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Comparison of a Diflufenican-Containing Premixture to Current Commercial Standards for Residual Palmer Amaranth (*Amaranthus palmeri*) and Waterhemp (*Amaranthus tuberculatus*) Control

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Abstract

With Palmer amaranth and waterhemp evolving resistance to 9 and 6 different sites of action (SOA) globally, soybean producers continue to search for new options to control the problematic weeds. Bayer CropScience has announced its intentions to launch a Convintro™ brand of herbicides, one being a three-way premixture for preemergence use in soybean. The premixture will contain diflufenican (WSSA Group 12), metribuzin (WSSA Group 5), and flufenacet (WSSA Group 15), adding a new SOA for soybean producers throughout the United States. With the anticipated launch of the premixture, research is needed to evaluate the length of residual control provided by the new herbicide. Research trials were conducted in Fayetteville and Keiser, AR, and Morrice, MI, in 2022 and 2023. A 0.17:0.35:0.48 ratio of a diflufenican:metribuzin:flufenacet (DFF-containing premixture) was applied alone and in combination with additional metribuzin and dicamba. Also, metribuzin, acetochlor, a *S*-metolachlor:metribuzin premixture, and a flumioxazin:pyroxasulfone:metribuzin premixture were applied preemergence. The DFF-containing premixture was more effective in reducing Palmer amaranth/waterhemp emergence than acetochlor in four of six trials at 28 d after treatment (DAT). Plots treated with DFF-containing premixture had similar Palmer amaranth and waterhemp densities to the *S*-metolachlor:metribuzin premixture and the flumioxazin:pyroxasulfone:metribuzin premixture at 28 DAT. By 56 DAT, Palmer amaranth and waterhemp densities in plots with the DFF-containing premixture were comparable or superior to acetochlor and metribuzin and was comparable or superior to the *S*-metolachlor:metrbuzin premixture in five of six sites. The addition of dicamba or metribuzin to the DFF-containing premixture did not improve performance on Palmer amaranth and waterhemp over the DFF-containing premixture at 28 or 56 DAT. Overall, the DFF-containing premixture generally provided greater or comparable control to several standard herbicides, providing growers a new preemergence-applied product for control of Amaranthus species in soybean.

Nomenclature: Acetochlor; dicamba; diflufenican; flufenacet; flumioxazin; metribuzin; pyroxasulfone; Palmer amaranth, *Amaranthus palmeri* (S.) Wats.; waterhemp, *Amaranthus tuberculatus*; soybean, *Glycine max* (L.) Merr.

Keywords: Group 12, weed density, residual control

Introduction

Palmer amaranth and waterhemp are the two most problematic weeds in soybean in the United States (Van Wychen 2022). Characteristics of Amaranthus species that make them problematic include high seed production, rapid growth, extended germination periods, and drought tolerance mechanisms (Keeley et al. 1987; Sellers et al. 2003; Horak and Loughin 2000; Jha et al. 2009), resulting in a high degree of interference with a wide array of crops (Monks and Oliver 1988). Yield reductions of up to 60% have been noted in cotton (MacRae et al. 2013), 91% in corn (Massinga et al. 2001), and 78% in soybean (Bensch et al. 2003) from Palmer amaranth.

With the introduction of the glyphosate-resistant (GR) soybean, producers across the U.S. began to adopt the technology, quickly shifting management strategies and relying upon sequential applications of glyphosate postemergence (POST) to control weeds such as Palmer amaranth or waterhemp (Powles 2008; Duke 2014). With the heavy reliance on glyphosate to control weeds, herbicide diversity decreased, leading to the evolution of glyphosate resistance in weeds such as Palmer amaranth and waterhemp (Powles 2008). Currently, these two weed species have evolved resistance to glyphosate in 26 and 18 states, respectively, across the U.S. (Heap 2024), causing producers to alter weed management strategies.

With GR Palmer amaranth and waterhemp spreading across the U.S., producers began to change weed management to control the most troublesome weed species in their fields. Current recommendations to control herbicide-resistant Amaranthus species include starting with a preemergence (PRE) herbicide and making sequential applications POST in combination with soil residual herbicides (Kohrt and Sprague 2017). Additionally, recommendations include using herbicides in combination that contain multiple sites of action (SOA) that are effective against the most troublesome weed to slow the evolution of resistance (Norsworthy et al. 2012). Overall, a strong PRE herbicide can protect crop yields by reducing early-season competition due to the delayed emergence of troublesome weed species (Tursun et al. 2016).

