthus* species emergence across 10 site-years in Arkansas, Illinois, Missouri, Ohio, and Tennessee. Bars with the same letter are not different, LSD (0.05).

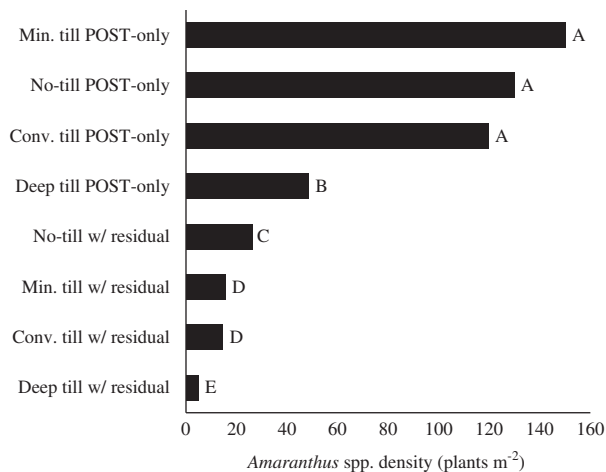


Figure 2. Influence of tillage treatment and herbicide program on *Amaranthus* species emergence in the field across 10 site-years in Arkansas, Illinois, Missouri, Ohio, and Tennessee. Min. till: minimum tillage; Conv. till: conventional tillage. Bars followed by the same letter are not different, LSD (0.05).

systems. Across both years in the experiment conducted in Indiana, there was a significant difference between the conventional- and no-tillage systems. In Indiana the conventional-tillage system resulted in a 64% reduction in emergence compared with the no-tillage system when averaged over all years, with 22 and 60 emerged plants m<sup>-2</sup>, respectively. The reason for the difference in results between Indiana and the other sites with regard to the relative effectiveness of the conventional and no-tillage systems is not readily apparent. Previous research utilizing similar treatments found that tillage systems that utilize a chisel plow (conventional treatment in this

study) resulted in the majority of weed seed remaining high in the soil profile, similar to no tillage (Ball 1992; Clements et al. 1996; Pareja et al. 1985; Yenish et al. 1992). A reduction in *Amaranthus* species emergence as a result of deep tillage was also observed in a study in Arkansas comparing effects of deep-tillage and no-tillage treatments on Palmer amaranth emergence (DeVore et al. 2013). DeVore et al. (2013) found that deep tillage in an early soybean production system reduced Palmer amaranth emergence by 97% compared with no tillage, while deep tillage in a full-season soybean production system reduced Palmer amaranth emergence by 70% compared with no tillage. The level of Palmer amaranth reduction reported by DeVore et al. is similar to the 73% reduction in *Amaranthus* species emergence observed in this multi-state study (Figure 1). In another study with Palmer amaranth in Arkansas, Bell et al. (2015) found that 14 d after planting soybean in a deep-tillage treatment, Palmer amaranth densities were reduced by 94% to 95% in one year and 73% to 87% in another. Similar results have also been observed in Iowa, where moldboard and chisel plow treatments each decreased waterhemp emergence 4-fold compared with the no-tillage treatments (Leon and Owen 2006). The reduction in *Amaranthus* species emergence in deep- and conventional-tillage systems compared with no-tillage systems can be explained by the less favorable conditions for germination and seedling establishment for small-seeded weeds like *Amaranthus* when the seeds are buried deeper in the soil profile (Felix and Owen 1999; Hoffman et al. 1998; Webster et al. 1998; Yenish et al. 1992).

