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Early-Season Palmer Amaranth and Waterhemp Control from Preemergence Programs Utilizing 4-Hydroxyphenylpyruvate Dioxygenase–Inhibiting and Auxinic Herbicides in Soybean

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Palmer amaranth and waterhemp have become increasingly troublesome weeds throughout the United States. Both species are highly adaptable and emerge continuously throughout the summer months, presenting the need for a residual PRE application in soybean. To improve season-long control of *Amaranthus* spp., 19 PRE treatments were evaluated on glyphosate-resistant Palmer amaranth in 2013 and 2014 at locations in Arkansas, Indiana, Nebraska, Illinois, and Tennessee; and on glyphosate-resistant waterhemp at locations in Illinois, Missouri, and Nebraska. The two *Amaranthus* species were analyzed separately; data for each species were pooled across site-years, and site-year was included as a random variable in the analyses. The dissipation of weed control throughout the course of the experiments was compared among treatments with the use of regression analysis where percent weed control was described as a function of time (the number of weeks after treatment [WAT]). At the mean (i.e., average) WAT (4.3 and 3.2 WAT for Palmer amaranth and waterhemp, respectively) isoxaflutole + *S*-metolachlor + metribuzin had the highest predicted control of Palmer amaranth (98%) and waterhemp (99%). Isoxaflutole + *S*-metolachlor + metribuzin, *S*-metolachlor + mesotrione, and flumioxazin + pyroxasulfone had a predicted control $\geq$ 97% and similar model parameter estimates, indicating control declined at similar rates for these treatments. Dicamba and 2,4-D provided some, short-lived residual control of *Amaranthus* spp. When dicamba was added to metribuzin or *S*-metolachlor, control increased compared to dicamba alone. Flumioxazin + pyroxasulfone, a currently labeled PRE, performed similarly to treatments containing isoxaflutole or mesotrione. Additional sites of action will provide soybean growers more opportunities to control these weeds and reduce the potential for herbicide resistance.
Nomenclature: 2,4-D; dicamba; isoxaflutole; metribuzin; *S*-metolachlor; Palmer amaranth, *Amaranthus palmeri* S. Watson; waterhemp *Amaranthus tuberculatus* (Moq.) Sauer; soybean, *Glycine max* (L.) Merr.
Key words: HPPD inhibitors, synthetic auxins, residual herbicides, weed control.

Amaranthus palmeri y *Amaranthus tuberculatus* se han convertido en malezas que son cada vez más problemáticas a lo largo de los Estados Unidos. Ambas especies son altamente adaptables y emergen en forma continua durante los meses de verano, lo que hace que sea necesaria la aplicación PRE de herbicidas residuales en soja. Para mejorar el control de *Amaranthus* spp. durante toda la temporada de crecimiento, se evaluaron 19 tratamientos PRE sobre *A. palmeri* resistente a glyphosate en 2013 y 2014 en sitios en Arkansas, Indiana, Nebraska, Illinois, y Tennessee; y sobre *A. tuberculatus* resistente a glyphosate en sitios en Illinois, Missouri, y Nebraska. Las dos especies de *Amaranthus* fueron analizadas en forma separada; los datos de los dos años fueron combinados para cada especie, y el efecto sitio-año fue incluido como un efecto aleatorio en los análisis. La disipación del control de malezas a lo largo del curso de los experimentos fue comparada entre tratamientos con el uso de análisis de regresión, donde el porcentaje de control de malezas fue descrito en función del tiempo (el número de

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semanas después del tratamiento [WAT]). En la media (i.e., promedio) WAT (4.3 y 3.2 WAT para *A. palmeri* y *A. tuberculatus*, respectivamente), isoxaflutole + *S*-metolachlor + metribuzin tuvo el mayor control predicho de *A. palmeri*, (98%) y *A. tuberculatus* (99%). Isoxaflutole + *S*-metolachlor + metribuzin, *S*-metolachlor + mesotrione, y flumioxazin + pyroxasulfone tuvieron un control predicho ≥97% y parámetros estimados del modelo similares, indicando que el control disminuyó a tasas similares entre estos tratamientos. Dicamba y 2,4-D brindaron algo de control residual de poca duración de *Amaranthus* spp. Cuando dicamba fue agregado a metribuzin o *S*-metolachlor, el control aumentó al compararse con dicamba solo. Flumioxazin + pyroxasulfone, un herbicida PRE actualmente registrado, mostró un desempeño similar a los tratamientos que contenían isoxaflutole o mesotrione. Sitios de acción adicionales brindarán a los productores de soja más oportunidades para el control de estas malezas y para reducir el potencial de aparición de resistencia a herbicidas.