Currently, herbicides belonging to WSSA Groups 2, 3, 4, 5, 14, and 15 are recommended for use PRE in soybean (Barber et al. 2023). Pyroxasulfone (WSSA Group 15) and metribuzin (WSSA Group 5) controlled Palmer amaranth 88% and 78%, respectively, 28 days after treatment (Houston et al. 2019). In addition, flumioxazin (WSSA Group 14) + pyroxasulfone provided greater than 95% control of Palmer amaranth 3 to 4 weeks after application (Meyer et

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al. 2015). While these herbicides can still offer high levels of control against problematic weeds, Palmer amaranth and waterhemp have evolved resistance to 9 and 6 different SOA globally (Heap 2024). Therefore, herbicide manufacturers continue to search for new SOA for producers to integrate into weed management programs.

In 2021, Bayer CropScience announced its intentions to launch a Convintro™ brand of herbicides, one being a premixture that will be labeled for use PRE in soybean (Anonymous 2021). The premixture will be composed of diflufenican (WSSA Group 12), metribuzin (WSSA Group 5), and flufenacet (WSSA Group 15) targeted at control of Amaranthus ssp. Currently, norflurazon, another WSSA Group 12 herbicide, is labeled for use in soybean, but restricted to the midsouthern United States (Anonymous 2015). Therefore, if labeled, diflufenican will be the first Group 12 labeled for use in soybean throughout the United States that will allow producers to incorporate multiple SOA to slow the evolution of herbicide resistance (Norsworthy et al. 2012).

Diflufenican is a phytoene desaturase inhibitor, with the typical symptomology being bleaching of leaf tissue due to the accumulation of phytoene in place of carotenoid formation (Bartels and Watson 1978). Diflufenican was originally discovered in the 1980s and registered for use PRE and early POST in European cereal production (Cramp et al. 1987). When used PRE in wheat (*Triticum aestivum* L.), diflufenican effectively controlled broadleaf weed species, but the overall spectrum of the herbicide appears to be limited (Haynes and Kirkwood 1992). Because control is limited to broadleaf weeds, the herbicide is typically paired with additional herbicides to achieve broad-spectrum weed control. For instance, diflufenican + flufenacet, a premixture registered for use in European cereals, reduced the growth of blackgrass (*Alopecurus myosuroides* Huds.), a problematic weed in wheat, by 90% (Ducker et al. 2019).

This research aims to understand the length of residual control provided by the diflufenican:metribuzin:flufenacet premixture (hereafter referred to as DFF-containing premixture) relative to other herbicides commonly used in soybean. The need for dicamba or additional metribuzin for the DFF-containing premixture is also examined.

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Material and Methods

Field experiments were conducted at the Milo J Shult Agriculture Research and Extension Center in Fayetteville, AR (36.09326, -94.17380), near Morrice, MI (42.838435, -84.149501), and the Northeast Arkansas Research and Extension Center in Keiser, AR (35.67491, -90.08076), in 2022 and 2023 (Table 1). The seedbed was prepared using conventional tillage, including chisel at MI, disk, and cultivation at all locations and bedding at the AR locations. Following ground preparation, soybean variety AG45XF0 (Bayer CropScience, St. Louis, MO) was planted at 346,000 seeds ha^{-1} at Fayetteville and Keiser, AR and AG26XF3 (Bayer CropScience, St. Louis, MO) in Morrice, MI at 370,000 seeds ha^{-1} using a four-row vacuum planter. Plots measured 7.6 m in length at all locations, and 3.7 m in width (91 cm spacing) at Fayetteville, 3.9 m in width (97 cm spacing) at Keiser, and 3.0 m in width (76 cm spacing) at Morrice. Preplant fertilizer was applied when needed based on soil test results and fertilizer recommendations from the University of Arkansas and Michigan State University for soybean (Ross et al. 2022; Warncke et al. 2009). Furrow or overhead irrigation occurred if 2.5 cm of rainfall did not occur within a seven-day period for trials conducted in Arkansas while trials in MI were conducted under non-irrigated conditions.

