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Acetochlor; flumioxazin; pyroxasulfone; *S*-metolachlor; Palmer amaranth, *Amaranthus palmeri* S. Wats.; waterhemp, *Amaranthus tuberculatus* (Moq) Sauer; cereal rye, *Secale cereale* L.; hairy vetch, *Vicia villosa* Roth; soybean, *Glycine max* (L.) Merr.

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Efficacy of residual herbicides influenced by cover-crop residue for control of *Amaranthus palmeri* and *A. tuberculatus* in soybean

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Abstract

Field studies were conducted in 2018 and 2019 in Arkansas, Indiana, Illinois, Missouri, and Tennessee to determine if cover-crop residue interfered with herbicides that provide residual control of Palmer amaranth and waterhemp in no-till soybean. The experiments were established in the fall with planting of cover crops (cereal rye + hairy vetch). Herbicide treatments consisted of a nontreated or no residual, acetochlor, dimethenamid-P, flumioxazin, pyroxasulfone + flumioxazin, pendimethalin, metribuzin, pyroxasulfone, and *S*-metolachlor. Palmer amaranth took 18 d and waterhemp took 24 d in the cover crop–alone (nontreated) treatment to reach a height of 10 cm. Compared with this treatment, all herbicides except metribuzin increased the number of days until 10-cm Palmer amaranth was present. Flumioxazin applied alone or in a mixture with pyroxasulfone were the best at delaying Palmer amaranth growing to a height of 10 cm (35 d and 33 d, respectively). The herbicides that resulted in the lowest Palmer amaranth density (1.5 to 4 times less) integrated with a cover crop were pyroxasulfone + flumioxazin, flumioxazin, pyroxasulfone, and acetochlor. Those four herbicide treatments also delayed Palmer amaranth emergence for the longest period (27 to 34 d). Waterhemp density was 7 to 14 times less with acetochlor than all the other herbicides present. Yield differences were observed for locations with waterhemp. This research supports previous research indicating that utilizing soil-residual herbicides along with cover crops improves control of Palmer amaranth and/or waterhemp.

Introduction

Winter-annual cover crops have become more readily used as a soil conservation practice across the United States. This conservation technique has been proven to improve soil quality, increase soil organic matter, conserve soil moisture, reduce soil erosion, and provide early-season weed suppression when implemented in an agronomic cropping system (Reddy 2001b; White and Worsham 1990). Winter-annual grasses and legumes have been planted as cover crops in soybean, cotton (*Gossypium hirsutum* L.), and corn (*Zea mays* L.) (Reddy 2001b; White and Worsham 1990). Cover crops have been documented to provide early-season weed suppression by both physical and chemical interference (Barnes and Putnam 1986; Reddy 2001b; Teasdale and Mohler 2000). According to a recent United States Department of Agriculture survey, two-thirds of growers who planted a cereal rye cover crop have noticed improved control of multiple herbicide–resistant weeds across the United States (SARE 2017). Research has shown that cover-crop residues are allelopathic, that is, they release phytotoxins that inhibit germination and early growth of some weed species (Blackshaw et al. 2001; Davis and Liebman 2003; Yenish et al. 1996). In light of the uncertainty about the commercialization of new herbicide sites of action, the need for biological, cultural, and mechanical weed control measures is paramount (Heap 2018; Norsworthy et al. 2012). The integration of these cover crops with new herbicide-resistant crops can be effective alternatives for managing multiple herbicide–resistant *Amaranthus* spp. and other problematic weeds (Cahoon et al. 2015; Culpepper et al. 2000; DeVore et al. 2013; Montgomery et al. 2017; Ryan et al. 2011; Wiggins et al. 2015, 2016).

Palmer amaranth is the most troublesome and economically damaging summer-annual weed across the mid-South (Beckie 2011; Van Wychen 2016). Palhano et al. (2017) reported that cereal rye cover-crop plots had 83% less Palmer amaranth emergence compared with plots

Table 1. Details of field experiments conducted in multiple states to evaluate efficacy of residual herbicides influenced by cover-crop residue for control of *Amaranthus* spp. in soybean.