Residual herbicides are the cornerstone of a diversified herbicide program that utilizes multiple effective sites of action to manage herbicide-resistant weeds (Norsworthy et al. 2012). As herbicide-resistant weeds become more widespread throughout the United States, growers are increasing their usage of PRE herbicides as an effective means for managing resistance (Prince et al. 2012). Despite innovative management strategies, *Amaranthus* spp. (pigweeds), such as Palmer amaranth and waterhemp, persist in agricultural systems and continue to evolve resistance to herbicides (Heap 2015). Pigweeds emerge continuously throughout the growing season (Jha and Norsworthy 2009) and acclimate to shaded conditions (Jha et al. 2009), presenting even greater challenges for season-long control. Even when emergence occurs later in the season, pigweeds can rapidly acquire biomass sufficient to compete with a crop and eventually produce seed (Horak and Loughin 2000; Keeley et al. 1987; Sellers et al. 2003). Therefore, highly effective PRE applications that control pigweeds > 3 WAT across soil textures and environmental conditions are needed to help manage herbicide-resistant pigweeds for the entire growing season.

New herbicide-resistant soybean traits include resistance to dicamba, 2,4-D, isoxaflutole, and mesotrione. No one cultivar will have tolerance to all of the aforementioned herbicides; however, the new cultivars will allow for PRE applications of auxinic herbicides (e.g., 2,4-D and dicamba) and 4-hydroxyphenylpyruvate dioxygenase (HPPD) inhibitors (e.g., isoxaflutole and mesotrione). Dicamba and 2,4-D are synthetic auxin herbicides used to control emerged weeds prior to planting in the case of most dicot crops or over-the-top control in many monocot crops. Both 2,4-D and dicamba have soil activity, although weed control is selective, rapid, and relatively short lived (Anonymous 2010; Thompson et al. 2007). If used in combination with other residual herbicides that require more time or rainfall to activate, auxinic herbicides may be a useful addition to PRE applications. Mesotrione and isoxaflutole have been shown to be effective on *Amaranthus* spp. when applied PRE (Johnson et al. 2012; Sutton et al. 2002). The use of these active ingredients will increase the number of sites of action labeled for use in transgenic soybean. Hence, the objective of this research was to evaluate, compare, and determine the relative length of residual control on Palmer amaranth and waterhemp provided by currently available and future PRE herbicide programs in six states located in the Midwest and the Midsouth.

Materials and Methods

The effectiveness of various future herbicide programs were evaluated on naturally occurring glyphosate-resistant Palmer amaranth in 2013 and 2014 at locations in Arkansas, Indiana, Nebraska, Illinois, and Tennessee. These same programs were also evaluated on naturally occurring glyphosate-resistant waterhemp at locations in Illinois, Missouri, and Nebraska. Palmer amaranth field experiments were conducted in 2013 and 2014 at the following locations: Northeast Research and Extension Center in Keiser, AR (silty clay); a grower field near Twelve Mile, IN (loamy fine sand); University of Nebraska Lincoln Havelock Farm, Lincoln, NE (silty clay); a grower field near Collinsville, IL (silt loam); and West Tennessee Research and Education Center, Jackson, TN (silt loam). Waterhemp experiments were conducted in 2013 and 2014 at various locations in the Midwest and Midsouth: a grower field near De Soto, IL (silt loam); a grower field near Moberly, MO (silt loam); and a grower field near Fremont, NE (silty clay). None of the locations were irrigated at any point during the experiment. Rainfall data are summarized in

Table 1. PRE application date for Palmer amaranth site-years and rainfall data for each week after the PRE application.

