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Palmer amaranth (*Amaranthus palmeri*) control affected by weed size and herbicide spray solution with nozzle type pairings

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Abstract

Palmer amaranth can grow 4.2 mm in height per degree day; hence, delays of a few days in weed control deployment can result in applications of herbicides to weeds that are larger than those for which the herbicide label recommends. Therefore, it is critically necessary to understand the effect of plant size at the time of herbicide application in conjunction with herbicide spray solution and nozzle type pairings on the effectiveness of weed management programs in the Enlist E3 and XtendFlex production systems. Field experiments were conducted in 2020, in no-crop conditions, at two locations in Arkansas, to evaluate the influence of Palmer amaranth size on its control with glufosinate, dicamba, and 2,4-D applied alone and in mixture with specific nozzle pairings as mandated by label requirements. Also, a laboratory experiment was conducted to evaluate the droplet size and velocity of the spray solutions and nozzles used in the field experiments. A 5- and 10-percentage point reduction in control was observed when dicamba (66%) and 2,4-D (63%) were applied alone, respectively, compared with those herbicides mixed with glufosinate (71% and 73%, respectively). Palmer amaranth density increased to 55, 73, 100, 115, and 140 plants m^{-2} when plants were sprayed at heights of 15, 25, 41, 61, and 76 cm, respectively, compared with plants that were sprayed when they were 5 cm tall (9 plants m^{-2}). Nozzle type did not affect weed control or density. The percentage of driftable fines increased when a mixture of glufosinate and 2,4-D were used compared with 2,4-D alone. Effective short-term and long-term chemical control of Palmer amaranth will require growers to correctly time their weed management practices and overlay residuals, and expect the need for sequential applications.

Introduction

Palmer amaranth is a major threat to productivity in many cropping systems (Riar et al. 2013). It has reduced corn (*Zea mays* L.) yield by up to 91% (Massinga et al. 2001) and soybean [*Glycine max* (L.) Merr.] yield by up to 79% (Bensch et al. 2003) with just 8 plants m^{-1} row. It is known to have evolved resistance to herbicides with nine sites of action, including those that inhibit 5-enolpyruvylshikimate-3-phosphate (EPSP) synthase (Norsworthy et al. 2008a), acetolactate synthase (ALS) (Burgos et al. 2001), microtubule assembly (Gossett et al. 1992), 4-hydroxyphenylpyruvate dioxygenase (Jhala et al. 2014), photosystem II (Heap 2022), glutamine synthetase (Heap 2022), protoporphyrinogen oxidase (Varanasi et al. 2018), very long chain fatty acid elongase (Kouame et al. 2022a), and auxin mimics (Heap 2022). Timely control of Palmer amaranth is required to ensure crop productivity and prevent an increase in the soil seedbank, as a single female plant is capable of producing up to 600,000 seeds (Ward et al. 2013). The optimization of Palmer amaranth control requires an in-depth understanding of the biology of the weed (emergence, growth, and reproduction; Norsworthy et al. 2012), optimal application parameters (nozzle type, droplet size, and velocity), and effective chemical combinations.

Best management practices for controlling problematic Palmer amaranth include the use of multiple effective modes of action (Norsworthy et al. 2012). The introduction of the XtendFlex and Enlist E3 technologies for cotton (*Gossypium hirsutum* L.) and soybean provided the opportunity to integrate dicamba (XtendFlex) or 2,4-D (Enlist E3), and glufosinate in Palmer amaranth control programs. In implementing these technologies, it has become commonplace to use postemergence (POST) herbicide mixtures to control Palmer amaranth (Meyer and Norsworthy 2019). However, concerns over the drift of auxin herbicides led to the mandate that

Table 1. Herbicides and nozzles used in field studies.

Nozzle[a]	Herbicide[b]	Product and manufacturer	Chemical name	Rate
				g ha^{-1}
XR	Glufosinate-ammonium	Interline®; UPL NA Inc., King of Prussia, PA	2-amino-4-(hydroxymethylphosphinyl) butanoic acid	656
AIXR	2,4-D	Enlist One™; Corteva Agriscience, Indianapolis, IN	(2,4-dichlorophenoxy)acetic acid	1,065
	2,4-D + Glufosinate-ammonium			1,065 + 656
TTI	Dicamba	Engenia®; BASF Corporation, Research Triangle Park, NC	3,6-dichloro-2-methoxybenzoic acid	560
	Dicamba + Glufosinate-ammonium			560 + 656

[a]Nozzle information: XR, Extended Range Flat Fan; AIXR, Air Induction Extended Range; TTI, Turbo TeeJet Induction. All nozzles were 110015 size tips and were manufactured by TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL.
[b]Glufosinate-ammonium (g ai ha^{-1}); dicamba and 2,4-D (g ae ha^{-1}).

distinct nozzle types be used to apply dicamba (Anonymous 2022c) and 2,4-D (Anonymous 2022b).