The experiment was designed as a randomized complete block with four replications and one factor (herbicide treatment). Seven different herbicides or herbicide combinations were evaluated PRE in this study (Table 2). Due to the differences in soil texture across the three different locations, herbicide rates were adjusted for each soil type (Table 3). Applications were made using a CO_2-pressurized backpack sprayer and a four-nozzle boom, using AIXR 110015 nozzles (TeeJet Technologies, Springfield, IL) calibrated to deliver 140 L ha^{-1} at 4.8 km hr^{-1} in Fayetteville and Keiser, AR. In MI, applications were made using a tractor-mounted sprayer using AIXR 11003 nozzles (TeeJet Technologies, Springfield, IL) calibrated to deliver 178 L ha^{-1} at 6.1 km hr^{-1}. Visible injury ratings were collected on a scale of 0 to 100%, with 0% being no crop injury and 100% being complete crop death 14, 28, and 42 days after treatment (DAT) in 2022 and 2023 at Fayetteville and Keiser, and 28, 35, and 42 DAT in 2023 at Morrice (Frans and Talbert 1977). Palmer amaranth (AR) and waterhemp (MI) counts in two 0.5 m^{-2} quadrats per plot were collected 14, 28, 42, and 56 DAT at all locations. Following counts, the entire trial was

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over-sprayed with glufosinate at 656 g ai ha^{-1} at each evaluation. Grain yield was not collected because applications of glufosinate occurred after the R1 growth stage.

Data analysis

Statistical analysis was performed using R Studio, version 4.3.2 (R Core Team 2022), and JMP Pro, version 17.2 (SAS Institute, Cary, NC). Cumulative Palmer amaranth plus waterhemp counts were fitted to a generalized linear mixed model using a Poisson distribution (Gbur et al. 2012), with herbicide and site-year as a fixed effect and replication as a random effect. At each evaluation time, the interaction of herbicide and site-year was significant, which is partially attributed to the drastic differences in Palmer amaranth density among years and differences in rainfall. Therefore, locations and site-years were analyzed separately to understand the consistency of each herbicide within the environments and years across different *Amaranthus* species. Means were separated using Tukey's HSD (α=0.05) to reduce type one error. Percent reduction in Palmer amaranth and waterhemp density was calculated relative to the nontreated check using the formula below:

Eq.1 $$\left(1-\left(\frac{Average\ density\ of\ treated\ plot}{Average\ density\ of\ nontreated\ plot}\right)\right)*100$$

Injury data were bound between 0 and 1 and fit to a generalized linear mixed-effect model (Stroup 2015) using the "glmmTMB" function (glmmTMB package; Brooks et al. 2017) with a beta distribution (Gbur et al. 2012). Herbicide was considered a fixed effect, and replication was considered a random effect. Data were analyzed by location and year due to the differences in injury observed between years at the various research sites. An analysis of variance (car package) was performed on the fitted model (Fox and Weisberg 2019) with the Type III Wald chi-square test. Estimated marginal means (emmmeans package; Searle et al. 1980) were obtained and separated using Tukey's HSD (α=0.05). A compact letter display (multcomp package; Hothorn et al. 2008) was generated to visually represent groups that were significantly different.

Results and Discussion

The DFF-containing premixture was evaluated against a range of herbicides with one, two, three, or four SOA for effectiveness on Palmer amaranth and waterhemp. In all site years, Palmer amaranth density was reduced by 94% or more by the DFF-containing premixture at 14 DAT

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relative to the nontreated. Regarding the single SOA treatments, acetochlor and metribuzin, the DFF-containing premixture was more effective in reducing Palmer amaranth density than acetochlor in both years at Keiser by 14 DAT but not more effective than metribuzin (Table 4). By 28 DAT, acetochlor and metribuzin were less effective than the DFF-containing premixture in reducing the Amaranthus weed density in four and one site years, respectively (Table 5). The greater effectiveness of the DFF-containing premixture on Palmer amaranth and waterhemp compared to acetochlor and to a lessor extent metribuzin generally continued through 42 and 56 DAT (Tables 6 and 7). Other researchers have found acetochlor to provide >89% control of Palmer amaranth up to 14 DAT (Wiggins et al. 2016). However, residual Palmer amaranth control with acetochlor is short-lived, as less than 65% control was reported by 28 DAT. In other research, metribuzin at 420 g ai ha^{-1} averaged across three soil textures provided 68 to 71% Palmer amaranth control at 28 DAT in 2016 and 2017 (Houston et al. 2021). However, adding metribuzin to other commonly used PRE herbicides, such as pyroxasulfone or flumioxazin, increased Palmer amaranth control (Houston et al. 2021). Since the DFF-containing premixture includes metribuzin in combination with two additional SOA, the reduction in Palmer amaranth and waterhemp density compared to metribuzin is not surprising. Overall, the DFF-containing premixture appears more effective than acetochlor and to a lessor extent metribuzin, both single SOA, providing longer residual control of Palmer amaranth and waterhemp.