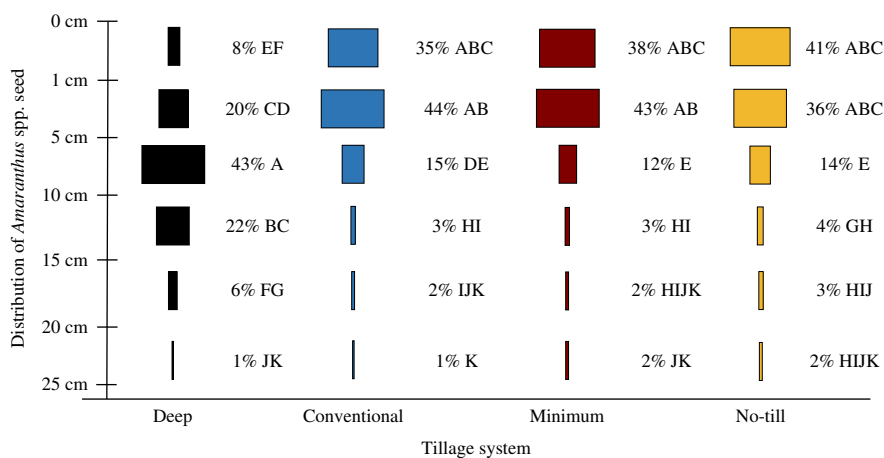


Figure 3. Influence of tillage method on the vertical distribution of *Amaranthus* species seeds in the soil profile. Results combined across the Missouri and Illinois sites. Each bar proportionally represents the average number of *Amaranthus* species that emerged from each soil core segment. Percentages followed by the same letter are not different, LSD (0.05).

The residual herbicide program resulted in an 87% reduction in *Amaranthus* species emergence compared with the POST-only program, when averaged over all except the Indiana sites, with 13 and 103 plants m<sup>-2</sup>, respectively. For the Indiana sites, the residual program resulted in a 98% reduction in emergence compared with the POST-only program, with 5 and 232 plants m<sup>-2</sup> emerged, respectively. These results are similar to those reported by Schultz et al. (2015a), where a PRE fb POST with residual program had greater waterhemp density reduction (99%) than two-pass POST-only applications of glufosinate (72%) when compared to the non-treated control. Similar results have been observed across 4 site-years in Missouri in a study of herbicide programs in glufosinate-resistant soybean, where a residual program resulted in 93% control of waterhemp while two-pass POST-only program using glufosinate resulted in only 74% control (Craigmyle et al. 2013). In a study with GR waterhemp in Missouri, Legleiter et al. (2009) observed 97% and 98% GR waterhemp density reductions with residual herbicide programs, but less than 40% reduction with POST-only programs. Use of PRE herbicide applications of metolachlor plus metribuzin have also been shown to provide much higher economic returns than POST-only applications of glyphosate when GR weeds are present (Legleiter et al. 2009). These results support the recommendation to plant into fields that are weed-free and to keep them weed-free by utilizing residual herbicide applications before and/or after planting (Norsworthy et al. 2012), thus reducing the selection pressure for resistance to POST-only herbicides (Neve et al. 2003; Neve et al. 2011).

We observed an interaction between tillage system and herbicide program at all sites except the Indiana sites. The lowest emergence of *Amaranthus* species occurred with the combination of deep tillage and residual herbicide program (Figure 2). The combination of any tillage system with residual herbicides resulted in less *Amaranthus* emergence than the combination of any tillage system and the POST-only herbicide program. There were no differences in *Amaranthus* species emergence among the conventional-, minimum-, and no-tillage systems where the POST-only herbicide program was used. The deep-tillage system in combination with the residual herbicide program resulted in a 97% reduction in *Amaranthus* species emergence compared with the

minimum-tillage system combined with the POST-only program, which resulted in the highest *Amaranthus* species emergence. Similar results were observed in an Arkansas study with an application of flumioxazin plus pyroxasulfone (3-[[5-(difluoromethoxy)-1-methyl-3-(trifluoromethyl)pyrazol-4-yl]methylsulfonyl]-5,5-dimethyl-4H-1,2-oxazole) applied PRE in combination with deep tillage (Bell et al. 2015). This combination resulted in >98% Palmer amaranth control in both years of the study, and the authors concluded that deep tillage resulted in fewer Palmer amaranth plants present at the times of the POST herbicide applications (Bell et al. 2015). DeVore et al. (2013) concluded that adding a residual herbicide program to a deep-tillage early soybean production system would further reduce Palmer amaranth emergence, providing even greater control. The results of this research support this conclusion, as the deep-tillage system with the addition of a residual herbicide program provided the greatest reduction of *Amaranthus* species emergence across the major soybean-producing area in the United States (Figure 2).