Because of its C_4 photosynthetic pathway, Palmer amaranth has a higher carbon dioxide assimilation rate, with the ability to keep assimilating CO_2 under light conditions that are saturating for C_3 species. As a result, Palmer amaranth has a high growth rate (Ward et al. 2013) with height increases of 1.8 to 2.1 mm per degree day (Horak and Loughin 2000) and reaching 4.2 mm per degree day (Norsworthy et al. 2008b). Palmer amaranth size can influence both herbicide performance and herbicide interactions in mixtures (Meyer and Norsworthy 2019). Previous research reported 90% or greater control of cotyledon-size Palmer amaranth with desmedipham and phenmedipham, whereas a control failure was noticed when the same herbicides were applied to 7-cm-tall Palmer amaranth plants (Beiermann et al. 2021). Likewise, applying glyphosate earlier in the season provided better control of Palmer amaranth than applying the herbicide 6 wk after soybean emergence, in part due to the size of the weed (Norsworthy 2005). However, the effect of Palmer amaranth size on the efficacy of glufosinate, dicamba, and 2,4-D alone and in mixtures is unclear (Meyer and Norsworthy 2019).

Droplet size and velocity are among the most important parameters to consider in weed control (Kouame et al. 2022b), and differences have been reported in what the optimal droplet size might be for Palmer amaranth control using dicamba, 2,4-D, and glufosinate (Butts et al. 2018b, 2019a, 2019c). An increase in Palmer amaranth control was correlated with an increase in glufosinate-ammonium deposit and a decrease in volume median diameter, defined as the droplet diameter at which the spray volume is composed of droplets of a smaller diameter (Womac et al. 2017). However, optimal droplet size may be affected by mixtures of different herbicides (Butts et al. 2019a, 2019c). More research is needed to improve our understanding of the effect of droplets produced by different nozzle types on Palmer amaranth control and how these are affected by Palmer amaranth size.

The first objective of this research was to evaluate the influence of Palmer amaranth size on its control with glufosinate, dicamba, and 2,4-D applied alone and in mixture with specific nozzle pairings as mandated by label requirements. The second objective was to evaluate droplet dynamics (droplet size and velocity) and to determine how nozzle type combinations affected those dynamics.

Materials and Methods

Field Experiments

Field experiments were conducted in 2020 in no-crop conditions at the University of Arkansas Milo J. Shult Agricultural Research & Extension Center (MSAREC), Fayetteville, AR, and the Jackson County Extension Center (JCEC) near Newport, AR. At both locations, a split-plot design was established with four replications. The whole plot and sub-plot factors were Palmer amaranth size and herbicide combination, respectively. The experimental units were 2 m wide by 7.6 m long. The herbicide combinations and nozzle type pairings included dicamba (nozzle TTI110015), 2,4-D (nozzle AIXR110015), glufosinate (nozzle XR110015), dicamba + glufosinate (product not labeled; nozzle TTI110015), and 2,4-D + glufosinate (nozzle AIXR110015) (Table 1). Herbicides were applied to Palmer amaranth at six different sizes: 5, 15, 25, 41, 61, and 76 cm. The range of plant sizes for this study was selected to cover the plant size (<10 cm tall) according to the herbicide label and heights that can be reached within a couple of weeks under favorable conditions, given the rapid growth rate of the species. A nontreated control was included as a reference for weed control evaluation. The palmer amaranth populations were resistant to ALS and EPSP synthase inhibitors at the MSAREC location, and to ALS, microtubule assembly, and EPSP synthase inhibitors at the JCEC location (JK Norsworthy and TR Butts, personal communication). The herbicides were applied using CO_2-pressurized backpack sprayers calibrated to deliver 140 L ha^{-1} of spray solution at 276 kPa. The entire trial area was sprayed 1 d after the first herbicide application (when Palmer amaranth was 5 cm tall) with a labeled rate (1,068 g ai ha^{-1}) of *S*-metolachlor (Dual Magnum®; Syngenta Crop Protection, Greensboro, NC) to prevent new weed emergence.

Data Collection

Mean daily air temperature, minimum and maximum air temperatures, relative humidity, and total precipitation were recorded from nearby weather stations for the duration of the experiments. Visual assessment of Palmer amaranth control was conducted 21 d after each herbicide application on a scale of 0% to 100% (where 0% represented no control and 100% represented complete control). The density of Palmer amaranth plants that survived the herbicide application was recorded from two 0.25-m^2 quadrats randomly selected per plot, 21 d after the last herbicide application (to 76-cm-tall Palmer amaranth plants). Shortly prior to weed density count and experiment termination at both locations, aerial digital images of all plots and replications were collected. Images were collected at the JCEC location with a DJI Matrice 210V2 drone (SZ DJI Technology Co., Shenzhen, China) at 20-m altitude with a MicaSense RedEdge MX (AgEagle Inc., Wichita, Kansas) multispectral sensor camera that collected five discrete spectral bands (blue, green, red, red edge, and near infrared) producing a spatial resolution of 1.4 cm pixel^{-1}. Imagery was collected via an automated flight that was mapped using the MicaSense Atlas Flight (AgEagle Inc.) application with 80% front and 70% side overlap. Pre-processing of raw images, including ortho-rectification and radiometric calibrations, was completed using Pix4D Mapper software (version 4.8.4; Pix4D Inc., Lausanne, Switzerland) with the Ag Multispectral automated workflow. Red, green, and blue (RGB) layers were imported into ArcGIS Pro software (version 3.0.2; Esri Inc., Redlands, CA) and combined into a single composite RGB layer using the Composite Band data management tool.