The DFF-containing premixture was compared to a mixture of *S*-metolachlor plus metribuzin, a herbicide premixture widely used for Palmer amaranth control in soybean in the midsouthern United States (Schwartz-Lazaro et al. 2018). The *S*-metolachlor plus metribuzin premixture provides two SOA with activity against Palmer amaranth and waterhemp. The DFF-containing premixture was comparable to the *S*-metolachlor:metribuzin premixture at 14 DAT on Palmer amaranth, but by 28 DAT, it was more effective at one of four site years (Table 5). Similarly for waterhemp, the DFF-containing premixture was more effective than the *S*-metolachlor:metribuzin premixture for one of two site years. These trends held through 56 DAT. There was only one site year where the DFF-containing premixture was less effective than the *S*-metolachlor:metribuzin premixture (Table 7). Except for the Keiser site in 2022, Palmer amaranth and waterhemp densities were reduced by more than 91% relative to the nontreated by both the DFF-containing premixture and the *S*-metolachlor:metribuzin premixture. Similarly, others have found the *S*-metolachlor:metribuzin premixture controlled common waterhemp

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(*Amaranthus rudis* Sauer) 94% or more through 35 DAT (Sarangi et al. 2017). It should be noted that resistance to *S*-metolachlor has been documented in multiple Palmer amaranth accessions in Arkansas (Brabham et al. 2019). If widespread resistance to *S*-metolachlor is observed in a field, the DFF-containing premixture could be a viable alternative option. Overall, the DFF-containing premixture was similar to or more effective than the *S*-metolachlor:metribuzin premixture with only one site year in which the *S*-metolachlor:metribuzin premixture provided longer residual control of Palmer amaranth and waterhemp.

The flumioxazin:pyroxasulfone:metribuzin premixture is a premium option for PRE use in soybean, containing three highly effective herbicides with differing SOA against Palmer amaranth and waterhemp. Therefore, the DFF-containing premixture was compared against the flumioxazin:pyroxasulfone:metribuzin premixture, with both treatments having a similar number of herbicides and SOAs. Except for Keiser in 2022 and 2023, the DFF-containing premixture was as effective as the flumioxazin:pyroxasulfone:metribuzin premixture in reducing Palmer amaranth and waterhemp through 42 DAT (Tables 4, 5, and 6). Previous research found that flumioxazin:pyroxasulfone:metribuzin premixture delayed the critical time of Palmer amaranth removal as much as 45 days after soybean emergence when applied PRE (Sanctis et al. 2021). Through the final evaluation at 56 DAT, Palmer amaranth and waterhemp densities were reduced by more than 93% by the flumioxazin:pyroxasulfone:metribuzin premixture. In earlier research, flumioxazin plus pyroxasulfone reduced Palmer amaranth density by 93 and 98%, respectively, relative to the nontreated check 28 DAT in 2016 and 2017 (Houston et al. 2021).

The DFF-containing premixture was spiked with additional metribuzin and mixed with dicamba to see if it would increase the effectiveness of the herbicide on Amaranthus species. The addition of metribuzin to the DFF-containing premixture generally did not improve effectiveness of the herbicide on Palmer amaranth or waterhemp. In only one site year at 42 DAT, did plots treated with additional metribuzin have fewer Palmer amaranth plants (Table 6). Similarly, dicamba addition to the DFF-containing premixture did not improve herbicide performance on either species in any site year or evaluation timing compared to the premixture alone. The lack of improved suppression of Palmer amaranth and waterhemp emergence with the addition of dicamba is not surprising, considering that the herbicide has a short half-life (17 to 32 days) and readily leaches with minimal rainfall (Altom and Stritzke 1973; Harris 1964). In five of six site years, rainfall greater than 1.5 cm occurred within a seven-day period after planting (data not shown), likely leaching the dicamba from the uppermost depths of the soil profile.

Differing levels of crop response resulted from the various treatments evaluated in Keiser in 2022 and Morice in 2023 (Table 8). All treatments containing diflufenican had the highest levels of injury through 28 DAT at Keiser and through 35 DAT at Morrice. In general, the herbicide treatments not containing diflufenican were less injurious to soybean and on no occasion more injurious. It is important to note soybeans recovered from early-season injury at sites where injury was most prevalent, with less than 8% injury at Keiser in 2022 by 42 DAT (Table 8) and no injury at Morrice in 2023 by 42 DAT (data not shown). As a result of exceeding the maximum annual use rate of glufosinate in soybean and applications beyond the R1 growth stage, grain yield was not measured; hence, it is unknown whether the early-season injury observed would translate to yield loss.