**Vertical Distribution of *Amaranthus* Seed.** The conventional-, minimum-, and no-tillage systems resulted in similar *Amaranthus* species emergence from all soil depths (Figure 3). These results were also observed in a separate analysis across both years in Indiana in a comparison of the conventional and no-tillage systems ( $P = 0.2061$ , data not shown). The deep-tillage system resulted in lower *Amaranthus* species emergence at the 0 to 1 cm, 5 to 10 cm, 10 to 15 cm, and 15 to 20 cm depths compared with the other tillage systems. Seventy-two percent of the *Amaranthus* seeds in the deep-tillage system were located deeper than 5 cm. These results are similar to those reported by Nichols et al. (2015), who utilized previous tillage research (Dorado et al. 1999; Mohler 1993) to predict that moldboard plowing would place the majority of seeds within the 5 to 15 cm soil profile range. Swanton et al. (2000) also reported that moldboard plowing resulted in less uniform vertical weed seed distribution in locations with sandy soils, but that 63% of the seeds were concentrated at depths of 10 to 15 cm. The results from this study indicate that 28% of the *Amaranthus* seeds were placed in the top 5 cm of the soil profile by deep tillage. In contrast, 79%, 81%, and 77% of the *Amaranthus* seed in the conventional-, minimum-, and no-tillage systems was located in the top 5 cm of



the soil profile, respectively. These results are comparable to other studies, conducted across multiple soil types, that found that the majority of weed seed was located in the top 5 cm of the soil after conventional-, minimum-, and no-tillage treatments (Clements et al. 1996; Pareja et al. 1985; Swanton et al. 2000; Yenish et al. 1992). For example, Swanton et al. (2000) reported that 90% of the weed seedbank was concentrated in the top 5 cm of soil in a no-tillage system.

Based on the results of this research, deep-tillage systems utilizing a one-time inversion tillage implement, such as a moldboard plow, provide the greatest reduction in *Amaranthus* species emergence when compared with conventional-, minimum-, and no-tillage systems. However, deep-tillage systems are prone to increased soil erosion as well and can incur higher fuel and labor costs (Logan et al. 1987). Reducing tillage intensity through conservation-tillage practices has been shown to reduce soil erosion and water runoff (Baumhardt and Lascano 1996; Reeves 1997) and increase soil organic matter, soil water-holding capacity, the quantity and diversity of soil organisms, and water infiltration (Bruce et al. 1992; Heisler 1998; Kemper and Derpsch 1981; Reeves 1997; Truman et al. 2003). Therefore, producers will need to weigh all of the potential risks, costs, and benefits before making a decision on either system. The results from this research also illustrate the effectiveness of a residual herbicide program when used in either tillage system. The incorporation of a residual herbicide, particularly a PRE herbicide prior to soybean planting, has been shown to provide better control and density reduction of *Amaranthus* species, as well as greater economic benefit, than POST-only programs (Legleiter et al. 2009; Schultz et al. 2015a). The combination of a residual herbicide program and a deep-tillage system provided the greatest reduction in *Amaranthus* species emergence throughout the season. These results support the recommendation to combine effective cultural practices with residual herbicide programs; using both together has been shown to be more effective than utilizing any one management technique alone (Norsworthy et al. 2012; Schultz et al. 2015a). As herbicide-resistant *Amaranthus* species become more prevalent throughout US soybean production systems, integrating cultural practices such as tillage, where appropriate, with residual herbicide programs that utilize multiple, effective

sites of action can provide substantial reductions in herbicide-resistant *Amaranthus* species in soybean.

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