Weed Technology 2016 30:377–390

Effect of Nozzle Selection and Spray Volume on Droplet Size and Efficacy of Engenia Tank-Mix Combinations

Christopher J. Meyer, Jason K. Norsworthy, Greg R. Kruger, and Tom L. Barber*

Sprayer applicator-controlled variables, such as nozzle selection and spray volume, will become increasingly important for making labeled POST applications of dicamba in next-generation cropping systems. A field experiment was conducted in 2013 and 2014 at the Northeast Research and Extension Center in Keiser, AR. Tank mixtures of Engenia (a new form of dicamba), glyphosate, glufosinate, and *S*-metolachlor were applied with TeeJet AIXR, AITTJ60, and TTI nozzles. Two nozzle sizes, 11003 and 11006, were used to vary spray volume from 94 L ha^{-1} to 187 L ha^{-1}, respectively. For barnyardgrass, a significant decrease in control was observed when spray volume was reduced for glyphosate + dicamba in 2013. In 2014, an overall decrease in control was observed for the TTI nozzle when spray volume was reduced to 94 L ha^{-1}, averaged across all herbicide treatments. The addition of the product *S*-metolachlor to glyphosate + glufosinate + dicamba significantly reduced the droplet spectra for all nozzle types. For example, adding *S*-metolachlor into the tank-mix decreased the volume median diameter (D_{v50}) for the TTI nozzle at 187 L ha^{-1} spray volume from 789 μm to 570 μm. The results from this research demonstrate that using low spray volume and coarser nozzles could reduce efficacy of the herbicides on the weed species evaluated. Nozzle selection and spray volume have key roles in maximizing efficacy of POST applications in dicamba-resistant crops. Additionally, evaluating droplet spectra of potential dicamba-containing tank-mixtures is critical for producing the desired droplet size to minimize off-target movement.

Nomenclature: Dicamba, *N*,*N*-Bis-(aminopropyl)methylamine (Engenia, BASF Corporation, Research Triangle Park, NC); glufosinate (Liberty, Bayer CropScience LP, Research Triangle Park, NC); glyphosate (Roundup PowerMax, Monsanto Company, St. Louis, MO); *S*-metolachlor (Dual Magnum, Syngenta Crop Protection, LLC, Greensboro, NC); barnyardgrass, *Echinochloa crus-galli* (L.) Beauv.

Key words: Dicamba, glufosinate, glyphosate, nozzle selection, spray volume, weed control.

Las variables controladas por el aplicador, tales como la selección de la boquilla y el volumen de aspersión, serán cada vez más importantes para realizar aplicaciones POST de dicamba según la etiqueta, en los sistemas de cultivos de siguiente generación. En 2013 y 2014, se realizó un experimento de campo en el Centro de Investigación y Extensión del Noreste, en Keiser, Arkansas. Mezclas en tanque de Engenia (una nueva forma de dicamba), glyphosate, glufosinate, y *S*-metolachlor fueron aplicadas con boquillas TeeJet AIXR, AITTJ60, y TTI. Dos tamaños de boquillas, 11003 y 11006, fueron usados para variar el volumen de aspersión de 94 L ha^{-1} a 187 L ha^{-1}, respectivamente. En el caso de *Echinochloa crus-galli*, se observó un a disminución significativa de su control cuando se redujo el volumen de aspersión con glyphosate + dicamba, en 2013. En 2014, una disminución generalizada en el control fue observada con la boquilla TTI cuando el volumen de aspersión se redujo a 94 L ha^{-1}, al promediarse todos los tratamientos de herbicidas. La adición del producto *S*-metolachlor a glyphosate + glufosinate + dicamba redujo significativamente el espectro de gota en todos los tipos de boquillas. Por ejemplo, el agregar *S*-metolachlor a la mezcla en tanque disminuyó el diámetro de volumen medio (D_{v50}) para la boquilla TTI a 187 L ha^{-1} de volumen de aspersión de 789 μm a 570 μm. Los resultados de esta investigación demuestran que el usar bajos volumen de aspersión y boquillas de gota más grande podría reducir la eficacia de los herbicidas en las especies evaluadas. La selección de boquilla y de volumen de aspersión tiene un papel clave para maximizar la eficacia de aplicaciones POST en cultivos resistentes a dicamba. Adicionalmente, el evaluar el espectro de gota de mezclas en tanque que contengan dicamba es crítico para producir el tamaño de gota deseado y así minimizar el movimiento a lugares no deseados.

Palmer amaranth (*Amaranthus palmeri* S. Wats) has been confirmed to have resistance to five sites of action (SOAs), including glyphosate (Heap 2015). In a survey conducted among roadside Palmer amaranth populations in the Mississippi Delta region of Arkansas, Bagavathiannan and Norswor-

---

DOI: 10.1614/WT-D-15-00141.1

* First, second, and fourth authors: Graduate Research Assistant, Professor, and Associate Professor, Department of Crop, Soil, and Environmental Sciences, University of Arkansas, Fayetteville, AR 72704; third author: Assistant Professor, University of Nebraska-Lincoln, North Platte, NE 69101. Corresponding author's E-mail: cjmeyer@uark.edu

thy (2013) reported that $> 90\%$ of Palmer amaranth populations survived applications (labeled rate) of glyphosate and pyrithiobac, an acetolactate synthase (ALS)–inhibiting herbicide. Herbicide-resistant Palmer amaranth continues to cause growers millions of dollars in financial losses annually across the midsouth (Riar et al. 2013). Maximizing efficacy of herbicide applications on species prone to herbicide resistance, such as Palmer amaranth and barnyardgrass, is imperative for effective management and prevention of new-herbicide resistance mechanisms.

Applicator-controlled variables for herbicide applications, such as nozzle selection and spray volume, will become more important as auxin-resistant crop varieties become commercially available and as herbicide resistance continues to threaten agricultural production. Palmer amaranth and barnyardgrass are two weeds that have evolved resistance to many different SOAs and remain difficult to control across the midsouth. To better control these problematic weeds, a full understanding is needed of the effects of manipulating application variables on the control of irrepressible and resistant-prone species.

Herbicide efficacy has been correlated to droplet size and spray volume (L ha^{-1}), but the relationship differs widely among herbicides and species (Knoche 1994; McKinlay et al 1974; Ramsdale and Messersmith 2001). Even so, it is still helpful to identify common trends related to the interactions among droplet size, spray volume, herbicide, and weed species. At equal spray volumes, smaller droplets tend to be more effective than larger droplets are. Small droplet size is more important for retention on upright grass weeds than it is on broadleaf weeds with horizontal structures (Etheridge et al. 2001; McKinlay et al. 1974). The ability of the droplet to spread on the leaf is dependent on the weed species, contributing to differential tolerances to the same herbicide among species (Norsworthy et al. 2001). Both droplet contact with the leaf and droplet spread on the leaf affect herbicide uptake. Thus, it is not surprising that the effect of droplet size on herbicide efficacy appears to be dependent on species. In addition, the importance of adequate coverage, typically achieved with smaller droplets, has a more-consistent effect on the efficacy of contact herbicides, such as glufosinate (Etheridge et al. 2001).