Practical Implications

The DFF-containing premixture proved highly effective against Palmer amaranth and waterhemp through 28 DAT, providing better than a 96% reduction in the density of both weeds (Table 5). Overlapping of residual herbicides, where a PRE herbicide is followed by POST plus residual herbicides, is a common recommendation in soybean and other agronomic crops (Norsworthy et al. 2012). With the application of PRE herbicides, the need for in-crop weed removal with POST application that includes a residual herbicide occurs 4-6 weeks after planting (Knezevic et al. 2019); hence, the DFF-containing premixture appears to maintain a high level of Palmer amaranth and waterhemp control through the normal timing of the POST application. At the final evaluation (56 DAT), the density of Palmer amaranth and waterhemp was similar in plots treated with the three-way premium premixture of flumioxazin + pyroxasulfone + metribuzin compared to the DFF-containing premixture. If the DFF-containing premixture is priced lower than the premium three-way mixture product, growers should strongly consider the later product because there does not appear to be a significant reduction in performance on Palmer amaranth or waterhemp. Another reason for using the DFF-containing premixture is the occurrence of protoporphyrinogen oxidase resistance in Palmer amaranth and waterhemp. There was no known Group 14 resistance at any of the test sites where the trials were conducted, which likely benefited the performance of the flumioxazin-containing premixture.

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With the planned introduction of the DFF-containing premixture in the upcoming years, diflufenican will be the first Group 12 herbicide labeled for use in soybean throughout the United States. With the premixture including three different SOAs, producers will be able to utilize multiple effective herbicides to target two of the most resistant-prone and troublesome weeds in U.S. soybean production. Overall, the DFF-containing premixture appears to be highly effective against Palmer amaranth and waterhemp with consistent residual control up to 28 DAT. The DFF premixture appears to be more effective than both single active ingredient herbicides evaluated in this study. Additionally, the DFF-containing premixture was superior or comparable to the *S*-metolachlor:metribuzin premixture in five of six site years. The DFF-containing premixture was never more effective than the flumioxazin:pyroxasulfone:metribuzin premixture; however, similar weed densities were observed in four site years. All herbicides evaluated had high reductions of weeds relative to the nontreated plots, reducing the selection for resistance to POST herbicides. Soybean injury >15% was observed from the DFF-containing premixture 28 DAT; however, it is unknown if the early-season injury would translate to yield loss. Starting with a strong PRE herbicide, like the DFF-containing premixture, should be a cornerstone of an effective weed management plan.

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Competing Interests

The authors declare none.

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Table 1. Soil series, texture, sand (%), silt (%), clay (%), organic matter (%), pH, planting date, application date, emergence date, and total rainfall (cm) for Fayetteville, AR, Morrice, MI, and Keiser, AR in 2022 and 2023.

	Location					
	Fayetteville, AR		Morrice, MI		Keiser, AR	
	2022	2023	2022	2023	2022	2023
Soil series[d]	Leaf		Macomb		Sharkey	
Soil texture	Silt loam		Sandy clay loam		Clay	
Sand (%)	18	-[b]	49	36	17	-[c]
Silt (%)	69	-	26	37	34	-
Clay (%)	13	-	25	27	49	-
OM[a] (%)	1.6	-	2.6	1.3	2.3	-
pH	6.6	-	6.1	6.1	6.9	-
Planting date	May 19	May 9	May 24	May 23	May 4	May 17
Application date	May 19	May 10	May 24	May 23	May 4	May 18
Emergence date	May 25	May 18	May 29	May 30	May 9	May 22
Total rainfall 28 DAT (cm)	11.4	10.8	3.70	0.50	10.4	5.2

[a]Abbrevitations: OM, organic matter; DAT, days after treatment

[b]Trial was conducted in an adjacent location within the field in 2023

[c] Trial was conducted in an adjacent location within the field in 2023

[d]Soil series and texture were obtained from USDA-NRCS 2024

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Table 2. Herbicide information for all products used in experiments.