Location	Year	PRE	Rainfall								
			Weeks after PRE								
			1	2	3	4	5	6	7	8	9
			cm								
Keiser, AR	2013	May 16	0.9	5.6	4.9	3.7	2.1	4.1	2.3	0.2	0.2
	2014	May 23	0.0	4.7	6.1	6.1	0.5	7.6	3.9	1.9	2.3
Collinsville, IL	2013	June 5	0.7	6.0	8.4	6.7	2.3	0.4	1.3	1.3	2.3
	2014	June 3	2.6	2.2	0.2	1.4	0.7	4.9	0.1	1.5	0.1
Twelve Mile, IN	2013	May 13	1.1	0.3	7.3	0.1	5.2	0.2	0.7	3.5	3.0
	2014	May 1	0.3	1.0	5.2	0.0	0.0	2.1	3.3	1.1	2.0
Lincoln, NE	2013	May 23	2.3	13.9	2.5	0.6	0.1	3.1	0.0	0.0	0.0
	2014	May 8	0.8	7.6	1.8	3.1	6.8	0.0	5.8	2.4	0.0
Jackson, TN	2013	May 16	2.1	8.4	3.8	1.8	1.9	2.0	0.6	3.0	0.2
	2014	May 7	1.0	7.0	0.0	1.7	15.8	9.0	0.0	2.9	5.0
Mean			1.2	5.7	4.0	2.5	3.5	3.3	1.8	1.8	1.5

Table 1 for the Palmer amaranth locations and in Table 2 for waterhemp locations.

Nineteen PRE herbicide treatments plus one nontreated control were evaluated. These treatments were based on those likely to be recommended by the companies that will market the new herbicide traits. The herbicides used in the treatments included flumioxazin (70 g ai ha^{-1}), pyroxasulfone (89 or 178 g ai ha^{-1}), *S*-metolachlor (1,068 to 1,872 g ai ha^{-1}), metribuzin (420 or 630 g ai ha^{-1}), isoxaflutole (105 g ai ha^{-1}), dicamba (560 or 1,120 g ae ha^{-1}), 2,4-D (532 or 1,064 g ae ha^{-1}), and mesotrione (185 g ai ha^{-1}) (Table 3). The rate of *S*-metolachlor was 1,068 g ha^{-1} unless it was part of a premix with mesotrione (*S*-metolachlor at 1,872 g ha^{-1}). Similarly, the rate of pyroxasulfone was 178 g ha^{-1} unless it was part of a premix with flumioxazin (pyroxasulfone at 89 g ha^{-1}). The rate of metribuzin was adjusted for the soil texture and soil organic matter (OM) present at a given location according to product label recommendations. Metribuzin was applied at 420 g ha^{-1} on coarser textured or lower soil OM sites including Havelock, NE; Fremont, NE; and Twelve Mile, IN and at 630 g ha^{-1} on fine-textured or higher soil OM sites including Keiser, AR; Collinsville, IL; De Soto, IL; Moberly, MO; and Jackson, TN.

Table 2. PRE application date for waterhemp site-years and rainfall data for each week after the PRE application.

	Year	PRE	Rainfall					
			Weeks after PRE					
			1	2	3	4	5	6
			cm					
De Soto, IL	2013	May 24	1.8	4.2	0.4	0.9	4.0	0.8
	2014	May 5	4.0	6.4	0.3	1.9	4.9	0.2
Moberly, MO	2013	June 5	0.1	2.4	0.3	0.6	0.8	0.0
	2014	May 21	0.4	0.4	1.6	1.0	0.5	1.4
Fremont, NE	2013	June 7	1.2	0.6	2.0	0.0	0.0	0.1
	2014	May 7	3.4	2.1	0.7	3.5	9.1	0.0
Mean			1.8	2.7	0.9	1.3	3.2	0.4

Weed control ratings were recorded periodically from 1 to 8 wk after treatment (WAT) for Palmer amaranth and 1 to 5 WAT for waterhemp. Following the last rating, the trial was destroyed at each location in a given year. The number of weekly ratings varied depending on the location and year. Ratings were based on a scale of 0 to 100% control, relative to the nontreated control, with 0% being no control and 100% being complete death of the respective species. Weed densities (plants m^{-2}) were collected 5 WAT for both species by counting the number of individuals in two 0.5 m^{-2} quadrats in each plot. Counts were taken at the same time as a weed control rating 5 WAT.