Reducing carrier volumes to rates typical for commercial ground applicators (140 L ha^{-1}) decreases performance of various systemic and contact herbicides (Knoche 1994). However, this general rule does not hold true in all situations. McKinlay et al. (1974) demonstrated that at more-extreme comparisons, 5.5 L ha^{-1} compared with 22 L ha^{-1}, applying paraquat at the lower spray volume had greater efficacy on common sunflower (*Helianthus annuus* L.) than it does at the greater spray volume. The magnitude of this effect was also dependent on the droplet size because a greater difference between spray volumes was observed with a homogenous spray of 100-μm droplets than it was with 350-μm droplets (McKinlay et al. 1974). Carfentrazone efficacy, when applied without an adjuvant, was lower on common sunflower at 47 L ha^{-1} than it was at either 94 or 190 L ha^{-1} (Ramsdale and Messersmith 2001).

The final droplet spectrum is most closely correlated with the behavior of the spray once it leaves the nozzle. The spray solution exits the nozzle as a thin, liquid sheet, which is quickly acted upon by both intrinsic and extrinsic forces. The final size of the droplet is correlated with the thickness of the sheet at ligament formation (Dombrowski and Johns 1963; Dombrowski et al. 1960; Squire 1953). The factors that affect the sheet thickness at disintegration, such as the physiochemical properties of the solution and the orifice size, are important for determining the spray-droplet spectra. The physiochemical properties (e.g., surface tension) of the solution are affected by what and how much of a product or chemical is in that solution, thereby influencing how the spray sheet forms and disintegrates. In the case of altering the spray volume while maintaining the same rate of herbicide applied per area, the concentration of the herbicide in the solution will affect the surface tension of the solution, ultimately affecting the droplet spectra. Increasing the size of the nozzle orifice for a given nozzle type will produce thicker sheets and larger droplets (Nuyttens et al. 2007). Therefore, the same nozzle type will have larger droplets at larger orifice sizes.

Beyond simply the herbicides and concentrations that make up a solution, the solution properties are also greatly affected by the specific herbicides used. Two products containing the same form of the active ingredient will not always produce similar droplet sizes when applied under the same conditions. Three glyphosate formulations, two containing the same isopropylamine salt, all produced different volume median diameter (D_{v50}) values (Mueller and Womac 1997). Thus, identifying the specific herbicide product, as opposed to the herbicide common name, is critical for proper interpretation of results from droplet spectra analyses. Ultimately, the effect of sprayer applicator–controlled variables, such as nozzle selection and spray volume, appear to depend on the specifics of the comparison, the specific herbicides in question, and the species being evaluated. The objective of this research was to evaluate various aspects of application technology, including nozzle selection and spray volume, on the efficacy of potential herbicide applications that could be made in dicamba-resistant crops. The hypotheses were (1) increasing droplet size decreases efficacy of the herbicides on the target weeds, (2) increasing spray volume increases efficacy of the herbicides when the same nozzle type is used, and (3) increasing droplet size decreases coverage spray on the target surface.

Materials and Methods

A field and a laboratory experiment were conducted to evaluate the effects of nozzle selection and spray volume on the efficacy of various herbicides. The field experiment was established in 2013 and 2014 at the Northeast Research and Extension Center in Keiser, AR. Plots (3.9 m wide by 15.2 m long) were established on a Sharkey clay soil (very fine, montmorillonitic, nonacid, thermic, Vertic Haplaquept) with 22% sand, 25% silt, and 53% clay (pH = 6.7, 1.7% organic matter). Soil texture, pH, and organic matter information were obtained by analyzing soil samples collected from the experimental area to a depth of 10 cm. Soil analysis was conducted at the University of Arkansas Agricultural Diagnostic Laboratory in Fayetteville, AR. The purpose of the laboratory experiment was to measure the droplet spectra of the nozzle and herbicide combinations used in the field.

The experimental design of the field experiment was a randomized complete-block factorial with four replications and three factors: herbicide solution, nozzle type, and spray volume. The herbicide treatments were (1) glufosinate at 594 g ai ha^{-1} + dicamba at 560 g ae ha^{-1}, (2) glyphosate at 867 g ae ha^{-1} + dicamba, (3) glufosinate + dicamba + glyphosate, and (4) glufosinate + dicamba + glyphosate + *S*-metolachlor at 1,068 g ai ha^{-1}. A total of 25 treatments were evaluated, including a nontreated control. The specific products used were Liberty (glufosinate, Bayer CropScience LP, Research Triangle Park, NC), Roundup PowerMax (glyphosate, Monsanto Company, St. Louis, MO), Dual Magnum (*S*-metolachlor, Syngenta Crop Protection, LLC, Greensboro, NC), and Engenia, a new formulation of dicamba, marketed by BASF Corporation (Research Triangle Park, NC) for use in dicamba-resistant crops. Additionally, 0.25% (v/v) of Induce (Helena Chemical Company, Collierville, TN), a nonionic surfactant, was added to all treatments containing Engenia, unless Roundup PowerMax was included as a tank-mix partner.

TeeJet (TeeJet Technologies, Springfield, IL) Air Induction Extended Range (AIXR), Air Induction Turbo Twinjet (AITTJ60), and Turbo TeeJet Induction (TTI) nozzles were used to apply each herbicide combination. Applications were made with a MudMaster multiboom sprayer (Bowman Manufacturing Co., Inc. Newport, AR) at 14.5 km h^{-1} calibrated to deliver 141 L ha^{-1} spray volume at 276 kPa with a 48-cm nozzle spacing, and two nozzle sizes (11003 and 11005 rated at 1.14 L min^{-1} and 1.89 L min^{-1}, respectively) were used to vary spray volume from 93.5 L ha^{-1} to 187 L ha^{-1} for the three nozzle types. Treatments were applied at 4:00 P.M. on July 17, 2013, and 9:00 A.M. on August 13, 2014. Air temperature was 32 C and 24 C, relative humidity was 56 and 78%, and wind speed was 3 and 2 km hr^{-1} in 2013 and 2014, respectively, based on in-field observations.

The experimental area was overseeded with Palmer amaranth, velvetleaf (*Abutilon theophrasti* Medik.), hemp sesbania [*Sesbania herbacea* (P. Mill.) McVaugh], and prickly sida (*Sida spinosa* L.) immediately before planting in both years. Two other species, barnyardgrass and pitted morningglory (*Ipomoea lacunosa* L.), were indigenous to the field and present in sufficient quantity for data collection. Glyphosate-resistant corn (*Zea mays* L.) was planted in 97-cm rows at 9 seeds m-row^{-1} to simulate the effect of a typical crop canopy on herbicide application. A SmartStax variety (Genuity, Monsanto Company and Dow AgroSciences, Indianapolis, IN) was selected because SmartStax

Table 1. Height and density of weed species present in the field experiments in 2013 and 2014.