Herbicide	Trade name	Manufacturer
Metribuzin	Tricor® 4L[a]	UPL, King of Prussia, PA
Metribuzin	Mauler®[b]	Valent USA, San Ramon, CA
Acetochlor	Warrant®	Bayer CropScience, St. Louis, MO
S-metolachlor Metribuzin	Boundary® 6.5 EC	Syngenta USA, Greensboro, NC
Diflufenican Metribuzin Flufenacet	Convintro™	Bayer CropScience, St. Louis, MO
Dicamba	Xtendimax® with VaporGrip® Technology	Bayer CropScience, St. Louis, MO
Flumioxazin Pyroxasulfone Metribuzin	Fierce® MTZ	Valent USA, San Ramon, CA

[a]Product used in AR

[b]Product used in MI

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Table 3. Trade name, herbicide treatments, and herbicide rates in g ai/ae ha^{-1} evaluated at Fayetteville, AR, Morrice, MI, and Keiser, AR.

Trade name	Herbicide	Rate		
		Fayetteville, AR[a]	Morrice,MI[b]	Keiser, AR[c]
		---------------------------g ai/ae ha^{-1}---------------------------		
Nontreated	n/a	n/a	n/a	n/a
Warrant	Acetochlor	1260	1260	1260
Tricor/Mauler	Metribuzin	560	560	1120
Boundary	*S*-metolachlor	1100	1100	1840
	Metribuzin	260	260	440
Convintro	Diflufenican	120	150	180
	Metribuzin	240	300	360
	Flufenacet	330	410	490
Convintro +	Diflufenican	120	150	180
Tricor/Mauler	Metribuzin	240	300	360
	Flufenacet	330	410	490
	Metribuzin	320	320	760
Fierce MTZ	Flumioxazin	70	70	105
	Pyroxasulfone	90	90	135
	Metribuzin	210	210	315
Convintro +	Diflufenican	120	150	180
Xtendimax	Metribuzin	240	300	360
	Flufenacet	330	410	490
	Dicamba	560	560	560

[a]Rates for Fayetteville, AR based on a silt loam soil

[b]Rates for Morrice, MI based on a sandy clay loam soil

[c]Rates for Keiser, AR based on a silty clay soil

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Table 4. Influence of herbicide treatment on cumulative Palmer amaranth density 14 DAT at Fayetteville, AR, and Keiser, AR, and waterhemp density at Morrice, MI, in 2022 and 2023.[a,b,c]

		Cumulative Palmer amaranth density										Cumulative waterhemp density		
		Fayetteville, AR				Keiser, AR						Morrice, MI		
Treatment	SOA	2022		2023		2022			2023			2022		2023
		------------------------------Plants m^{-2} ------------------------------												
Acetochlor	1	0.0	(100)[d]	12.2	(82.7)	28.2	a	(91.0)	11.7	a	(77.6)	1.0	(99.7)	NA
Metribuzin	1	0.0	(100)	0.0	(100)	12.1	bc	(96.1)	0.0	b	(100)	0.0	(100)	NA
S-metol. + Met.	2	0.0	(100)	0.0	(100)	11.4	bc	(96.4)	1.7	b	(96.7)	0.0	(100)	NA
DFF premix	3	0.0	(100)	0.0	(100)	5.2	cd	(98.3)	3.2	b	(93.8)	0.3	(99.9)	NA
DFF premix + Met.	3	0.0	(100)	0.0	(100)	13.4	b	(95.7)	0.0	b	(100)	0.0	(100)	NA
Flum. + Pyro. + Met.	3	0.0	(100)	0.0	(100)	0.5	d	(99.8)	2.2	b	(93.8)	0.0	(100)	NA
DFF premix + Dic.	4	0.0	(100)	0.0	(100)	6.9	bc	(95.7)	0.5	b	(99.0)	0.2	(100)	NA
P-value		1.000		0.0846		<0.0001			<0.0001			0.0541		NA

[a]Abbreviations: DAT, days after treatment; SOA, sites of action; *S*-metol, *S*-metolachlor; Met, metribuzin; DFF premix, diflufenican:metribuzin:flufenacet premixture; Flum, flumioxazin; Pyro, pyroxasulfone; Dic, dicamba

[b]Columns within year by location not containing the same letter are significantly different according to Tukey's HSD (α=0.05)

[c]P-values were generated using a generalized linear mixed model in JMP Pro V 17.2 with a Poisson distribution

[d]Numbers in parentheses represent percent reduction relative to the nontreated check

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Table 5. Influence of herbicide treatment on cumulative Palmer amaranth density 28 DAT at Fayetteville, AR, and Keiser, AR, and waterhemp density at Morrice, MI, in 2022 and 2023.[a,b,c]