Imagery from the MSAREC location was collected via a DJI Phantom 4 Pro V2.0 drone (SZ DJI Technology Co.) flying at 110-m altitude with a DJI FC6310 (SZ DJI Technology Co.) sensor collecting RGB composite images at 0.75 cm pixel^{-1} spatial resolution. Images were collected by manually navigating the small, unmanned aircraft system (sUAS). Raw RGB sUAS images were imported into ArcGIS Pro software. Plot images were aligned and combined into a single composite RGB layer using the geo-reference and merge raster tools. A vector layer of plot boundaries for MSAREC and JCEC sUAS imagery was used to extract groups of pixels representing individual plots for each site. RGB composite layers extracted from MSAREC and JCEC images were exported in eight-bit portable graphics format (PNG). The PNG files were then imported into Field Analyzer software (Anonymous 2022a) and the "Place Rectangle" tool was used to select plot areas to be analyzed for Palmer amaranth canopy coverage. Field Analyzer parameters low and high hue were set to 0 and 267, respectively; low and high saturation were set to 17 and 100, respectively, and low and high brightness were set to 25 and 100, respectively, to selectively include green leaves in plot imagery.

Droplet Dynamics Laboratory Experiment

A laboratory experiment was conducted at the University of Arkansas Agricultural Experiment Station in Lonoke, AR, to evaluate the droplet size and velocity of the spray solutions and nozzles used in the field experiments. Droplet dynamics were measured using the VisiSize P15 Portable Particle/Droplet Image Analysis System (Oxford Lasers, Oxford, UK), and the experiment was conducted as a completely randomized design with three replications. The VisiSize P15 system was installed within a Generation 4 Research Track Sprayer (Devries Manufacturing, Hollandale, MN) as described previously by Kouame et al. (2022b). The distance between the nozzle tip and the measurement zone was set to 51 cm to allow droplet size and velocity to be measured from the entire spray plume when it crossed the space between the main body and the light delivery block. This also allowed us to measure droplet velocity that would have occurred at the weed canopy level. Herbicide solutions were mixed to match the 140 L ha^{-1} spray volume from the field experiment and were applied using a 276-kPa operating pressure. Data acquisition was set to measure diameter and velocity of 2,500 individual droplets per replication, giving a total of 7,500 droplets measured per treatment.

Data Processing and Analysis

To understand the potential impact of environmental factors on differences in Palmer amaranth canopy coverage, the thermal time (in growing degree days [GDD]) accumulated from the first herbicide application to the end of the experiment was calculated at both location (Eq. 1) (McMaster and Wilhelm 1997) as follows:

$$GDD = \sum\left(\frac{T_{max} + T_{min}}{2}\right) - T_{base} \quad [1]$$

where T_{max} and T_{min} are the daily maximum and minimum air temperatures, respectively, and T_{base} is the temperature below which development ceases (also known as the base temperature for Palmer amaranth growth, which is 11 C) (Chahal et al. 2021).

Palmer amaranth size was first considered as a quantitative variable, and Palmer amaranth control (21 d after application [DAA]), density count, and canopy coverage were regressed against Palmer amaranth size at application. Results indicated a large variability in the data. Most of the R^2 values of the linear regression fittings were approximately 0.30 or lower for control and density count. Additionally, the linear, quadratic, cubic, quartic, and quintic polynomial models were fit to canopy coverage data and compared using Akaike information criterion. This regression analysis demonstrated that the quintic polynomial model was the only model that could provide adequate data fit. However, the difficulty in interpretating and applying this complex model, along with overfitting the data, led to the decision that regression analysis was not suitable for this dataset, and results from these initial regression analyses are not presented. As a result, ANOVA was used for final data analysis and is presented throughout the manuscript. Visual Palmer amaranth control (at 21 DAA), density count, and canopy coverage were compared among herbicides and plant sizes. Locations were considered to be fixed effects, whereas blocks nested within locations were considered to be random effects. Data were subjected to ANOVA using the GLIMMIX procedure with SAS software (version 9.4; SAS Institute Inc, Cary, NC). Visual Palmer amaranth control and canopy coverage data were analyzed assuming a beta distribution (Gbur et al. 2012; Stroup 2015), while Palmer amaranth density count data were analyzed assuming a negative binomial distribution (Stroup 2015).

The $DV_{0.1}$, $DV_{0.5}$, and $DV_{0.9}$ values (representing 10%, 50%, and 90% of the spray volume being composed of droplets of a smaller diameter, respectively), the relative span (RS) (Kouame et al. 2022b), and the average and maximum droplet velocity data were also subjected to ANOVA using the GLIMMIX procedure with SAS software assuming a gamma distribution (Butts et al. 2019b). Treatment means were separated using Tukey's adjustment ($\alpha = 0.05$). The percent of driftable fines (% spray volume containing droplets <150 µm in diameter) were predicted using the Rosin-Rammler equation (Eq. 2) (Nie et al. 2019) as follows:

$$V(d) = 100 - 100 * \exp\left(-\left(\frac{d}{c}\right)^m\right) \quad [2]$$

where V is the cumulative % volume of droplets with the diameter lower than a certain value (d); c is the characteristic droplet diameter, defined as the diameter at which the cumulative volume fraction is 63.2%; and m is a constant indicating the uniformity of the distribution (Kouame et al. 2022b; Nie et al. 2019).