Weed species	2013 Density	2013 Height	2014 Density	2014 Height
	plants m^{-2}	cm	plants m^{-2}	cm
Palmer amaranth	6	6–10	1	12–22
Hemp sesbania	9	5–9	10	20–24
Velvetleaf	7	4–7	7	15–20
Pitted morningglory	8	2–6	3	3–10
Barnyardgrass	4	8	15	14–20
Prickly sida	—	—	7	8–12

varieties available on the market can tolerate POST applications of glufosinate, glyphosate, and dicamba. Planting dates and trial establishment occurred on June 26, 2013, and July 8, 2014, for both experiments.

Treatments were applied to large, actively growing weeds. Average weed densities and heights at the time of application are summarized in Table 1. Weed densities in 2014 were comparable to 2013, except there were fewer Palmer amaranth plants per square meter and almost three times as many barnyardgrass plants per square meter (15 plants m^{-2}). In 2014, weeds were, on average, 10 to 15 cm taller. Prickly sida was present in 2014 only, with an average density of 7 plants m^{-2} and 8 to 12 cm in height.

Percentage of control of Palmer amaranth, hemp sesbania, velvetleaf, pitted morningglory, barnyardgrass, and, in 2014, prickly sida, was assessed 2 and 4 wk after treatment (WAT). Weed control ratings were based on a scale of 0 to 100% control, with 0% being no control and 100% being complete death of the respective species, relative to that in the nontreated plots. The aboveground biomass of three barnyardgrass individuals that survived the herbicide application were collected per plot 4 WAT. Three prickly sida plants were also collected per plot in 2014 only. The weights of the three plants for each respective species were averaged to give an average biomass in grams per plant. For most treatments, control was > 90% for all species; hence, individual plants that escaped control were chosen, rather than collecting biomass per square meter because most plots had relatively few surviving weeds. Barnyardgrass and prickly sida were selected for biomass measurements because more plants survived the applications, more variability between plant sizes existed between treatments, and plants that survived the application had a larger range of sizes.

Water-sensitive papers, or droplet cards, can be a useful tool for assessing various aspects of herbicide applications (Hoffmann and Hewitt 2005). Before the field applications, water-sensitive droplet cards were placed in the field to determine the percentage of coverage obtained by each treatment. Two cards were placed in the field at the height of the crop canopy by clipping them to the newest fully collared corn leaf. Once all treatments were applied, the cards were left to dry and collected to be analyzed in the laboratory. DropletScan 2.5 software (WRK of Oklahoma, Stillwater, OK) was used to determine the percentage of coverage for the cards. When measuring percentage of coverage using droplet cards, the ability of droplets to spread is dependent on the properties of the solution. Therefore, spread factors for each herbicide solution were calculated and used to adjust the coverage measurements (Hoffmann and Hewitt 2005). Spread factors were determined by measuring the diameter of the droplets produced from a set volume (30 μL from a micropipette) in the laboratory.

Droplet-size spectra for each nozzle and herbicide combination were analyzed in a low-speed wind tunnel at the University of Nebraska-Lincoln West Central Research and Extension Center in North Platte, NE. Droplet spectra were determined using a Sympatec Helos Vario KR particle-size analyzer (Sympatec GmbH, Clausthal-Zellerfeld, Germany) equipped with an R7 lens capable of detecting particle sizes in a range from 18 to 3,500 μm. The laser was positioned 30 cm from the tip of the nozzle, and a linear actuator was used to move the entire width of the nozzle plume across the laser. Testing was performed in a low-speed wind tunnel at 24 km h^{-1}. All nozzle and spray solution combinations respective to each experiment were analyzed, each treatment was replicated three times, and the same products used in the field experiment were used for particle-size analysis. Spray parameters that were of interest were the D_{v10}, D_{v50} D_{v90}, relative span (RS), and the percentage of fines. D_{v10} is the diameter below which 10% of the liquid volume is atomized into smaller droplets. D_{v50} and D_{v90} are similar values for 50 and 90% of the volume, respectively. D_{v50} is also commonly referred to as the *volume median diameter*. The percentage of driftable fines were classified as the percentage of the volume containing droplets with a diameter < 150 μm ($\%_{\mathrm{vol}}$ fines). The RS is a parameter of the spray plume that has no units and describes the range of droplet sizes of the plume using Equation 1.

$$RS = (D_{v90} - D_{v10})D_{v50}^{-1} \qquad [1]$$

All field data were analyzed in JMP Pro 11 (SAS Institute Inc., Cary, NC) using the MIXED procedure, with years analyzed separately, and replication included as a random effect. However, statistical analysis of the percentage of coverage obtained via the water-sensitive droplet cards was not significantly different across years, so data were pooled. Data that did not meet the equal variance and normality assumptions of ANOVA were not analyzed, and individual treatment means and standard error of the mean (SEM) were reported where appropriate. Field data that met the assumptions for ANOVA were analyzed, and means were separated using Fisher's protected LSD test ($\alpha = 0.05$). For the particle-size analysis, a completely randomized design was used, and a more-conservative Tukey adjustment ($\alpha = 0.05$) was used to identify differences among means.

The biomass data were subject to a natural log transformation to better meet the assumptions for ANOVA, which is common with continuous variables, such as biomass weight. Log transformation improved the model for barnyardgrass, but not for prickly sida. Therefore, analysis was conducted on the transformed values for barnyardgrass, and values were back-transformed for discussion and reporting.

Of the broadleaf weeds on which data were collected, including Palmer amaranth, hemp sesbania, velvetleaf, pitted morningglory, and prickly sida, only weed-control data for velvetleaf in 2014 and prickly sida in 2014 were analyzed with ANOVA. Barnyardgrass data from both years and from both experiments also met the assumptions for ANOVA. Full-factorial models, with factors according to their respective experiments, were used to fit the data, and only significant factors ($\alpha = 0.05$) are discussed, where appropriate. Biomass measurements were considered separate response variables from weed-control ratings for the same species and were analyzed separately.

Results and Discussion

Palmer amaranth, hemp sesbania, velvetleaf, and pitted morningglory are particularly sensitive to dicamba, especially when applied at recommended weed sizes. Most treatment combinations had $> 90\%$ control for all weeds and timings. The effects of nozzle selection and spray volume depended on both the herbicide treatment and the individual species. The results from the particle-size analysis from the low-speed wind tunnel for nozzle and herbicide combinations are presented after the results from the field experiment.

Palmer Amaranth. Palmer amaranth control was $\geq 90\%$ for most treatments in both years, and few large differences in control between nozzles or spray volumes were observed (Table 2). For glyphosate + dicamba, applied using the TTI nozzle, Palmer amaranth control at 94 L ha^{-1} was 5% less than when applied at 187 L ha^{-1} in 2013 (94 compared with 99% control) and 7% less in 2014 (87 compared with 94% control). This suggests that, with ultracoarse droplets, decreasing spray volume from 187 L ha^{-1} to 94 L ha^{-1} can reduce the efficacy of dicamba + glyphosate. In addition, for glyphosate + dicamba, only one effective SOA was acting on Palmer amaranth because most of the plants in this field were glyphosate resistant (personal observation). All other treatments provided $\geq 96\%$ Palmer amaranth control at both timings in both years, showing the benefit of applying multiple effective SOAs.