Plot sizes approximately 3.9 by 7.6 m were established at each location. Plot size differed slightly between locations, primarily as a function of the row spacing common to individual locations (e.g., in Arkansas, the trial area was bedded to

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Table 3. Herbicide information for all products used in the experiments.

Herbicide common name	Herbicide trade name	Timing	Rate	Manufacturer	Address	Web site
			g ai or g ae ha^{-1}			
Dicamba	Clarity	PRE	560 and 1,120	BASF Corporation	Research Triangle Park, NC	http://www.basf.com
S-metolachlor	Dual Magnum	PRE	1,068	Syngenta Crop Protection, LLC	Greensboro, NC	http://www.syngenta.com
Metribuzin	Metribuzin 75	PRE	420 or 630	Loveland Products, Inc.	Greeley, CO	http://www.lovelandproducts.com
2,4-D	Weedar	PRE	532 and 1,065	Nufarm Inc.	Burr Ridge, IL	http://www.nufarm.com/US/Home
Isoxaflutole	Balance Pro	PRE	105	Bayer CropScience LP	Research Triangle Park, NC	http://www.bayercropscienceus.com
Pyroxasulfone	Zidua	PRE	179	BASF Corporation	Research Triangle Park, NC	http://www.basf.com
Flumioxazin + pyroxasulfone	Fierce	PRE	70 + 89	Valent U.S.A. Corporation	Walnut Creek, CA	http://www.valent.com
S-metolachlor + mesotrione	Zemax	PRE	1,872 + 185	Syngenta Crop Protection, LLC	Greensboro, NC	http://www.syngenta.com

facilitate furrow irrigation, with beds spaced 97 cm apart). Soybeans were not planted at any experimental site because of cultivar availability and tolerance; therefore, weed emergence was not reduced by a crop canopy in these experiments. Typical preplant procedures (tillage, burndown herbicide applications, etc.) common to each individual state were used to prepare a weed-free area at the time of trial establishment.

Weed control and density data were pooled across locations and years for each species. Data were analyzed in JMP 11 Pro (SAS Institute Inc., Cary, NC) with the use of analysis of variance (ANOVA) and analysis of covariance (ANCOVA) in the MIXED procedure. Weed densities were analyzed by treatment with the use of ANOVA with site-year and replication included as random variables and means were separated with a Fisher's protected LSD ($\alpha = 0.05$). No count data were collected in Nebraska for either the Palmer amaranth or waterhemp location in both years. Also, no count data were collected from the Missouri location in 2014. Weed control data for all weeks were analyzed together with the use of ANCOVA, with site-year as a random variable. At each time point from which data were collected for each site-year, data were averaged across replications. Then, the logit transformation was used on the decimal equivalent of the weed control data to improve normality with the use of Equation 1:

$$\text{logit} = \ln \frac{p}{1-p}, \qquad [1]$$

where p is the decimal equivalent of percent control. As the logit transformation for 0 is undefined and the logit of 1 is zero, weed control data were manipulated to remove such values. For any treatment at a given time point in a given site-year (e.g., treatment X; 4 WAT; Fayetteville, AR) with an average weed control of 0 was assigned a value of 0.025 (2.5% control) and any treatment with an average weed control of 1 was assigned a value of 0.995 (99.5% control). The logit transformed data were then fit to Equation 2 with the use of ANCOVA

$$\begin{aligned} \text{logit} = {} & \beta_0 + \beta_1(Treatment) + \beta_2(WAT) \\ & + \beta_3(Treatment)(WAT - W\bar{A}T) \\ & + \beta_4(WAT - W\bar{A}T)^2 \\ & + \beta_5(Treatment)(WAT - W\bar{A}T)^2 \\ & + \beta_6(Site_{Year}) + \epsilon \end{aligned} \qquad [2]$$

where Treatment corresponds to the herbicide treatment and WAT is the number of weeks after treatment. Higher-order terms containing the independent variable (WAT) are centered to the mean $W\bar{A}T$ (improve correlation estimates, interpretation of the parameters, and meaningfulness of the statistical tests (Bradley and Srivastava 1979; Freund et al. 2003). Model parameters that were