Additionally, the four-parameter log-logistic model (Eq. 3) was fit to droplet size and velocity paired measurements data:

$$Y = c + \frac{d - c}{1 + \exp[b(\log(x) - \log(e)]} \quad [3]$$

where Y is the droplet exit velocity (m s^{-1}), b is the slope at the inflection point, c is the lower limit (m s^{-1}), d is the upper limit (m s^{-1}),

Table 2. Palmer amaranth visual control and density as affected by herbicide spray mixture and nozzle type pairings averaged across location and Palmer amaranth size.[a]

Nozzle[b]	Herbicide	Control 21 DAA		Density	
		——%——		—plants m^{-2}—	
XR	Glufosinate	64	bc	85	ab
AIXR	2,4-D	63	c	100	a
AIXR	2,4-D + glufosinate	73	a	64	c
TTI	Dicamba	66	c	91	ab
TTI	Dicamba + glufosinate	71	ab	74	bc

[a]Means within a column followed by different letters are different based on Tukey's adjustment (α = 0.05).
[b]Nozzle information: XR, Extended Range Flat Fan; AIXR, Air Induction Extended Range; TTI, Turbo TeeJet Induction. All nozzles were 110015 size tips and were manufactured by TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL.

Table 3. Palmer amaranth visual control and density as affected by plant size averaged across location and herbicide spray mixture with nozzle type pairings.[a,b]

Plant size	Control 21 DAA		Density	
cm	——%——		——plants m^{-2}——	
5	91	a	9	e
15	66	b	55	d
25	64	bc	73	c
41	62	bc	100	b
61	62	bc	115	ab
76	58	c	140	a

[a]Abbreviation: DAA, days after application.
[b]Means within a column followed by different letters are different based on Tukey's adjustment (α = 0.05).

e is the inflection point, and x is the droplet size (μm) (Butts et al. 2018a).

All curve fittings were accomplished using nonlinear least squares regression with R software (version 4.0.0; R Core Team 2020).

The root mean square error (RMSE, Eq. 4) was used to evaluate the goodness of fit of each model (Moriasi et al. 2007):

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(Y_i - \hat{Y}_i\right)^2} \quad [4]$$

where Y_i is the measured value and s$\hat{Y}_i$ is the corresponding value predicted by the model, and N represents the total number of observations. Smaller RMSE values indicate a better model fit to the data. Perfect fit is indicated by RMSE values of 0 (Moriasi et al. 2007; Wallach et al. 2006).

Results and Discussion

Palmer Amaranth Control and Density

No significant interactions (between location, Palmer amaranth size, and herbicide/nozzle type pairings) were detected for visual Palmer amaranth control 21 DAA, and density at the end of the experiment. Across locations and Palmer amaranth sizes, the mixtures of glufosinate with either dicamba or 2,4-D provided greater control of Palmer amaranth than either herbicide applied alone (Table 2). A 5-percentage-point reduction was observed when dicamba was applied alone (66%) compared with dicamba mixed with glufosinate (71%). Similarly, a 10-percentage-point reduction was observed when 2,4-D was applied alone (63%) compared to its use in mixture with glufosinate (73%; Table 2). Also, a mixture of 2,4-D and glufosinate caused a 36% and 25% reduction in Palmer amaranth density (64 plants m^{-2}) versus 2,4-D (100 plants m^{-2}) and glufosinate (85 plants m^{-2}) applied alone, respectively (Table 2).

The greatest Palmer amaranth control occurred when 5-cm-tall plants were sprayed. Effective control (>90%) of Palmer amaranth was achieved only when 5-cm-tall plants were sprayed, and poor control (<75%) occurred when herbicides were applied to plants at all other sizes. On average, a 28-percentage-point decrease resulted from applying herbicides to plants that were 15, 25, 41, and 61 cm tall (63%) instead of 5 cm (91%); and a 33-percentage-point decrease resulted when herbicides were applied to plants that were 76 cm tall (58%) instead of 5 cm (91%; Table 3). Also, Palmer amaranth density at the end of the experiment was lowest when 5-cm-tall plants were sprayed, which was consistent with visual ratings. Palmer amaranth density increased to 55, 73, 100, 115, and 140 plants per square meter when plants were sprayed at heights of 15, 25, 41, 61, and 76 cm, respectively, compared with plants that were sprayed when they were 5 cm tall (9 plants m^{-2}) (Table 3).

Palmer amaranth at 15 cm in height and greater are too large according to labels of the herbicides that were used in this research. Failure to control Palmer amaranth that was larger than 7 cm was previously reported in a dose-response study when desmedipham and phenmedipham were applied, but 90% control or greater was recorded when the same herbicides were applied to cotyledon-size Palmer amaranth (Beiermann et al. 2021). Similarly, application of glyphosate 6 wk after soybean emergence resulted in reduced control of Palmer amaranth compared with applications earlier in the season, regardless of soybean population (Norsworthy 2005). Differences in Palmer amaranth control due to its size were also reported by Beesinger et al. (2022) with an application of florpyrauxifen-benzyl to <10-cm-tall Palmer amaranth providing up to 95% mortality while no rate of the herbicide applied to 20- or 40-cm-tall Palmer amaranth provided season-long control of the weed. Additionally, consistent control of Palmer amaranth with glufosinate was reported to be possible only when the weed was ≤7.5 cm (Vann et al. 2017). Antagonistic interactions were previously reported for dicamba and glufosinate mixtures for Palmer amaranth control and percent mortality (Meyer and Norsworthy 2019; Priess et al. 2022). Although an antagonism analysis was not conducted in the present study, the increased control of the mixture would likely result in an additive response at minimum.