		Cumulative Palmer amaranth density												Cumulative waterhemp density					
		Fayetteville, AR						Keiser, AR						Morrice, MI					
Treatment	SOA	2022			2023			2022			2023			2022			2023		
		Plants m^{-2}																	
Acetochlor	1	2.5	a	(95.3)[d]	13.2	a	(81.4)	33.7	a	(90.5)	17.1	a	(89.2)	15.4	a	(96.6)	1.2	ab	(84.8)
Metribuzin	1	1.2	a	(97.7)	0.1	b	(99.9)	13.5	b	(96.2)	1.5	b	(98.4)	6.6	b	(98.6)	1.3	ab	(83.4)
S-metol. + Met.	2	0.5	a	(99.1)	0.1	b	(99.8)	14.0	b	(96.0)	4.5	b	(97.2)	0.9	c	(99.8)	3.3	a	(55.8)
DFF premix	3	0.1	a	(99.8)	0.2	b	(99.7)	6.2	c	(98.3)	5.7	b	(96.4)	2.6	bc	(99.9)	0.4	b	(94.5)
DFF premix + Met.	3	0.1	a	(99.9)	0.0	b	(100)	13.4	bc	(96.3)	0.0	b	(100)	1.3	c	(99.7)	0.0	b	(100)
Flum. + Pyro. + Met.	3	0.4	a	(99.2)	0.0	b	(100)	0.7	d	(99.8)	3.2	b	(97.2)	0.0	c	(100)	0.9	b	(87.6)
DFF premix + Dic.	4	0.2	a	(99.8)	0.0	b	(100)	7.4	bc	(97.9)	2.5	b	(98.0)	3.1	bc	(99.3)	0.2	b	(97.2)
P-value		0.0415			<0.0001			<0.0001			<0.0001			<0.0001			<0.0001		

[a]Abbreviations: DAT, days after treatment; SOA, sites of action; *S*-metol, *S*-metolachlor; Met, metribuzin; DFF premix, diflufenican:metribuzin:flufenacet premixture; Flum, flumioxazin; Pyro, pyroxasulfone; Dic, dicamba
[b]Columns within year by location not containing the same letter are significantly different according to Tukey's HSD (α=0.05)
[c]P-values were generated using a generalized linear mixed model in JMP Pro V 17.2 with a Poisson distribution
[d]Numbers in parentheses represent percent reduction relative to the nontreated check

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Table 6. Influence of herbicide treatment on cumulative Palmer amaranth density 42 DAT at Fayetteville, AR, and Keiser, AR and waterhemp density at Morrice, MI, in 2022 and 2023.[a,b,c]

		Cumulative Palmer amaranth density												Cumulative waterhemp density					
		Fayetteville, AR						Keiser, AR						Morrice, MI					
Treatment	SOA	2022			2023			2022			2023			2022			2023		
		------------------------------Plants m^{-2} ------------------------------																	
Acetochlor	1	3.9	a	(92.6)[d]	18.7	a	(74.6)	70.1	a	(86.7)	19.4	a	(90.2)	20.3	a	(95.7)	3.6	bc	(98.2)
Metribuzin	1	2.3	a	(95.7)	2.3	b	(96.8)	109.4	a	(79.2)	2.7	cd	(98.6)	14.5	ab	(97.0)	5.8	a	(97.2)
S-metol. + Met.	2	1.1	a	(97.8)	1.7	b	(97.7)	71.5	b	(86.4)	7.1	bc	(96.4)	1.9	d	(99.6)	9.4	a	(94.7)
DFF premix	3	0.2	a	(99.7)	1.6	b	(97.8)	41.7	c	(92.1)	10.1	b	(94.9)	7.7	bc	(98.4)	0.7	c	(99.4)
DFF premix + Met.	3	0.1	a	(99.8)	1.5	b	(97.9)	47.1	c	(91.0)	0.7	d	(99.6)	6.8	cd	(98.6)	0.0	c	(100)
Flum. + Pyro. + Met.	3	0.4	a	(99.2)	0.3	b	(99.6)	5.3	d	(98.9)	3.7	cd	(98.6)	5.3	cd	(98.9)	1.7	bc	(98.6)
DFF premix + Dic.	4	0.3	a	(99.4)	1.2	b	(98.4)	55.5	bc	(89.4)	4.7	bcd	(97.6)	7.7	bc	(98.4)	0.4	c	(99.7)
P-value		0.0065			<0.0001			<0.0001			<0.0001			<0.0001			<0.0001		

[a]Abbreviations: DAT, days after treatment; SOA, sites of action; *S*-metol, *S*-metolachlor; Met, metribuzin; DFF premix, diflufenican:metribuzin:flufenacet premixture; Flum, flumioxazin; Pyro, pyroxasulfone; Dic, dicamba