	Location	Soil organic matter	Soil	Soil texture	Cover-crop planting	Soybean planting
Location	Decimal Degrees	%	pH		Dates	Dates
Fayetteville, AR	36.06°N, 94.14°W	2.1	5.6	Silt–loam	Oct 8, 2017 and Oct 13, 2018	May 28, 2018 and May 20, 2019
Farmland, IN	40.12°N, 85.09°W	3.3	6.3	Silty–Clay–Loam	Oct 27, 2017 and Oct 22, 2018	May 17, 2018 and June 7, 2019
Carbondale, IL	37.44°N, 89.06°W	1.7	7.3	Silt–loam	Oct 9, 2017 and Oct 25, 2018	May 10, 2018 and May 18, 2019
Urbana, IL	40.08°N, 88.26°W	3.6	6.1	Silty–Clay–Loam	Oct 26, 2017	May 22, 2018
Columbia, MO	38.58°N, 92.13°W	2.4	5.5	Silt–Loam	Oct 25, 2018	May 16, 2019
Jackson, TN	35.38°N, 88.41°W	2.7	6.1	Silt–Loam	Oct 7, 2017 and Oct 12, 2018	May 10, 2018 and May 31, 2019

with no cover crop. Wiggins et al. (2016) reported 20% greater control of Palmer amaranth when integrating multiple cover-crop species with glufosinate and glyphosate in cotton. Palmer amaranth biotypes have evolved resistance to six different herbicide sites of action in agronomic crops in the United States (Heap 2018). Therefore, successful herbicide programs must focus on use of multiple, effective herbicide sites of action and sequential applications of residual herbicides for season-long control of *Amaranthus* spp. (Cahoon et al. 2015; Riar et al. 2013).

Waterhemp is another annual *Amaranthus* species that demonstrates a very rapid growth rate and can be very competitive with crops––specifically, soybean (Horak and Loughin 2000). When Palmer amaranth and waterhemp emerged at a density of 8 weeds m^{-2}, soybean yield was reduced 78% and 56%, respectively (Bensch et al. 2003). Waterhemp at a density of 42 plants m^{-2} reduced soybean yield by 10% when they emerged as late as the V4 soybean growth stage (Steckel and Sprague 2004a).

Cover crops have been adopted for use as a conservation practice, because cover crops have been documented to increase soil quality, increase soil organic matter, increase soil moisture retention, reduce erosion, and provide supplemental weed control (Hartwig and Hoffman 1975). Cereal rye and winter wheat (*Triticum aestivum* L.) are commonly used winter-annual grass cover crops that reduce pressure of several weed species (Moore et al. 1994). Two legume cover crops, hairy vetch and crimson clover (*Trifolium incarnatum* L.), have been investigated for weed suppression as well as their ability to biologically fix atmospheric nitrogen that becomes available for the subsequent crop (Duck and Tyler 1996; Fisk et al. 2001; Norsworthy et al. 2014). Winter-annual grasses and legumes have been implemented in several crops, such as corn, cotton, and soybean (Reddy 2001b; White and Worsham 1990). Although cover crops suppress many winter-annual weed during the early spring, cover-crop residues typically do not provide adequate in-season weed control for agronomic crops (Teasdale and Mohler 2000. Thus, herbicides are commonly needed alongside cover-crop residues to achieve adequate weed control.

Previous research has shown that the use of residual herbicides in cover crops prolong in-season weed control (Cornelius and Bradley 2017; Wiggins et al. 2016). Herbicides that are applied PRE can reduce early-season weed interference and often improve season-long control of *Amaranthus* spp. (Culpepper and York 1998; Keeling et al. 2006; Reddy 2001a; Toler et al. 2002; Whitaker et al. 2008). Residual herbicides applied PRE are actively promoted to aid management of glyphosate-resistant *Amaranthus* spp. and to delay further evolution of resistance (Steckel 2020; Stephenson et al. 2008; York and Culpepper 2009). The research reported here was conducted to determine the potential efficacy of different soil-residual herbicides on Palmer amaranth and waterhemp in the presence of cover-crop residue and develop recommendations for the best residual herbicides for use in cover-crop systems where soybean is the crop.

Table 2. Herbicide active ingredient and application rates based on soil texture and organic matter content applied in field experiments conducted in multiple states to evaluate efficacy of residual herbicides influenced by cover-crop residue for control of *Amaranthus* spp. in soybean.