Palmer amaranth control and its density reduction in this study seemed to be more dependent on the type of herbicide than the nozzle used to apply it. Nozzle types did not affect weed control or density because mixtures of glufosinate with either dicamba (using the TTI nozzle) or 2,4-D (with the AIXR nozzle) provided similar levels of control. Furthermore, the three herbicides applied alone using the XR (glufosinate), AIXR (2,4-D), and TTI (dicamba) nozzles also provided similar levels of control and Palmer amaranth densities (Table 2). These results corroborate previous research in which nozzle selection (XR, TT, AIXR, and TTI) did not affect dicamba spray solution efficacy at 140 to 187 L ha^{-1} (Legleiter et al. 2018). Because Palmer amaranth is a prolific seed producer (Ward et al. 2013) that has evolved resistance to herbicides from nine sites of action (Heap 2022), one of the best management practices is one of zero-tolerance (Norsworthy et al.

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Table 4. Palmer amaranth canopy coverage measured with drone imagery as affected by plant size and herbicide spray mixtures with nozzle type pairings.[a,b]

Plant size	Nozzle	Herbicide	Canopy coverage MSAREC		Canopy coverage JCEC	
cm			—%—			
5	XR	Glufosinate	1	c	47	ab
	AIXR	2,4-D	24	b	47	ab
	AIXR	2,4-D + glufosinate	1	c	42	ab
	TTI	Dicamba	35	b	41	ab
	TTI	Dicamba + glufosinate	1	c	41	ab
15	XR	Glufosinate	69	a	53	a
	AIXR	2,4-D	81	a	54	a
	AIXR	2,4-D + glufosinate	78	a	45	ab
	TTI	Dicamba	80	a	54	a
	TTI	Dicamba + glufosinate	79	a	52	a
25	XR	Glufosinate	79	a	62	a
	AIXR	2,4-D	80	a	61	a
	AIXR	2,4-D + glufosinate	75	a	53	a
	TTI	Dicamba	80	a	57	a
	TTI	Dicamba + glufosinate	75	a	55	a
41	XR	Glufosinate	78	a	58	a
	AIXR	2,4-D	78	a	61	a
	AIXR	2,4-D + glufosinate	77	a	56	a
	TTI	Dicamba	78	a	58	a
	TTI	Dicamba + glufosinate	79	a	55	a
61	XR	Glufosinate	73	a	61	a
	AIXR	2,4-D	78	a	52	a
	AIXR	2,4-D + glufosinate	77	a	54	a
	TTI	Dicamba	78	a	49	ab
	TTI	Dicamba + glufosinate	77	a	49	ab
76	XR	Glufosinate	77	a	54	a
	AIXR	2,4-D	79	a	38	bc
	AIXR	2,4-D + glufosinate	78	a	38	bc
	TTI	Dicamba	77	a	28	c
	TTI	Dicamba + glufosinate	80	a	26	c

[a]Abbreviations: JCEC, Jackson County Extension Center near Newport, AR; MSAREC, University of Arkansas Milo J. Shult Agricultural Research & Extension Center, Fayetteville, AR.
[b]Nozzle information: XR, Extended Range Flat Fan; AIXR, Air Induction Extended Range; TTI, Turbo TeeJet Induction. All nozzles were 110015 size tips and were manufactured by TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL.

2012). Consequently, delays in Palmer amaranth management that allow an increase in the weed size and density should be avoided.

Palmer Amaranth Canopy Coverage

A significant location-by-herbicide spray mixture-by-plant size interaction of Palmer amaranth canopy coverage was detected. When 5-cm-tall Palmer amaranth was sprayed, canopy coverage was the least at the MSAREC location with glufosinate sprayed either alone or as a mixture with dicamba or 2,4-D (Table 4). The application of dicamba or 2,4-D alone to 5-cm-tall Palmer amaranth led to canopy coverage that was 35 times (35%) and 24 times (24%) greater, respectively, than their respective mixtures or glufosinate alone (1%). However, all herbicide combinations and nozzle type pairings applied to 5-cm-tall Palmer amaranth plants at the MSAREC location resulted in a significant reduction of the canopy coverage in comparison to when they were applied to plants that were ≥15 cm tall. Nozzle type paired with herbicide combinations applied to Palmer amaranth plants that were ≥15 cm tall led to canopy coverage values that were between 69% and 81% compared with values of 1%, 35%, and 24% when glufosinate alone or in mixture, dicamba alone, and 2,4-D alone were applied to 5-cm-tall plants, respectively. Spraying Palmer amaranth that were ≥15 cm tall resulted in the same canopy coverage at the end of the experiment regardless of herbicide combination with nozzle type pairing. This result is consistent with previous research that reported a decline in Palmer amaranth groundcover following herbicide application to plants that were <10.2 cm tall (which is the size indicated by the product label) regardless of nozzle type or herbicide (Priess et al. 2021).