Hemp Sesbania. Hemp sesbania control was $\geq 95\%$ for all treatments, with most treatments exhibiting 100% control 2 and 4 WAT in both years (Table 3). Control with glyphosate + dicamba applied with the TTI nozzle was slightly less in 2013 (95 to 98% control) for both spray volumes

Table 2. POST Palmer amaranth control 2 and 4 wks after treatment (WAT), as influenced by the interaction between herbicide treatment nozzle type and spray volume in 2013 and 2014.

				Visual control[c]							
				2013				2014			
				2 WAT		4 WAT		2 WAT		4 WAT	
Treatments[a]	Rate	Nozzle[b]	Spray volume	%	SEM	%	SEM	%	SEM	%	SEM
	g ai ha^{-1}		L ha^{-1}								
Dicamba + glufosinate	560[d] + 594	AIXR	94	100	0	100	0	98	1	100	0
			187	100	0	99	1	99	1	100	0
		AITTJ60	94	100	0	100	0	99	1	100	0
			187	100	0	96	1	100	1	100	0
		TTI	94	98	2	97	1	100	0	98	3
			187	100	0	98	2	100	0	100	0
Dicamba + glyphosate	560[d] + 867[d]	AIXR	94	98	1	99	1	93	2	92	2
			187	97	1	97	1	94	1	94	2
		AITTJ60	94	97	1	98	1	93	1	91	1
			187	96	1	95	2	95	1	91	2
		TTI	94	91	1	94	1	86	2	87	2
			187	93	2	99	1	90	2	94	2
Dicamba + glufosinate + glyphosate	560[d] + 594 + 867[d]	AIXR	94	100	0	100	0	98	1	98	1
			187	100	0	100	1	100	0	100	0
		AITTJ60	94	100	0	98	1	99	1	100	1
			187	100	0	99	1	99	1	100	0
		TTI	94	98	1	97	1	100	0	100	0
			187	97	1	97	1	100	1	100	0
Dicamba + glufosinate + glyphosate + *S*-metolachlor	560[d] + 594 + 867[d] + 1,068	AIXR	94	100	0	100	0	99	0	100	0
			187	100	0	100	0	99	1	98	2
		AITTJ60	94	100	0	98	1	98	1	98	1
			187	100	0	100	1	100	1	100	0
		TTI	94	100	0	99	1	99	1	100	1
			187	99	1	96	2	100	0	100	0

[a] All treatments containing glufosinate used the product Liberty, treatments containing dicamba used the product Engenia, treatments containing glyphosate used the product Roundup PowerMax, and treatments containing *S*-metolachlor used the product Dual Magnum.

[b] AIXR indicates TeeJet Air Induction Extended Range nozzle; AITTJ60, TeeJet Air Induction Turbo TwinJet nozzle; TTI, TeeJet Turbo TeeJet Induction nozzle.

[c] Mean and the standard error of the mean (SEM).

[d] Rate is in grams of acid equivalence (g ae ha^{-1}).

compared with the rest of the treatments. Although 95 to 98% would be considered an effective application, many other treatments provided 100% control and were more stable across timings and years.

Velvetleaf. For some nozzles and herbicide combinations, the effect of spray volume on velvetleaf efficacy did not perform as expected. In 2013, dicamba + glyphosate with the AITTJ60 provided 98% control at 94 L ha^{-1} and only 93% at 187 L ha^{-1} 4 WAT (Table 4). A significant difference between spray volumes was observed 4 WAT in 2014 for the same herbicide and nozzle combination, with the larger spray volume having lower efficacy. However, control with dicamba + glyphosate and the AITTJ60 nozzle did not exceed that achieved with the AIXR nozzle at either spray volume. Control was also different between spray volumes with dicamba + glyphosate + glufosinate + *S*-metolachlor for the TTI nozzle. Identifying the specific causes of these results is difficult because differences in efficacy could be attributed to one of many factors (particle size, distribution of particle size, herbicide interactions at different concentrations, differences in uptake, etc.). Based on the data collected on other species, altering one variable, such as spray volume, to maximize efficacy on one

Table 3. POST hemp sesbania control 2 and 4 wk after treatment (WAT), as influenced by the interaction between herbicide treatment nozzle type and spray volume in 2013 and 2014.

				Visual control[c]							
				2013				2014			
Treatments[a]	Rate	Nozzle[b]	Spray volume	2 WAT		4 WAT		2 WAT		4 WAT	
	g ai ha^{-1}		L ha^{-1}	%	SEM	%	SEM	%	SEM	%	SEM
Dicamba + glufosinate	560[d] + 594	AIXR	94	100	0	100	0	100	0	100	0
			187	100	0	99	1	100	0	100	0
		AITTJ60	94	100	0	100	0	100	0	100	0
			187	100	0	100	0	100	0	100	0
		TTI	94	100	0	100	0	100	0	100	0
			187	100	0	100	1	100	0	100	0
Dicamba + glyphosate	560[d] + 867[d]	AIXR	94	100	0	100	0	100	0	100	0
			187	100	0	99	1	100	0	100	0
		AITTJ60	94	100	0	100	0	99	1	100	0
			187	97	1	96	1	100	0	100	0
		TTI	94	97	1	95	2	98	2	100	0
			187	96	1	98	1	99	1	100	0
Dicamba + glufosinate + glyphosate	560[d] + 594 + 867[d]	AIXR	94	100	0	99	1	100	0	100	0
			187	100	0	100	0	100	0	100	0
		AITTJ60	94	100	0	100	0	100	0	100	0
			187	99	1	98	1	98	1	100	0
		TTI	94	100	0	99	1	100	0	100	0
			187	100	0	97	1	100	0	100	0
Dicamba + glufosinate + glyphosate + *S*-metolachlor	560[d] + 594 + 867[d] + 1,068	AIXR	94	100	0	100	0	100	1	100	0
			187	100	0	100	0	100	0	100	0
		AITTJ60	94	100	0	99	1	100	0	100	0
			187	100	0	100	1	100	0	100	0
		TTI	94	100	0	99	1	100	0	100	0
			187	100	0	100	0	100	0	100	0

[a] All treatments containing glufosinate used the product Liberty, treatments containing dicamba used the product Engenia, treatments containing glyphosate used the product Roundup PowerMax, and treatments containing *S*-metolachlor used the product Dual Magnum.

[b] AIXR indicates TeeJet Air Induction Extended Range nozzle; AITTJ60, TeeJet Air Induction Turbo TwinJet nozzle; TTI, TeeJet Turbo TeeJet Induction nozzle.

[c] Mean and the standard error of the mean (SEM).

[d] Rate is in grams of acid equivalence (g ae ha^{-1}).

weed may not necessarily optimize it for all the other weeds in the field.