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Table 4. Model parameter estimates and predicted control at the mean rating timing (approximately 4 WAT) for Palmer amaranth.[a,b]

Treatment	Rate	Parameter estimate		Predicted control at 4 WAT	
		Treatment	Slope	Logit	Control
	g ai ha^{-1} or g ae ha^{-1}				%
Dicamba	560	−2.80 a	−0.56 a	−0.71	33 a
Dicamba	1,120	−1.34 d	−0.27 b	0.75	68 c
S-metolachlor	1,068	−0.58 e	0.00 c–g	1.51	82 d
Metribuzin	420	−1.29 d	−0.05 b–g	0.81	69 c
Dicamba + *S*-metolachlor	1,120 + 1,068	−0.03 fg	−0.13 bcd	2.06	89 de
Dicamba + metribuzin	1,120 + 420	0.05 fg	−0.11 b–e	2.14	89 e
Dicamba + *S*-metolachlor + metribuzin	1,120 + 1,068 + 420	1.16 hij	0.14 fgh	3.26	96 fg
2,4-D	532	−2.44 b	−0.19 bc	−0.35	41 b
2,4-D	1,065	−1.97 c	−0.14 bcd	0.13	53 b
2,4-D + *S*-metolachlor	1,065 + 1,068	−0.39 ef	−0.18 bc	1.71	85 de
2,4-D + metribuzin	1,065 + 420	0.09 g	0.08 d–h	2.18	90 e
2,4-D + *S*-metolachlor + metribuzin	1,065 + 1,068 + 420	0.87 h	0.16 gh	2.96	95 f
Isoxaflutole	105	0.10 g	−0.05 b–g	2.20	90 e
Isoxaflutole + *S*-metolachlor	105 + 1,068	1.15 hij	0.17 gh	3.24	96 fg
Isoxaflutole + metribuzin	105 + 420	1.40 j	0.25 hi	3.50	97 fgh
Isoxaflutole + *S*-metolachlor + metribuzin	105 + 1,068 + 420	1.90 k	0.43 i	3.99	98 h
Pyroxasulfone	179	1.00 hi	0.15 gh	3.09	96 f
Flumioxazin + pyroxasulfone	70 + 89	1.56 jk	0.13 e–h	3.65	97 gh
S-metolachlor + mesotrione	1,872 + 185	1.56 jk	0.18 ghi	3.66	97 gh

[a] Abbreviation: WAT, weeks after treatment.

[b] Means within a column followed by the same lowercase letter are not different according to Fisher's protected LSD ($\alpha = 0.05$).

not significant ($\alpha = 0.05$) were removed from the model. The most refined model for Palmer amaranth is described with Equation 3.

$$\text{logit} = \beta_0 + \beta_1(Treatment) + \beta_2(WAT) + \beta_3(Treatment)(WAT - \bar{WAT}) + \beta_4(WAT - \bar{WAT})^2 + \beta_5(Site_{Year}) + \epsilon \quad [3]$$

The most refined model for waterhemp is described with Equation 4.

$$\text{logit} = \beta_0 + \beta_1(Treatment) + \beta_2(WAT) + \beta_3(WAT - \bar{WAT})^2 + \beta_4(Site_{Year}) + \epsilon \quad [4]$$

For Equation 4, $\beta_0 = 5.65$, $\beta_2 = -0.78$, and $\beta_3 = -0.195$ for all waterhemp treatments. The model parameter estimates for β_1 are dependent upon the treatment and can be found in Table 5. With the use of the equation respective to each species, logit control was estimated for each treatment at the average (mean) WAT. By treating WAT as a quantitative variable, the average WAT was determined by taking the average of the WAT in which assessments were collected (mean WAT for Palmer amaranth = 4.3 and mean WAT for waterhemp = 3.2). The predicted logit control was backtransformed to percent control. Both the predicted logit and percent control are presented in Table 4 for Palmer amaranth and Table 5 for waterhemp. Treatment means, predicted values, and parameter estimates were separated with Fisher's protected LSD ($\alpha = 0.05$).