At the JCEC location, Palmer amaranth canopy coverage did not differ between plants that were sprayed when they were 5 cm tall or ≥15 cm (Table 4). Dicamba or 2,4-D applied alone or as a mixture with glufosinate to Palmer amaranth plants that were 76 cm tall resulted in decreased canopy coverage at the end of the experiment compared with herbicides applied earlier. These discrepancies might be due to multiple interrelated factors including weather conditions that might have interfered with plant responses to the herbicides. The weather was warmer at JCEC than MSAREC (Figure 1) with maximum temperatures reaching 36 C and an average maximum temperature of 32 C between the first application date and the sUAS imagery collection date. On the other hand, the maximum temperatures at MSAREC reached 34 C with an average maximum temperature of 31 C. At JCEC Palmer amaranth might have reached its peak photosynthetic rates several times when it was 36 C. An increase in air temperature was previously shown to increase Palmer amaranth dry matter accumulation (Wright et al. 1999), and its net photosynthetic rate is known to be strongly dependent on temperature with photosynthetic rates reaching 81 μmol m^{-2} s^{-1} at 42 C, 90% of peak photosynthetic rate between 36 C and 46 C, and only approximately 50% of the maximum photosynthetic rate reached at 25 C (Ehleringer 1983). Between June and August, more rain fell at JCEC (206 mm) than at MSAREC (148 mm). This greater amount of precipitation at JCEC might have also increased Palmer amaranth stomatal conductance and photosynthesis, as stomata opening for water loss via transpiration and carbon dioxide assimilation are strongly correlated (Kropff and van Laar 1993). Moreover, 1,044 GDD were accumulated at JCEC between herbicide application to 5-cm-tall Palmer amaranth plants and the sUAS imagery collection date, while only 703 GDD were accumulated at MSAREC during a similar period. Palmer amaranth growth was previously reported to be dependent on GDD when sufficient soil moisture and nutrients contents are met (Norsworthy et al. 2008b).

According to Takano and Dayan (2021), weed control by glufosinate is highly dependent on environmental conditions (light, temperature and humidity at the time of application). Also, relative humidity was previously reported to be a critical factor in the efficacy of glufosinate to act on Palmer amaranth (Coetzer et al. 2001).

Nozzle type did not seem to affect Palmer amaranth canopy coverage in this study, which is in alignment with previous studies reporting that nozzle selection did not affect Palmer amaranth groundcover when dicamba was applied. But the same study reported that nozzle selection affected Palmer amaranth groundcover when 2,4-D was applied (Priess et al. 2021).

Droplet Size and Velocity

Droplet parameters ($DV_{0.1}$, $DV_{0.5}$, $DV_{0.9}$, RS, average velocity, and maximum velocity) were affected by herbicide spray solution and nozzle type pairings. As expected, $DV_{0.1}$, $DV_{0.5}$, and $DV_{0.9}$ values were ranked from smallest to greatest as XR < AIXR < TTI. The $DV_{0.5}$ and $DV_{0.9}$ values were identical for spray solutions applied with the same nozzle (Table 5). For the TTI nozzle, the mixture of dicamba and glufosinate increased the $DV_{0.1}$ value (Table 5), and

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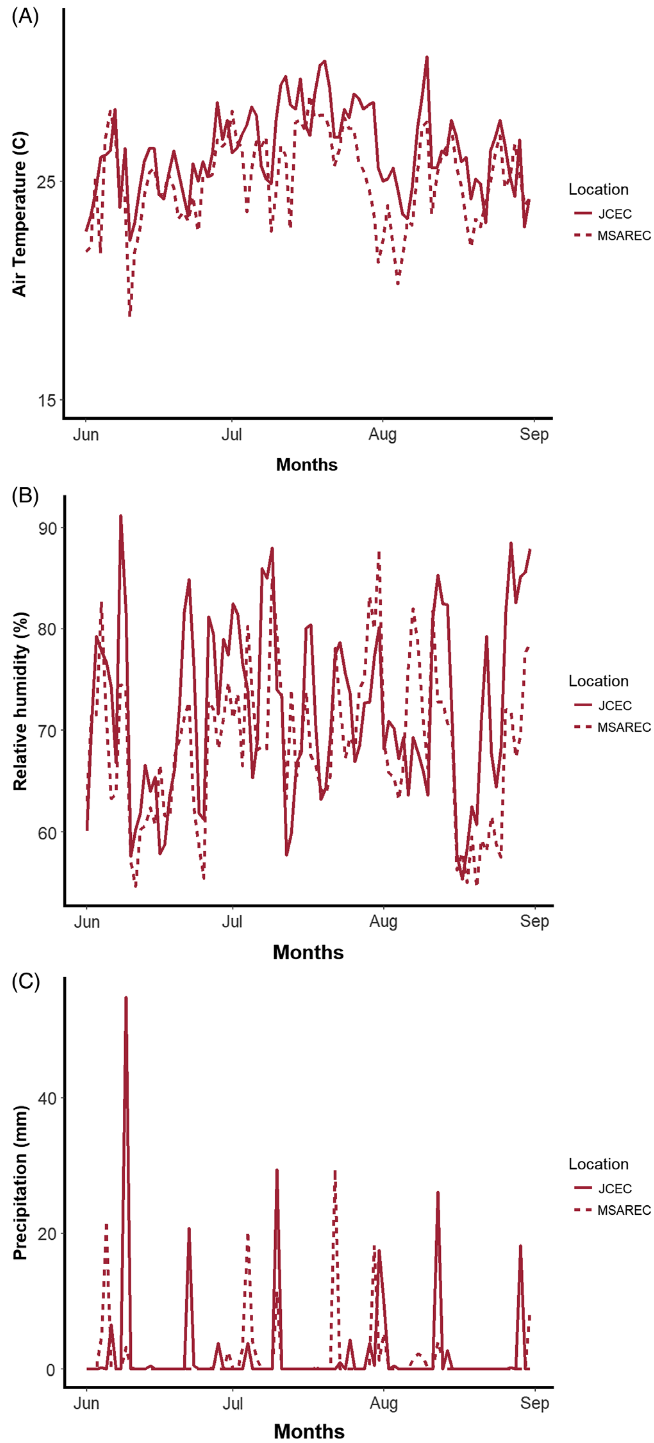