Pitted Morningglory. Although pitted morningglory was present at the time of application in 2013, many treatments provided complete control 2 WAT, but by 4 WAT, additional emergence occurred. By 4 WAT, it was not possible to differentiate survivors from the later emergence, so the subsequent emergence is included in the data, resulting in a decrease in control from 2 WAT to 4 WAT even when control was often 100% at the first rating. For many nozzle, spray volume, and herbicide combinations, pitted morningglory control was $\geq$ 97% in both years (Table 5). For certain treatments and timings, control decreased as spray volume decreased. For example, pitted morningglory control with dicamba + glyphosate and the TTI nozzle was less at 94 L ha^{-1} than it was at 187 L ha^{-1} both at 2 and 4 WAT in both years. Control was also less at 94 L ha^{-1} with dicamba + glufosinate applied with the TTI nozzle at 4 WAT (88%) than it was at 187 L ha^{-1} (95%). No treatment provided < 85% control in either year; however, some treatments provided improved control at a greater spray volume.

Table 4. POST velvetleaf control 2 and 4 wk after treatment (WAT), as influenced by the interaction between herbicide treatment and nozzle type and spray volume in 2013 and 2014.

				Visual control					
				2013[c]				2014[d]	
Treatments[a]	Rate	Nozzle[b]	Spray volume	2 WAT		4 WAT		2 WAT	4 WAT
	g ai ha^{-1}		L ha^{-1}	%	SEM	%	SEM	%	
Dicamba + glufosinate	560[e] + 594	AIXR	94	100	0	100	0	96 a–f	100 ab
			187	100	0	100	0	96 a–f	97 a–e
		AITTJ60	94	100	0	100	0	97 a–e	93 d–h
			187	99	1	98	1	95 c–g	98 a–c
		TTI	94	99	1	97	2	93 f–h	91 gh
			187	100	1	99	1	94 d–h	93 e–h
Dicamba + glyphosate	560[e] + 867[e]	AIXR	94	100	0	100	0	97 a–e	96 a–f
			187	100	1	100	0	92 g–i	95 b–g
		AITTJ60	94	92	1	98	1	93 e–h	96 a–f
			187	91	1	93	1	91 hi	90 h
		TTI	94	84	2	91	1	89 i	95 c–g
			187	96	1	98	1	90 hi	90 h
Dicamba + glufosinate + glyphosate	560[e] + 594 + 867[e]	AIXR	94	100	0	100	0	96 b–g	97 a–d
			187	100	0	100	0	99 ab	99 ab
		AITTJ60	94	100	0	99	1	98 a–c	98 a–c
			187	100	0	99	1	92 g–i	95 b–g
		TTI	94	99	1	99	1	97 a–d	100 a
			187	100	0	100	0	98 a–d	99 a–c
Dicamba + glufosinate + glyphosate + S-metolachlor	560[e] + 594 + 867[e] + 1,068	AIXR	94	100	0	100	0	100 a	100 a
			187	99	1	100	0	97 a–e	98 a–c
		AITTJ60	94	100	0	100	0	97 a–e	99 ab
			187	100	0	100	1	98 a–d	98 a–c
		TTI	94	100	0	98	1	98 a–d	99 a–c
			187	100	0	99	1	96 b–g	92 f–h

[a] All treatments containing glufosinate used the product Liberty, treatments containing dicamba used the product Engenia, treatments containing glyphosate used the product Roundup PowerMax, and treatments containing *S*-metolachlor used the product Dual Magnum.

[b] AIXR indicates TeeJet Air Induction Extended Range nozzle; AITTJ60, TeeJet Air Induction Turbo TwinJet nozzle; TTI, TeeJet Turbo TeeJet Induction nozzle.

[c] Timings that did not meet the assumptions of ANOVA are reported as means followed by the standard error of the mean (SEM).

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

[e] Rate is in grams of acid equivalence (g ae ha^{-1}).

Barnyardgrass. Analysis of barnyardgrass control and biomass in 2013 resulted in a three-way interaction between herbicide, nozzle type, and spray volume. A reduction in control and biomass as spray volume was reduced was also observed with dicamba + glyphosate with the TTI nozzle in 2013. In 2014, the main effect of herbicide and the interaction between nozzle type and spray volume were the significant factors in the model for barnyardgrass control and biomass; therefore, the appropriate means are presented in Table 6. Control at 4 WAT in 2014 with the TTI nozzle at 94 L ha^{-1} was less than it was at 187 L ha^{-1} (91 compared with 94% control, respectively; Table 6). For the main effect of herbicide in 2014, control with dicamba + glyphosate + glufosinate + *S*-metolachlor was greater than it was with all other treatments at 4 WAT, showing the benefit of including a strong residual product with a POST application.

In general, differences in biomass measurements among treatments correlated well with differences observed in the weed-control ratings. However, the biomass measurements did not always correlate with

Table 5. POST pitted morningglory control 2 and 4 wk after treatment (WAT), as influenced by the interactions among herbicide treatment, nozzle type, and spray volume in 2013 and 2014.

				Visual control[c]							
				2013				2014			
Treatments[a]	Rate	Nozzle[b]	Spray volume	2 WAT		4 WAT		2 WAT		4 WAT	
	g ai ha^{-1}		L ha^{-1}	%	SEM	%	SEM	%	SEM	%	SEM
Dicamba + glufosinate	560^{d} + 594	AIXR	94	100	0	96	2	99	1	99	1
			187	100	0	99	1	100	0	99	1
		AITTJ60	94	100	0	98	1	100	0	100	0
			187	100	0	91	2	100	0	100	0
		TTI	94	96	2	88	2	100	0	98	2
			187	100	0	95	2	100	0	99	1
Dicamba + glyphosate	560^{d} + 867^{d}	AIXR	94	100	0	95	2	95	2	97	2
			187	100	0	96	2	99	1	100	0
		AITTJ60	94	91	2	87	1	99	1	99	1
			187	97	2	95	2	100	0	99	1
		TTI	94	97	2	86	1	99	1	100	0
			187	100	0	91	1	93	1	93	1
Dicamba + glufosinate + glyphosate	560^{d} + 594 + 867^{d}	AIXR	94	100	0	96	2	100	0	99	1
			187	100	0	93	5	100	0	99	1
		AITTJ60	94	100	0	90	3	99	1	99	1
			187	99	1	95	2	100	0	97	1
		TTI	94	100	0	91	5	100	0	100	0
			187	100	0	91	4	100	0	98	1
Dicamba + glufosinate + glyphosate + *S*-metolachlor	560^{d} + 594 + 867^{d} + 1,068	AIXR	94	100	0	92	2	99	0	99	1
			187	100	0	98	1	99	0	99	1
		AITTJ60	94	100	0	95	2	100	0	100	0
			187	100	0	93	3	100	0	100	0
		TTI	94	100	0	95	2	100	0	100	0
			187	100	0	94	2	99	1	100	0

---

[a] All treatments containing glufosinate used the product Liberty, treatments containing dicamba used the product Engenia, treatments containing glyphosate used the product Roundup PowerMax, and treatments containing *S*-metolachlor used the product Dual Magnum.