Results and Discussion

Palmer Amaranth. The nonlinear refined model describing Palmer amaranth control as a function of time (Equation 3) showed that control was negatively correlated with WAT. However, because of the relationship with the other parameters in the model, slope estimates β_3 (if each treatment were positive or negative, with smaller and negative slope estimates describing treatments with a greater rate of decline in percent control than treatments

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Table 5. Model parameter estimates and predicted control at the mean rating timing (approximately 3 WAT) for waterhemp.[a,b]

Treatment	Rate	Parameter estimate	Predicted control at 3 WAT	
		Treatment	Logit	Control
	g ai ha^{-1} or g ae ha^{-1}			%
Dicamba	560	−0.99 b	2.14	89 bc
Dicamba	1,120	−0.18 cd	2.95	95 c–f
S-metolachlor	1,068	−0.63 bc	2.49	92 cd
Metribuzin	420	−0.90 b	2.23	90 bc
Dicamba + *S*-metolachlor	1,120 + 1,068	0.73 ef	3.86	98 efg
Dicamba + metribuzin	1,120 + 420	0.50 def	3.63	97 d–g
Dicamba + *S*-metolachlor + metribuzin	1,120 + 1,068 + 420	0.87 ef	4.00	98 fg
2,4-D	532	−2.55 a	0.58	64 a
2,4-D	1,065	−2.04 a	1.08	75 ab
2,4-D + *S*-metolachlor	1,065 + 1,068	−0.48 bc	2.65	93 cde
2,4-D + metribuzin	1,065 + 420	−0.16 cd	2.97	95 c–f
2,4-D + *S*-metolachlor + metribuzin	1,065 + 1,068 + 420	0.44 def	3.57	97 d–g
Isoxaflutole	105	0.22 de	3.35	97 c–g
Isoxaflutole + *S*-metolachlor	105 + 1,068	1.00 f	4.13	98 fg
Isoxaflutole + metribuzin	105 + 420	0.84 ef	2.97	95 c–f
Isoxaflutole + *S*-metolachlor + metribuzin	105 + 1,068 + 420	1.20 f	4.33	99 g
Pyroxasulfone	179	0.56 ef	3.69	98 d–g
Flumioxazin + pyroxasulfone	70 + 89	0.59 ef	3.72	98 d–g
S-metolachlor + mesotrione	1,872 + 185	0.98 f	4.11	98 fg

[a] Abbreviation: WAT, weeks after treatment.

[b] Means within a column followed by the same lowercase letter are not different according to Fisher's protected LSD ($\alpha = 0.05$).

with larger and positive slope estimates (Table 4). Similarly, treatments with negative treatment effect estimates β_1 were more likely to have a lower control at a given time point than treatments with positive treatment effect estimates (Table 4). Treatments with similar slopes decline in control at similar rates, and likewise have parallel regression lines. However, the regression lines still may be different because of the treatment effect estimate. Thus, by comparing the predicted control at the mean WAT, slope estimates, and treatment effect estimates, the treatments that provide the greatest control for the longest duration can be identified.

Isoxaflutole + *S*-metolachlor + metribuzin, *S*-metolachlor + mesotrione, and flumioxazin + pyroxasulfone had the greatest predicted control (98, 97, and 97%, respectively) at the mean WAT (WAT = 4.3), similar slopes, and similar treatment effect estimates (Table 4). Thus, these three treatments provided the greatest and most stable PRE control of Palmer amaranth for the duration of the experiment. Other treatments (e.g., dicamba + *S*-metolachlor + metribuzin) provided similar predicted control at the mean WAT compared to isoxaflutole + *S*-metolachlor + metribuzin, but did not have similar slope and similar treatment effect estimates like *S*-metolachlor + mesotrione, and flumioxazin + pyroxasulfone (Table 4). Thus, two treatments that may provide similar control at the mean WAT and differ in the slope estimate or parameter estimate may result in control that differs later in the season.