Figure 1. Meteorological data acquired from nearby weather stations of the Milo J. Shult Agricultural Research & Extension Center (MSAREC) and the Jackson County Extension Center (JCEC) during the experiment in 2020 including (A) average air temperature, (B) average relative humidity, and (C) total precipitation.

the average velocity (Table 6) also increased from 398 μm and 321.75 m s^{-1} to 436 μm and 2.21 m s^{-1}, respectively, compared to dicamba alone. In contrast, adding glufosinate as a mixture with either dicamba or 2,4-D did not affect the other droplet size parameters in comparison to dicamba or 2,4-D alone. In general, the RS was smaller for droplets produced by the TTI nozzle. The smallest RS value was obtained from the dicamba and glufosinate mixture. A smaller RS value indicates a more homogenous spray mixture or narrowed droplet distribution. The average velocity of droplets produced by dicamba + glufosinate was also faster than that produced by 2,4-D + glufosinate (Table 6) likely due to the increase in droplet size.

The Rosin-Rammler equation (Eq. 2) provided a good fit to droplet size data of all spray solutions with RMSE values between 0.95 and 2.63 (Table 5). Dicamba and glufosinate in mixture had the smallest percentage of driftable fines (droplets less than 150 μm in diameter) (Table 5; Figure 2). With the AIXR nozzle, the addition of glufosinate to 2,4-D increased the percentage of droplets <150 μm to 15.0% compared to 2,4-D alone (12.6%). In contrast, the addition of glufosinate to dicamba provoked a decrease in the percentage of droplets <150 μm to 0.31% in comparison to dicamba alone (0.59%).

The four-parameter log-logistic model also provided a good fit to data with RMSE values ranging between 0.35 and 0.78 (Table 6). The fit of the model was better for droplets produced by the TTI nozzle than those produced by the AIXR and XR nozzles. In all cases, an increase in droplet size induced an increase in droplet velocity until the plateau was reached. The predicted velocity of 150 μm diameter spray droplets from lowest to highest followed the pattern TTI < AIXR < XR. This indicates that although the average velocities of each nozzle type generally followed the opposite pattern (likely due to the higher percentage of smaller droplets from the XR nozzle compared to the TTI nozzle), when comparing across droplets of similar size, the XR nozzle actually produced a greater velocity of those droplets than the AIXR and TTI nozzles. Furthermore, adding glufosinate to dicamba provoked a decrease in the predicted velocities of droplets that were 150 and 300 μm of diameter from 0.92 and 1.74 m s^{-1} to 0.88 and 1.70 m s^{-1}, respectively. Mixtures were previously reported to have the ability to induce a dramatic effect on the droplet spectrum and $DV_{0.5}$ (Meyer et al. 2016). A reduction in the $DV_{0.5}$ was reported when *S*-metolachlor was added to dicamba + glufosinate + glyphosate and increased the proportion of driftable fines (Meyer et al. 2016). Given the crucial role of droplet size on spray drift, deposition, spray coverage, canopy penetration, and biological efficacy (Ferguson et al. 2016, 2018; Nuyttens et al. 2007; Oliveira et al. 2021; Spillman 1984) spray solutions with smaller droplet size (the XR and AIXR nozzles) would likely have better spray coverage, thus improving weed control. Differences in droplet velocity being dependent on the herbicide solution being used corroborates previous research in which variations in droplet velocity were observed from spray formulations (Dorr et al. 2013). In general, coarser droplets in the present study displayed higher average velocities; however, when comparing across droplets of similar diameter, the XR nozzle produced a greater velocity than the TTI nozzle. Previous research documented a correlation between size and velocity away from the nozzle (Nuyttens et al. 2007), which changes depending on the distance away from the nozzle (Dorr et al. 2013).

Practical Implications

These studies suggest that herbicide spray solution and nozzle type pairings used to control Palmer amaranth ≥15 cm tall are not as effective as applications made to 5-cm-tall plants. Herbicides applied to ≥15-cm-tall plants tends to increase the density of surviving plants, reduce visual Palmer amaranth control, and increase the canopy coverage of the weed, which enhances light interception, and increases Palmer amaranth growth. The mixture

Table 5. Droplet size distribution parameters and driftable fines for herbicide spray solution and nozzle type pairings used in the field experiment.[a]

Nozzle[b]	Herbicide	Nozzle classification[c]	$DV_{0.1}$[d]		$DV_{0.5}$[d]		$DV_{0.9}$[d]		RS[e]		Driftable fines[f]	
			μm								%	RMSE
XR	Glufosinate	F	80	d	148	c	239	c	1.07	abc	51.6	1.84
AIXR	2,4-D	M	151	c	306	b	539	b	1.27	ab	12.6	2.31
	2,4-D + glufosinate	M	142	c	290	b	541	b	1.38	a	15.0	2.63
TTI	Dicamba	XC	398	b	813	a	1207	a	0.99	bc	0.59	1.17
	Dicamba + glufosinate	XC	436	a	787	a	1114	a	0.86	c	0.31	0.95

[a]A Rosin-Rammler model (Eq. 2) was fit to the droplet size distribution obtained from the laboratory experiment conducted at the Lonoke Extension Center in Arkansas to predict driftable fines and root mean square error (RMSE) was calculated to assess model fit. Means within a column followed by different letters are different based on Tukey's adjustment ($\alpha = 0.05$).
[b]Nozzle information: XR, Extended Range Flat Fan; AIXR, Air Induction Extended Range; TTI, Turbo TeeJet Induction. All nozzles were 110015 size tips and were manufactured by TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL 60139.
[c]Nozzle spray classifications were determined using standards established in ASABE S572.3. F = Fine, M = Medium, and XC = Extremely Coarse (ANSI/ASABE 2020).
[d]$DV_{0.1}$, $DV_{0.5}$, and $DV_{0.9}$ represent volume diameter (μm) in which smaller droplets represent 10%, 50%, and 90% of the total volume, respectively.
[e]RS is the relative span (dimensionless parameter used to measure the spread of the drop size in the spray and indicating the uniformity of the drop size distribution).
[f]Driftable fines are defined as the percent of spray volume containing droplets <150 μm in diameter.