[b] AIXR indicates TeeJet Air Induction Extended Range nozzle; AITTJ60, TeeJet Air Induction Turbo TwinJet nozzle; TTI, TeeJet Turbo TeeJet Induction nozzle.

[c] Mean and the standard error of the mean (SEM).

[d] Rate is in grams of acid equivalence (g ae ha^{-1}).

the weed-control ratings. For example, control with dicamba + glyphosate and the AITTJ60 nozzle did not differ between the two spray volumes. However, a significant difference was observed for the biomass measurements between spray volumes with 94 L ha^{-1} having less biomass than with 187 L ha^{-1}. This inconsistency may be explained by potential bias that could be present in the measurement because sampled plants were only those that survived the herbicide application were sampled. However, because most treatments exhibited $\geq$ 90% control with tank mixtures, biomass measurements collected on a per-plant basis were believed to be the best way to represent what occurred in the field, despite the possibility of bias. Even though biomass is a useful measurement for evaluating the efficacy of herbicides, in field situations, biomass is only one component of a weed-control rating.

Prickly Sida. There was only a sufficient density of prickly sida to collect meaningful data in 2014. For the percentage of prickly sida control, only the main effects of all three factors (herbicide, nozzle, and spray volume) were significant factors in the model, and means for their respective main effects are presented in Table 7, averaged across the other two factors. Only the main effect of herbicide was significant for biomass. For the main effect of

Table 6. POST barnyardgrass control 2 and 4 wk after treatment (WAT) and aboveground biomass, as influenced by the interactions among herbicide, nozzle type, and spray volume in 2013 and 2014.

Treatments[a]	Rate	Nozzle[b]	Spray volume	Visual control[c]					
				2013			2014[d]		
				2 WAT	4 WAT	Biomass	2 WAT	4 WAT	Biomass
	g ai ha^{-1}		L ha^{-1}	———%———		g plant^{-1}	———%———		g plant^{-1}
Dicamba + glufosinate	560[e] + 594	AIXR	94	98 a–d	97 ab	0.05 n	97 b	94 b	0.75 b
			187	99 a–c	97 a–c	0.21 j–m			
		AITTJ60	94	97 a–e	97 a–c	0.22 j–m			
			187	97 c–e	95 b–d	0.56 e–j			
		TTI	94	96 ef	90 f–h	0.82 d–i			
			187	97 b–e	93 d–f	0.58 e–j			
Dicamba + glyphosate	560[e] + 867[e]	AIXR	94	99 a–c	97 a–c	0.12l mn	92 c	94 b	1.15 a
			187	98 a–e	97 a–c	0.52 e–j			
		AITTJ60	94	92 g	88 h–j	0.95 e–h			
			187	92 g	90 f–h	2.75 a–c			
		TTI	94	81 h	83 k	3.41 ab			
			187	96 d–f	94 c–e	0.33 h–l			
Dicamba + glufosinate + glyphosate	560[e] + 594 + 867[e]	AIXR	94	100 a	94 c–e	0.08 mn	98 a	95 b	0.74 b
			187	99 ab	95 b–d	0.16 k–m			
		AITTJ60	94	98 a–e	89 g–i	1.45 a–f			
			187	97 b–e	92 e–g	0.72 e–i			
		TTI	94	94 fg	86 ij	2.54 a–d			
			187	93 fg	86 jk	4.14 a			
Dicamba + glufosinate + glyphosate + *S*-metolachlor	560[e] + 594 + 867[e] + 1,068	AIXR	94	100 a	98 a	0.44 f–k	97 ab	97 a	0.97 ab
			187	99 a–c	98 ab	0.42 g–k			
		AITTJ60	94	99 a–c	96 a–c	0.34 h–l			
			187	99 a–c	97 a–c	0.29 i–l			
		TTI	94	97 b–e	95 b–d	1.67 a–e			
			187	98 a–e	94 c–e	1.19 b–g			
Type × spray volume		AIXR	94	—	—	—	97 a	96 a	—
			187	—	—	—	97 ab	96 a	—
		AITTJ60	94	—	—	—	96 ab	95 ab	—
			187	—	—	—	96 ab	96 a	—
		TTI	94	—	—	—	93 c	91 c	—
			187	—	—	—	95 b	94 b	—

[a] All treatments containing glufosinate used the product Liberty, treatments containing dicamba used the product Engenia, treatments containing glyphosate used the product Roundup PowerMax, and treatments containing *S*-metolachlor used the product Dual Magnum.

[b] AIXR indicates TeeJet Air Induction Extended Range nozzle; AITTJ60, TeeJet Air Induction Turbo TwinJet nozzle; TTI, TeeJet Turbo TeeJet Induction nozzle.

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

[d] In 2014, the main effect of herbicide and the interaction between nozzle type and spray volume were significant in the model.

[e] Rate is in grams of acid equivalence (g ae ha^{-1}).

herbicide, control was significantly less than in all the other herbicide treatments, and biomass was significantly greater than in all other treatments (Table 7). For the nozzle-type main effect, control with the TTI nozzle (91%) was significantly less than it was with the AIXR nozzle (93%) at both 2 and 4 WAT, respectively, averaged across the other two factors. The volume main effect showed weed control using a 94-L ha^{-1} spray volume was 90% and was significantly less than control using 187 L ha^{-1} (93%) averaged across herbicides and nozzles.

Droplet Spectra Analysis. As previously described by Mueller and Womac (1997), different formula-

Table 7. POST prickly sida control 2 and 4 wk after treatment (WAT) and aboveground biomass, as influenced by herbicide treatment, nozzle type, and spray volume in 2014.

Main effect	Treatments	Rate	Control[a]		
			2 WAT	4 WAT	Biomass
		g ai ha^{-1}	———	%———	g plant^{-1}
Herbicide[b]	Dicamba + glufosinate	560[c] +594	97 a	97 a	0.36 a
	Dicamba + glyphosate	560[c] + 867[c]	85 b	85 b	0.71 a
	Dicamba + glufosinate + glyphosate	560[c] + 594 + 867[c]	97	97 a	0.33 b
	Dicamba + glufosinate + glyphosate + *S*-metolachlor	560[c] + 594 + 867[c] + 1,068	97 a	97 a	0.35 b
Nozzle type[d]	AIXR		95 a	93 a	—
	AITTJ60		94 a	91 b	—
	TTI		93 b	91 b	—
Spray volume	L ha^{-1}				
	94		93 b	90 b	—
	187		95 a	93 a	—

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

[b] All treatments containing glufosinate used the product Liberty, treatments containing dicamba used the product Engenia, treatments containing glyphosate used the product Roundup PowerMax, and treatments containing *S*-metolachlor used the product Dual Magnum.

[c] Rate is in grams of acid equivalence (g ae ha^{-1}).