Dicamba and 2,4-D treatments had the lowest predicted control; however, these data show that both of these herbicides do have some, albeit minimal and short-lived, residual activity. Dicamba at 1,120 g ha^{-1} provided the greatest control among the four auxin-alone treatments. For some treatments, the addition of dicamba (1,120 g ha^{-1}) improved control compared to the other product alone. At the mean WAT, the predicted control for metribuzin was 69% and the addition of dicamba improved control 20% over metribuzin alone. Of all the single active ingredient treatments, pyroxasulfone at 179 g ha^{-1} provided the greatest predicted control 4.3 WAT (96%) followed by isoxaflutole at 105 g ai ha^{-1} (90%).

Based upon plant densities collected 5 WAT, isoxaflutole + *S*-metolachlor, isoxaflutole + metri-

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Table 6. Palmer amaranth and waterhemp density adjusted as a percentage of the nontreated control for each herbicide program with data collected 5 wk after treatment.[a,b]

Herbicide	Rate	Density	
		Palmer amaranth	Waterhemp
	g ai ha^{-1} or g ae ha^{-1}	% of nontreated	
Dicamba	560	86 a	81 abc
Dicamba	1,120	58 bcd	72 a–e
S-metolachlor	1,068	47 de	77 a–e
Metribuzin	420	55 cd	69 b–e
Dicamba + *S*-metolachlor	1,120 + 1,068	38 ef	66 c–f
Dicamba + metribuzin	1,120 + 420	48 de	88 abc
Dicamba + *S*-metolachlor + metribuzin	1,120 + 1,068 + 420	28 fg	49 efg
2,4-D	532	69 b	81 abc
2,4-D	1,065	68 bc	98 ab
2,4-D + *S*-metolachlor	1,065 + 1,068	41 ef	100 a
2,4-D + metribuzin	1,065 + 420	47 de	91 abc
2,4-D + *S*-metolachlor + metribuzin	1,065 + 1,068 + 420	28 fg	71 b–e
Isoxaflutole	105	38 ef	50 d–g
Isoxaflutole + *S*-metolachlor	105 + 1,068	17 gh	36 gh
Isoxaflutole + metribuzin	105 + 420	20 gh	39 fgh
Isoxaflutole + *S*-metolachlor + metribuzin	105 + 1,068 + 420	12 h	28 gh
Pyroxasulfone	179	13 h	19 h
Flumioxazin + pyroxasulfone	70 + 89	10 h	29 gh
S-metolachlor + mesotrione	1,872 + 185	17 gh	29 gh

[a] Abbreviation: WAT, weeks after treatment.

[b] Means within a column followed by the same lowercase letter are not different according to Fisher's protected LSD ($\alpha = 0.05$).

buzin, isoxaflutole + *S*-metolachlor + metribuzin, pyroxasulfone, flumioxazin + pyroxasulfone, and *S*-metolachlor + mesotrione all reduced Palmer amaranth density 80 to 90% relative to the nontreated control (Table 6). Dicamba + *S*-metolachlor + metribuzin reduced Palmer amaranth density similar to isoxaflutole + *S*-metolachlor, isoxaflutole + metribuzin, and *S*-metolachlor + mesotrione, but did not reduce density as much as isoxaflutole + *S*-metolachlor + metribuzin, pyroxasulfone, flumioxazin + pyroxasulfone (Table 6). The treatments with the greatest plant densities were all four auxin-alone treatments. Dicamba at 1,120 g ha^{-1} reduced plant densities as much as *S*-metolachlor, metribuzin, dicamba + metribuzin, and 2,4-D + metribuzin; however, plant densities do not take into account the size of the weeds at the time of assessment, as do weed control ratings.