Herbicide active ingredient	Trade name	Application rate	Manufacturer
		g ai ha^{-1}	
Acetochlor	Warrant	1,260	Bayer Crop Sciences
Dimethenamid-P	Outlook	840	BASF Corp.
Flumioxazin	Valor	72	Valent U.S.A. Corp.
Metribuzin	Tricor	630	UPI
Pendimethalin	Satellite	1,060	UPI
Pyroxasulfone	Zidua	1.4	BASF Corp.
Pyroxasulfone + flumioxazin	Fierce	42.5 + 33.5	Valent U.S.A. Corp.
S-metolachlor	Dual Magnum	1,070	Syngenta Crop Protection, Inc.

Materials and Methods

This experiment was conducted in 10 environments total across the mid-South. The environments were located in Fayetteville, AR, Jackson, TN, Farmland, IN, and Carbondale, IL in 2018 and 2019; in Champaign, IL in 2018; and in Columbia, MO in 2019. Palmer amaranth was the recorded species in Tennessee and Arkansas. Waterhemp was the recorded species in Missouri, Illinois, and Indiana. The coordinates for each location can be referenced in Table 1.

The experimental design was a randomized complete block with nine treatments replicated four times in plots 3 m wide and 9.1 m long. Cover crops were planted in the previous fall in 18-cm row spacings and consisted of cereal rye at a rate of 67 kg ha^{-1} plus hairy vetch at a rate of 8 kg ha^{-1}. Cover-crop species and planting rates were selected as suggested by Wiggins et al. (2016, 2017). Cover-crop planting dates, soybean planting dates, and soil characteristics for each site can be found in Table 1. Cover crops were terminated 3 wk pre-plant with an application of glyphosate at 1,260 g ae ha^{-1} + dicamba at 560 g ae ha^{-1}. Soybeans were planted in 75-cm-wide rows to varieties that were Liberty Link (glufosinate resistant). Treatments consisted of a nontreated or no-residual plot, acetochlor, dimethenamid-P, flumioxazin, metribuzin, pendimethalin, pyroxasulfone, pyroxasulfone + flumioxazin, and *S*-metolachlor. Application rates were based on label specification for those herbicides. Active ingredient, trade names, and rates can be found in Table 2. Treatments were

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Table 3. The effect of cover crop (cereal rye + hairy vetch) with and without soil-residual herbicide on number of days required for *Amaranthus* spp. to reach 10-cm height, density, and soybean yield during field experiments conducted in multiple states to evaluate efficacy of residual herbicides influenced by cover-crop residue for control of *Amaranthus* spp. in soybean.

	Days to 10 cm tall		Density[a] at 10 cm tall		Densities 7 d after reaching 10 cm tall		Plant heights 7 d after reaching 10 cm tall		Soybean yield	
Herbicide	Palmer amaranth	Waterhemp	Palmer amaranth	Waterhemp	Palmer amaranth	Waterhemp	Palmer amaranth	Waterhemp	Palmer[c] amaranth	Waterhemp[d]
	—days—		—plants m^{-2}—		—plants m^{-2}—		——cm——		—kg ha^{-1}—	
Pyroxasulfone + flumioxazin	35 a[b]	34 a	9 c	114 b	11 bc	63 d	16	11.8 e	2,300	3,600 a
Flumioxazin	33 ab	34 a	5 c	112 b	6 c	86 cd	19	15.5 cde	2,400	3,700 a
Pyroxasulfone	29 bc	34 a	12 c	107 b	24 bc	74 d	18	12.1 e	2,300	3,700 a
Acetochlor	27 cd	–	13 c	16 c	20 bc	102 bcd	19	14.4 de	2,400	3,600 ab
Dimethenamid-P	26 cd	30 b	20 bc	178 ab	30 ab	135 abc	17	15.4 cde	2,400	3,400 b
S-metolachlor	26 cd	30 b	20 bc	235 a	33 ab	161 ab	20	17.8 bcd	2,500	3,600 ab
Pendimethalin	25 cd	24 c	20 bc	149 ab	20 bc	144 abc	25	19.3 ab	2,600	3,700 a
Metribuzin	22 de	30 b	22 b	214 a	26 bc	112 bcd	20	18.9 bc	2,500	3,400 b
No residual	18 e	24 c	87 a	205 a	50 a	180 a	22	23.1 a	2,400	3,700 a
F–value	9.7	3.0	6.0	5.0	3.0	4.0	1.0	7.0	0.99	2.5
Degrees of freedom	8, 62	7, 31	8, 97	8, 151	8, 132	8, 147	8, 27	8, 137	8, 119	8, 152
P value	< 0.001	< 0.001	< 0.001	< 0.001	0.014	< 0.001	0.355	< 0.001	0.445	0.015