[d] AIXR indicates TeeJet Air Induction Extended Range nozzle; AITTJ60, TeeJet Air Induction Turbo TwinJet nozzle; TTI, TeeJet Turbo TeeJet Induction nozzle.

tions of the same active ingredient will not affect the droplet size equally. Therefore, in this section concerning the droplet spectra analysis, the herbicides will be referred to by their product names (for example, *dicamba* will be referred to as the product *Engenia*).

The weed-control data correlated with the droplet spectra analysis because as D_{v50} increased from AIXR nozzles to the TTI nozzles, efficacy tended to decrease. Changing nozzle size or nozzle type or adding another herbicide into the tank-mix can have a dramatic effect on the droplet spectrum and D_{v50}. The addition of Dual Magnum to Engenia + Liberty + Roundup PowerMax decreased the D_{v50} for the TTI 11006 nozzle from 789 µm to 570 µm and increased the percentage of the volume with droplets < 150 µm ($\%_{\text{vol}}$ fines) from 0.64 to 1.85% (Table 8). Dual Magnum had a similar effect on the other nozzles and spray volumes when compared with those same treatments without Dual Magnum.

For most nozzles, increasing the orifice size from 1.14 and 1.89 L min^{-1} (in the case of this experiment, increasing spray volume) either significantly increased D_{v50} (and decreased $\%_{\text{vol}}$ fines) or had no effect when comparing within the same herbicide (Nuyttens et al. 2007). However, for certain nozzle and herbicide combinations, the opposite effect was observed. For Engenia + Liberty + Roundup PowerMax, increasing the orifice size of the AIXR decreased the D_{v50} from 560 to 501 µm. This result could be attributed to how the solution at this specific herbicide concentration interacted with that specific nozzle type. As previously described, droplet formation is a highly intricate process that quickly becomes convoluted with additions of more variables, such as tank-mixtures, for many herbicide products.

A facet of manipulating spray volume is the magnitude of the effect the herbicides have on droplet size. The statistical range of D_{v50} for the AIXR nozzle across all four herbicides was 28 µm for 187 L ha^{-1} and 175 µm for 94 L ha^{-1} (ranges not shown in Table 8). Thus, as the concentration of herbicide in solution increased, the effect was greater on the droplet size. This effect is important to consider because commercial applicators prefer to use lower spray volumes to cover more field area per load. If a product has a dramatic effect on droplet spectra, that effect could be magnified at lower spray

Table 8. Spray characteristics of nozzle type, spray volume, and herbicide combinations, including the volume diameter[a] (D_{v10}, D_{v50}, D_{v90}), relative span, and percentage of the volume ($\%_{vol}$) containing droplets with diameters < 150 µm.

Treatments[b]	Rate	Nozzle[c]	Spray volume	Droplet spectra parameters[d]				
				D_{v10}	D_{v50}	D_{v90}	Relative span[e]	< 150 µm
	g ai ha^{-1}		L ha^{-1}	——µm	——	——		$\%_{vol}$
Dicamba[c] + glufosinate	560[f] + 594	AIXR	94	208 kl	459 k	778	1.24 a–c	4.15 c
			187	23 6j	515 i	844 g	1.18 e–h	2.88 e
		AITTJ60	94	311 ef	629 d–f	978 d–f	1.06 k	1.04
			187	295 f–h	620 ef	1,000 de	1.14 hi	1.23 h–l
		TTI	94	373 b	743 c	1,106 bc	0.99 l	0.41 mn
			187	340 cd	757 bc	1,289 a	1.25 ab	0.84 k–n
Dicamba + glyphosate	560[f] + 867[f]	AIXR	94	171 m	385 l	663 h	1.28 a	7.20 a
			187	223 jk	487 i–k	797 g	1.18 e–h	3.66 cd
		AITTJ60	94	274 hi	570 gh	929	1.15 g–i	1.56 g–i
			187	285 gh	611 fg	1,000 de	1.17 e–i	1.48 g–j
		TTI	94	321 de	665 d	1,046 cd	1.09 jk	0.92 jk
			187	339 cd	746 c	1,255 a	1.23 b–d	0.70 k–n
Dicamba + glufosinate + glyphosate	560[f] + 594 + 867[f]	AIXR	94	264 i	560 h	925 f	1.18 e–h	1.85 fg
			187	226 jk	501 ij	817 g	1.18 e–h	3.50 d
		AITTJ60	94	308 ef	629 d–f	986 d–f	1.08 k	1.17 h–l
			187	302 e–g	653 de	1,086 bc	1.20 c–f	1.26 g–k
		TTI	94	414 a	800 a	1,130 b	0.90 m	0.29 n
			187	359 bc	789 ab	1,312 a	1.21 b–e	0.64 l–n
Dicamba + glufosinate + glyphosate + *S*-metolachlor	560[f] + 594 + 867[f] + 1,068	AIXR	94	193 l	399 l	658 h	1.17 e–i	4.90 b
			187	240 j	490 i–k	795 g	1.13 ij	2.38 ef
		AITTJ60	94	227 jk	469 jk	782 g	1.19 d–g	2.74 e
			187	242 j	499 ij	821 g	1.16 f–i	2.35 ef
		TTI	94	292 f–h	589 f–h	933 ef	1.09 jk	1.12 i–l
			187	274 hi	568 gh	940 ef	1.17 e–i	1.85 f–h

[a] D_{v10} is the diameter below which 10% of the liquid volume is atomized into smaller droplets. D_{v50} and D_{v90} are similar values for 50 and 90% of the volume, respectively.

[b] All treatments containing glufosinate used the product Liberty, treatments containing dicamba used the product Engenia, treatments containing glyphosate used the product Roundup PowerMax, and treatments containing *S*-metolachlor used the product Dual Magnum.

[c] AIXR indicates TeeJet Air Induction Extended Range nozzle; AITTJ60, TeeJet Air Induction Turbo TwinJet nozzle; TTI, TeeJet Turbo TeeJet Induction nozzle.

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

[e] Relative span is a unitless index of the range of droplet sizes in the spectrum.

[f] Rate is in grams of acid equivalence (g ae ha^{-1}).

volumes and increase the likelihood for off-target movement. Therefore, droplet spectra analysis for as many potential product mixtures as possible will be critical for proper management of off-target movement.

The RS, indicating the range in droplet sizes for a given spectrum, neither followed a set pattern nor provided much useful information about differences among treatments. For certain treatment combinations (e.g., Engenia + Liberty with the AIXR), increasing the orifice size decreased the RS, meaning there was a narrower range in droplet sizes. For other combinations, such as Engenia + Roundup PowerMax with the TTI nozzle, increasing the orifice size increased the RS. In the latter case, the increasing RS is likely attributed to formation of much larger droplets, as shown by the D_{v10} values that did not differ (321 and 339 µm), but the D_{v90} for the 1.89 L min^{-1} was greater (1,255 µm) than it was at 1.14 L min^{-1} (1,046 µm).

Percent Coverage. Data obtained from the water-sensitive droplet cards that were in the field at application may help explain some of the differences

Table 9. Percentage of coverage determined by water-sensitive droplet cards placed in the field at the time of application, as influenced by the interaction among herbicide, spray volume, and the main effect of nozzle type.