[b]Columns within year by location not containing the same letter are significantly different according to Tukey's HSD (α=0.05)

[c]P-values were generated using a generalized linear mixed model in JMP Pro V 17.2 with a Poisson distribution

[d]Numbers in parentheses represent percent reduction relative to the nontreated check

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Table 7. Influence of herbicide treatment on cumulative Palmer amaranth density 56 DAT at Fayetteville, AR, and Keiser, AR, and waterhemp density at Morrice, MI, in 2022 and 2023.[a,b,c]

		Cumulative Palmer amaranth/waterhemp density																	
		Fayetteville, AR						Keiser, AR						Morrice, MI					
Treatment	SOA	2022			2023			2022			2023			2022			2023		
		------------------------------Plants m^{-2}------------------------------																	
Acetochlor	1	7.6	a	(87.0)[d]	18.7	a	(74.6)	122.9	bc	(82.7)	33.1	a	(84.1)	20.3	a	(95.7)	6.4	bc	(97.2)
Metribuzin	1	3.6	ab	(93.9)	2.3	b	(96.8)	198.1	a	(72.1)	19.1	b	(90.8)	14.5	ab	(97.0)	11.6	ab	(95.0)
S-metol. + Met.	2	3.9	ab	(93.3)	1.7	b	(97.7)	191.0	a	(73.1)	18.6	bc	(91.1)	1.9	d	(99.6)	15.9	a	(93.1)
DFF premix	3	0.4	b	(99.4)	1.6	b	(97.8)	102.2	c	(85.6)	15.2	bcd	(92.7)	7.7	bc	(98.4)	0.9	d	(99.6)
DFF premix + Met.	3	1.0	b	(98.3)	1.5	b	(97.9)	108.3	bc	(84.7)	8.3	bc	(96.0)	6.8	cd	(98.6)	1.4	d	(99.4)
Flum. + Pyro. + Met.	3	1.1	b	(98.2)	0.3	b	(99.6)	34.3	cd	(95.2)	13.8	bcd	(93.4)	5.3	cd	(98.9)	2.0	cd	(99.1)
DFF premix + Dic.	4	0.6	b	(98.9)	1.2	b	(98.4)	131.6	b	(81.4)	10.0	cd	(95.2)	8.2	bc	(98.3)	0.5	d	(99.8)
P-value		0.0002			<0.0001			<0.0001			<0.0001			<0.0001			<0.0001		

[a]Abbreviations: DAT, days after treatment; *S*-metol, *S*-metolachlor; Met, metribuzin; DFF premix, diflufenican:metribuzin:flufenacet premixture; Flum, flumioxazin; Pyro, pyroxasulfone; Dic, dicamba

[b]Columns within year by location not containing the same letter are significantly different according to Tukey's HSD (α=0.05)

[c]P-values were generated using a generalized linear mixed model in JMP Pro V 17.2 with a Poisson distribution

[d]Numbers in parentheses represent percent reduction relative to the nontreated check

Table 8. Influence of evaluation timing and herbicide treatments on soybean injury in 2022 at Keiser, AR, and 2023 at Morrice, MI.[a,b,c]

	Injury									
	Keiser, AR						Morrice, MI			
	2022						2023			
Treatment	14 DAT		28 DAT		42 DAT		28 DAT		35 DAT	
	---%	---								
Acetochlor	0	b	4	c	0	c	0	c	0	b
Metribuzin	2	b	20	ab	9	a	0	c	0	b
S-metol. + Met.	0	b	10	bc	1	bc	0	c	0	b
DFF premix	28	a	23	ab	5	abc	18	ab	10	a
DFF premix + Met.	40	a	37	a	4	abc	21	a	11	a
Flum. + Pyro. + Met.	2	b	12	bc	7	ab	15	b	17	a
DFF premix + Dic.	32	a	23	ab	0	c	20	a	11	a
P-value[c]	<0.0001		<0.0001		0.0004		<0.0001		<0.0001	

[a]Abbreviations: DAT, days after treatment; *S*-metol, *S*-metolachlor; Met, metribuzin; DFF premix, diflufenican:metribuzin:flufenacet premixture; Flum, flumioxazin; Pyro, pyroxasulfone; Dic, dicamba

[b]Columns within evaluation timing not containing the same letters are statically different according to Tukey's HSD (α=0.05)

[c]P-values were generated using the "glmmTMB" function in R Studio 4.3.2 using a beta distribution

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