Waterhemp. Treatments that performed well on Palmer amaranth also provided excellent control of waterhemp. Unlike with Palmer amaranth, the refined regression equation describing waterhemp control as a function of WAT (Equation 4) does not include a term for unequal slopes; thus, the rate of decline in weed control did not differ between treatments. Therefore, the regression lines for any given pair of treatments are parallel, but may still be different based on the treatment parameter estimate. The lack of significance for the unequal slopes parameter in the waterhemp equation may partially be explained by differences in weekly rainfall between the Palmer amaranth and waterhemp locations (Tables 1 and 2). Palmer amaranth locations received more rain than the waterhemp locations for most WAT, especially 2 WAT (2.5 and 5.7 cm for the waterhemp and Palmer amaranth locations, respectively). Additionally, Palmer amaranth locations were rated up to 8 WAT, whereas waterhemp locations were only rated up to 5 WAT, allowing more time for differences among treatments to occur. Having more Palmer amaranth locations and observations likely improved the statistical power of the Palmer amaranth data compared to the waterhemp data.

Isoxaflutole + *S*-metolachlor + metribuzin had the greatest predicted control of waterhemp (99%)

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at the mean WAT (3.2 WAT), and was not different from dicamba + *S*-metolachlor, dicamba + metribuzin, dicamba + *S*-metolachlor + metribuzin, 2,4-D + *S*-metolachlor + metribuzin, isoxaflutole, isoxaflutole + *S*-metolachlor, pyroxasulfone, flumioxazin + pyroxasulfone, and *S*-metolachlor + mesotrione. According to these data, dicamba at 1,120 g ha^{-1} had a predicted control of 95% 3.2 WAT and did not differ from most other residual products such as *S*-metolachlor. However, as seen at the Palmer amaranth locations, dicamba alone is not a reliable PRE herbicide and relying on dicamba alone for control of waterhemp would likely place intense selection pressure on the POST herbicides. Dicamba soil activity rapidly diminishes after rainfall (Anonymous 2010; Thompson et al. 2007) and efficacy would decline rapidly in any field that experienced excessive rainfall after application. These data show that dicamba may be a tank-mix partner that provides some added benefit in weed control and increases number of sites of action applied PRE (Table 6).

Pyroxasulfone reduced waterhemp plant density by 81% relative to the nontreated control and did not differ from pyroxasulfone, pyroxasulfone + flumioxazin, *S*-metolachlor + mesotrione, and all treatments containing isoxaflutole. When weed densities were collected 5 WAT, dicamba- and 2,4-D-only treatments had waterhemp densities that were reduced $\geq$ 72% of the nontreated control. The weed density for 2,4-D + *S*-metolachlor was equal to the nontreated control (100%), but was not different from either 2,4-D or *S*-metolachlor alone. Data were normalized to the mean density in the nontreated control to produce equal variances, but the large variability in nontreated density and relatively low number of site-years (compared to the Palmer amaranth data) may be affecting the results so that a treatment has density similar to the nontreated 5 WAT. Furthermore, a weed density does not factor into account any differences in height that may exist between a treated plot and nontreated plot.

Practical Implications. Dicamba, 2,4-D, isoxaflutole, and mesotrione all have PRE activity on Palmer amaranth and waterhemp. When dicamba, 2,4-D, isoxaflutole, or mesotrione are applied in combination with other residual herbicides as a PRE program (e.g., isoxaflutole + *S*-metolachlor + metribuzin), > 95% control can be achieved for more than 3 wk after treatment. Although new PRE programs did not necessarily improve control over currently labeled ones, increasing the effective site-of-action diversity in soybean will reduce selection pressure on any one site of action and reduce the likelihood of herbicide resistance. The critical weed-free period that must be maintained to prevent yield loss in soybean is emergence up to the V1 to V4 stage (Knezevic et al. 2003; Van Acker et al. 1993). The critical weed-free period is dependent a number of factors including climate, row spacing, weed species, weed density, and others (e.g., irrigation) (Knezevic et al. 2003; Van Acker et al. 1993). PRE herbicides do not typically provide adequate control for the duration of the critical weed-free period, in most situations. Thus, a POST herbicide application 3 to 5 WA PRE treatment is necessary, and typically applied, to maintain the weed-free period.

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