[a]Plant densities measured in a 1-m^2 quadrant.
[b]Means not followed by a common letter within a column are significantly different ($P < 0.05$).
[c]Soybean yield at locations with waterhemp.
[d]Soybean yield at locations with Palmer amaranth.

applied at planting with a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} at 220 kPa using AIXR 11003 or a XR 11003 nozzles spaced 50 cm apart (AIXR; TeeJet Technologies, Wheaton, IL).

The number of days until *Amaranthus* spp. reached 10 cm height was recorded to estimate the residual capability from each herbicide treatment and corresponds with the plant height limit for POST control with most herbicides available for soybean (Anonymous 2020a, 2020b, 2020c). Density of *Amaranthus* spp. was estimated by counting the number of Palmer amaranth and waterhemp plants from two 1-m^2 quadrants recorded at each of the following evaluation timings: 14, 21, 28, 35 d. *Amaranthus* spp. plant heights were recorded at the 35-d evaluation timing. Soybean yield was taken by harvesting with a plot combine, and grain moisture was adjusted to 13% moisture.

Data were subjected to ANOVA using the PROC GLIMMIX procedure in SAS (version 9.4; SAS Institute, Cary, NC). Palmer amaranth and waterhemp data were analyzed separately for this analysis. Each year–location combination was considered an environment sampled at random from a population as described by Blouin et al. (2011) and Carmer et al. (1989). Designating environments random broadens the possible inference space to which the experimental results are applicable. Environments, replications (nested within environments), and interactions containing these effects were declared random effects in the model; herbicide treatments were designated fixed effects. Type III statistics were used to test the fixed effects, and least square means were separated using Fisher's protected LSD at $\alpha = 0.05$.

Results and Discussion

Days to Palmer Amaranth 10-cm Height

Palmer amaranth took 18 d in the cover crop–alone (nontreated) treatment to reach a height of 10 cm (data not shown). The number of days for Palmer amaranth to reach a height of 10 cm varied from 0 to 37 d in Arkansas and 12 to 27 d in Tennessee. This result supports Wiggins et al. (2017), who found that Palmer amaranth took 16.5 d to reach a height of 10 cm in cover-crop residues. The range of days to Palmer amaranth reaching 10-cm height on the herbicide treatments was much narrower (24 to 38 d). Compared with this treatment, all herbicides except metribuzin increased the number of days until 10-cm tall Palmer amaranth plants were present (Table 3), and the increase ranged from 7 to 17 d. Among the herbicide treatments evaluated, pyroxasulfone + flumioxazin and flumioxazin were best at delaying Palmer amaranth growing to a height of 10 cm by 35 and 33 d, respectively.

Days to Waterhemp 10-cm Height

Waterhemp took 34 d to grow to a height of 10 cm when treated with pyroxasulfone + flumioxazin, flumioxazin, and pyroxasulfone, and 30 d to grow to a height of 10 cm when treated with *S*-metolachlor and dimethenamid-P (Table 3). Cover crop alone or treatment with pendimethalin was able to suppress waterhemp emergence by 24 d.

Density of Palmer Amaranth

The herbicides that resulted in the lowest Palmer amaranth density were pyroxasulfone + flumioxazin, flumioxazin, pyroxasulfone, and acetochlor (Table 3). Those four herbicide treatments provided 1.5 to 4 times less Palmer amaranth density than other herbicides tested. Herbicides evaluated resulted in lower Palmer amaranth density than the nontreated. Palmer amaranth density in plots with soil-residual herbicides ranged from 5 to 22 plants m^{-2}, which was 94% to 75% compared with the cover crop without herbicide (87 plants m^{-2}). These data are consistent with Wiggins et al. (2016), where a cereal rye and hairy vetch cover crop in cotton reduced Palmer amaranth density by 62%, and fluometuron or acetochlor applied PRE increased control to 89% and 95%, respectively.