Table 6. Measured and predicted droplet velocity for herbicide spray solution and nozzle type pairings.[a]

Nozzle[b]	Herbicide	Average velocity		Maximum velocity		Predicted velocity		
		$m\ s^{-1}$				150 μm	300 μm	RMSE
XR	Glufosinate	1.78	c	8.29	a	1.87	3.98	0.75
AIXR	2,4-D	2.04	ab	8.64	a	1.45	3.53	0.78
	2,4-D + glufosinate	1.89	bc	9.23	a	1.49	3.19	0.70
TTI	Dicamba	1.75	c	5.32	b	0.92	1.74	0.35
	Dicamba + glufosinate	2.21	a	5.40	b	0.88	1.70	0.43

[a]A four-parameter log-logistic model was fit to droplet size and velocity data obtained from the laboratory experiment conducted at the Lonoke Extension Center in Arkansas and root mean square error (RMSE) was calculated to assess model fit.
[b]Nozzle information: XR, Extended Range Flat Fan; AIXR, Air Induction Extended Range; TTI, Turbo TeeJet Induction. All nozzles were 110015 size tips and were manufactured by TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL 60139

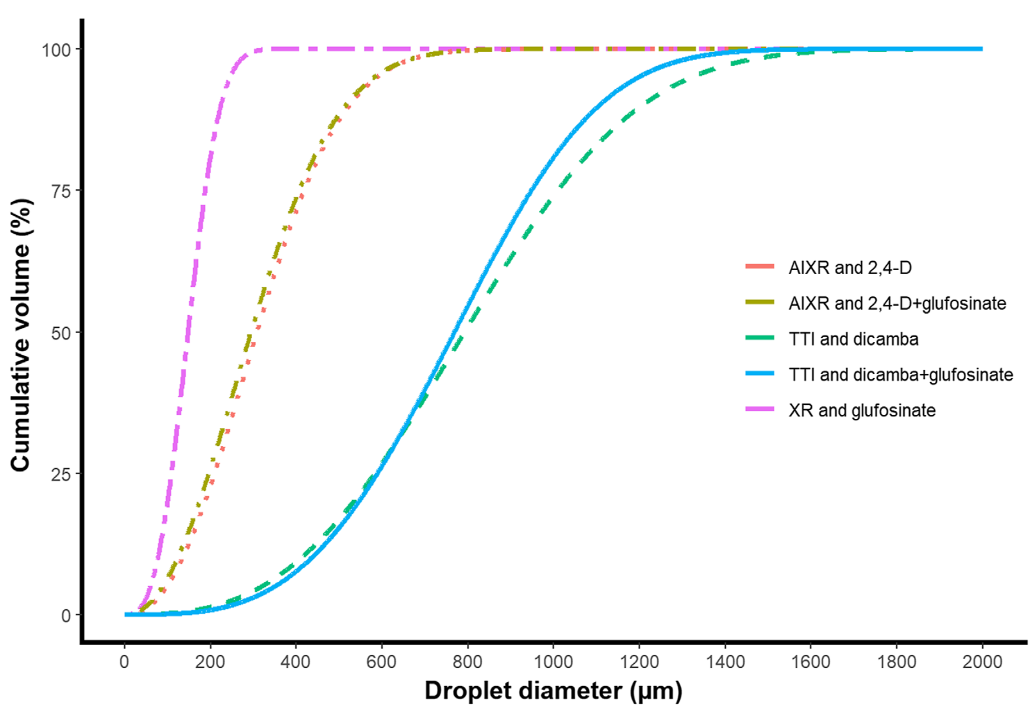

Figure 2. Cumulative volumetric droplet size distributions obtained from the laboratory experiment conducted at the University of Arkansas Agricultural Experiment Station in Lonoke, AR, of herbicide spray solutions and nozzle type pairings that were used in the field experiment.

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of dicamba or 2,4-D with glufosinate provided better control than the herbicides applied alone; however, it should be noted that the dicamba plus glufosinate mixture is not labeled for Palmer amaranth control due to concerns over the volatility of the combination. Dicamba and 2,4-D combinations provided similar levels of Palmer amaranth control. In general, the herbicide spray solution had a greater effect on the resulting Palmer amaranth control than the paired nozzle type. However, it should be emphasized that glufosinate (applied with the XR nozzle), 2,4-D (applied with the AIXR nozzle), and dicamba (applied with the TTI nozzle) applied alone all provided equivalent levels of Palmer amaranth control, indicating that the smaller droplet size of the XR nozzle likely aided in some capacity to improve glufosinate activity. Overall, producers should take care to appropriately select herbicide solution and nozzle type pairings that follow label guidelines and to maximize herbicide effectiveness.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/wet.2023.92

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