Effect	Herbicide[a]	Rate	Spray volume	Coverage[b]
		g ai ha^{-1}	L ha^{-1}	%
Herbicide × spray volume	Dicamba + glufosinate	560[c] + 594	94	45 c
			187	49 bc
	Dicamba + glyphosate	560[c] + 867[c]	94	46 c
			187	53 b
	Dicamba + glufosinate + glyphosate	560[c] + 594 + 867[c]	94	38 d
			187	53 b
	Dicamba + glufosinate + glyphosate + *S*-metolachlor	560[c] + 594 + 867[c] + 1,068	94	44 c
			187	59 a
Nozzle type[d]	AIXR			54 a
	AITTJ60			48 b
	TTI			43 c

[a] All treatments containing glufosinate used the product Liberty, treatments containing dicamba used the product Engenia, treatments containing glyphosate used the product Roundup PowerMax, and treatments containing *S*-metolachlor used the product Dual Magnum.

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

[c] Rate is in grams of acid equivalence (g ae ha^{-1}).

[d] AIXR indicates TeeJet Air Induction Extended Range nozzle; AITTJ60, TeeJet Air Induction Turbo TwinJet nozzle; TTI, TeeJet Turbo TeeJet Induction nozzle.

in efficacy due to nozzle selection and spray volume. Significant factors in the model produced from ANOVA included the interaction between herbicide and spray volume and the main effect of nozzle type. As would be expected when comparing three nozzle types, as D_{v50} decreased, the percentage of coverage increased (ranging from 54% with the AIXR nozzle to 43% with the TTI nozzle; Table 9). For the interaction between nozzle type and spray volume, the percentage of coverage was significantly greater at 187 L ha^{-1} than it was at 94 L ha^{-1} for all herbicides, except Engenia + Liberty. Coverage with Engenia + Liberty was 49% at 187 L ha^{-1} and 49% at 94 L ha^{-1}. Overall, one of the reasons why efficacy tended to be greater at the higher spray volume could be that the percentage of coverage was also greater. Droplet cards are not a perfect method for determining spray volume and have an innate number of weaknesses. Droplets smaller than 80 µm are not readable by the software, meaning the treatment combinations with a larger percentage of fines may have underestimated coverage. Droplet cards can only measure the area that is stained by the droplets, meaning droplets can overlap, smaller droplets can be covered by larger ones, droplets can smear, and high humidity can stain the card as well. Ultimately, droplet cards are an imperfect means of measuring the percentage of coverage, but they are a useful tool for measuring coverage in the field at the time of application.

Practical Implications. These results demonstrate that applicator-controlled variables, including nozzle selection and spray volume, can have an effect on the efficacy of applications made in dicamba-resistant cropping systems. From research scientists to sprayer applicators, anyone involved in making spray recommendations and applications needs to at least be aware of how applicator variables can influence herbicide efficacy. For management of off-target movement, coarser nozzles producing high D_{v50} values, such as the TTI nozzle, are recommended to minimize spray drift. Even though using ultracoarse nozzles may negatively affect efficacy, preventing spray drift may be of greater importance than efficacy maximization. Especially in these situations, an integrated weed-management strategy is paramount for preventing and managing herbicide resistance. Even in a system in which the likelihood for evolving resistance is low, a program approach to weed management, including PRE and POST applications with multiple effective SOAs and overlapping residual herbicides, is still important for long-term successful weed management (Norsworthy et al. 2012).

The results from the weed-control data indicate that, at large droplet sizes (using the TTI nozzle), reducing spray volume from 187 L ha^{-1} to 94 L ha^{-1} can result in a reduction in weed control. As sprayer applicators begin to use larger droplets to reduce drift of auxinic herbicides, combined with lower spray volumes to cover more hectares per sprayer load, a reduction in weed control could negatively affect herbicide-resistance management. An overarching conclusion from these experiments is that the effect applicator variables can have on efficacy will differ across species. Based on these results, spray volume appears to have a larger role in efficacy when herbicides are applied with coarser nozzles, such as the TeeJet TTI. For certain, nozzle selection will have a key role in maximizing the efficacy of POST applications in dicamba-resistant crops, and there appears to be better nozzles for ensuring adequate weed control than the TeeJet TTI nozzle. In addition, evaluating the droplet spectra of additional dicamba-containing tank-mixtures is critical for producing the desired efficacy with a droplet size that will minimize off-target movement.

Literature Cited

Bagavathiannan MV, Norsworthy JK (2013) Occurrence of arable weeds in roadside habitats: implications for herbicide resistance management. Page 163 *in* Proceedings of the 53rd Annual Weed Science Society of America. Lawrence, KS: Weed Science Society of America

Dombrowski N, Hasson D, Ward DE (1960) Some aspects of liquid flow through fan spray nozzles. Chem Eng Sci 12:35–50

Dombrowski N, Johns WR (1963) The aerodynamic instability and disintegration of viscous liquid sheets. Chem Eng Sci 18:203–214

Etheridge RE, Hart WE, Hayes RM, Mueller TC (2001) Effect of Venturi-type nozzles and application volume on postemergence herbicide efficacy. Weed Technol 15:75–80

Heap I (2015) International Survey of Herbicide Resistant Weeds. http://www.weedscience.com/summary/home.aspx. Accessed February 3, 2015

Hoffmann WC, Hewitt AJ (2005) Comparison of three imaging systems for water-sensitive papers. Appl Eng Agric 21:961–964

Knoche M (1994) Effect of droplet size and carrier volume on performance of foliage-applied herbicides. Crop Prot 13:163–178

McKinlay KS, Ashford R, Ford RJ (1974) Effects of drop size, spray volume, and dosage on paraquat toxicity. Weed Sci 22:31–34

Mueller TC, Womac AR (1997) Effect of formulation and nozzle type on droplet size with isopropylamine and trimesium salts of glyphosate. Weed Technol 11:639–643

Norsworthy JK, Burgos NR, Oliver LR (2001) Differences in weed tolerance to glyphosate involve different mechanisms. Weed Technol 15:725–731

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60 (suppl 1):31–62

Nuyttens D, Baetens K, De Schampheleire M, Sonck B (2007) Effect of nozzle type, size and pressure on spray droplet characteristics. Biosyst Eng 97:333–345

Ramsdale BK, Messersmith CG (2001) Nozzle, spray volume, and adjuvant effects on carfentrazone and imazamox efficacy. Weed Technol 15:485–491

Riar DS, Norsworthy JK, Steckel LE, Stephenson IV D, Eubank TW, Scott RC (2013) Assessment of weed management practices and problem weeds in midsouth United States—soybean: a consultant's perspective. Weed Technol 27:612–622

Squire HB (1953) Investigation of the instability of a moving liquid film. Br J Appl Phys 4:167

Received September 14, 2015, and approved October 24, 2015.

Associate editor for this paper: Lawrence Steckel, University of Tennessee