Density of Waterhemp

Unlike the results with Palmer amaranth, only four of the herbicides––pyroxasulfone + flumioxazin, flumioxazin, pyroxasulfone, and acetochlor––had fewer waterhemp plants than the nontreated. Those herbicides reduced waterhemp density 20% to 65% compared with the cover crop–alone treatment. Of those top four treatments, acetochlor provided the best control, with just 16 plants m^{-2} or 7 to 14 times fewer waterhemp plants than all the other herbicides. These data are consistent with Strom et al. (2019), who found that acetochlor provided better control of multiple herbicide–resistant waterhemp. Densities of waterhemp in treatments that contained dimethenamid-P, *S*-metolachlor, pendimethalin, and metribuzin were similar to the nontreated.

Amaranthus spp. density counts 7 d after achieving 10 cm in height were different among herbicide treatments for control of both species. Palmer amaranth density with flumioxazin remained the same after 7 d. All the other herbicide treatments resulted in increased Palmer amaranth density. However, pyroxasulfone + flumioxazin, flumioxazin, pyroxasulfone, pendimethalin, metribuzin, and acetochlor all brought about lower densities of Palmer amaranth than the nontreated. Treatments with *S*-metolachlor and dimethenamid-P had Palmer amaranth densities similar to the nontreated.

Flumioxazin, pyroxasulfone, pyroxasulfone + flumioxazin, acetochlor, and metribuzin provided 65% to 42% greater control of waterhemp compared with the nontreated 7 d after that weed reached 10 cm tall. Interestingly, at this later evaluation timing, densities of both *Amaranthus* spp. in the nontreated plots declined. We speculate that this decline could be due to the natural variation of the nontreated plots.

Height of Palmer Amaranth and Waterhemp

There were no differences in Palmer amaranth plant height. In contrast to the results with Palmer amaranth, all herbicides except pendimethalin reduced waterhemp plant heights compared with the nontreated. Palmer amaranth plants in pyroxasulfone- and pyroxasulfone + flumioxazin–treated plots were shorter than those in plots treated with pendimethalin, metribuzin, *S*-metolachlor, or not treated.

Soybean Grain Yield

Despite the substantially reduced control of Palmer amaranth and waterhemp with the cover crop–alone treatment, soybean yield was no less than yield where a cover crop was used with an herbicide. We suggest that one reason for the lack of substantial yield loss may be that the cover crop delayed weed emergence. This suggestion is consistent with numerous studies that suggest delaying emergence of *Amaranthus* spp. in relation to soybean emergence can greatly mitigate yield loss from competition (Bensch et al. 2003; Culpepper and York 1998; Culpepper et al. 2000; Steckel and Sprague 2004b). Notably, there were no yield differences for treatment environments infested with Palmer amaranth. In fact, yields among treatments were separated by only 260 kg ha^{-1}. Yield differences were observed for locations with waterhemp. Soybeans treated with dimethenamid-P and metribuzin yielded less than with other herbicides, except *S*-metolachlor and acetochlor. Similar to Palmer amaranth sites, yield among treatments only differed by 360 kg ha^{-1}

These findings agree with and add to the literature that adding a soil-residual herbicide improves the consistency of Palmer amaranth and waterhemp control in soybean planted into a cereal rye + hairy vetch cover crop. This research adds to the published literature on integration of cover crops with herbicides by suggesting that pyroxasulfone + flumioxazin, flumioxazin, pyroxasulfone, and acetochlor were the most effective among the herbicides tested in this study for control of Palmer amaranth when used with a cover crop. In addition, acetochlor was the most effective herbicide evaluated providing residual control of waterhemp. Cover crop alone did provide similar soybean yield compared to treatments when a cover crop was integrated with an herbicide despite providing much less *Amaranth* spp. control. We suggest that this result could be due to the cover crop delaying and reducing the *Amaranth* spp. enough to mitigate the yield-limiting interference that both these weed species have been well documented to offer. Though soybean yield was not negatively affected when no PRE herbicide was used, numbers of *Amaranth* spp. present were greatly increased, which would result in more selection pressure for any POST herbicide.

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