DRIFT POTENTIAL FROM GLYPHOSATE AND 2,4-D APPLICATIONS AS INFLUENCED BY NOZZLE TYPE, ADJUVANT, AND AIRSPEED

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HIGHLIGHTS

- The AIXR nozzle and modified vegetable oil reduce drift potential.
- Downwind spray deposition increases non-linearly as airspeed increases.
- Nozzle selection is more important than adjuvant to mitigate spray drift.

ABSTRACT. *Spray drift is a critical concern for pesticide applications and the largest focus for its reduction has been placed on increasing droplet size. The objectives of this research were to evaluate the influence of nozzle type, adjuvant, and airspeed on the droplet spectrum and spray drift deposits from applications of glyphosate plus 2,4-D in a wind tunnel. Two studies were conducted using three 11002 nozzle types (XR, DG, and AIXR) individually attached to a one-tip boom. The working pressure was 207 kPa. The first study evaluated drift from the potassium salt of glyphosate (1260 g ae ha⁻¹) plus 2,4-D amine (450 g ae ha⁻¹) tank-mixed with four adjuvants (individually) sprayed at 2.2 m s⁻¹ airspeed. A glyphosate plus 2,4-D solution with no tank-mixed adjuvants was also evaluated. The second study evaluated drift from glyphosate plus 2,4-D applications in four airspeeds (0.9, 2.2, 3.6, and 4.9 m s⁻¹). Drift potential was determined using 2 mm monofilament line collectors and a 1,3,6,8-pyrenetetrasulfonic acid tetra sodium salt (PTSA) fluorescent tracer added to solutions, quantified by fluorometry. Nozzles and adjuvants influenced droplet size distribution of glyphosate plus 2,4-D solutions. Among the nozzles, the AIXR produced the coarsest droplets and the lowest tracer deposits (12 ng cm⁻²) at 12 m downwind regardless of solution type. When nozzles were pooled, the modified vegetable oil (MVO) reduced the spray deposition by 36% at 12 m compared to the solution without adjuvant. At 4.9 m s⁻¹ airspeed, tracer deposit at 12 m downwind was 2-fold lower when applications were made through low-drift nozzles (DG and AIXR) compared to the XR nozzle. Results suggest that drift-reducing adjuvants tested in this study may not reduce drift and nozzle selection should be considered as a more important factor than adjuvants in order to mitigate spray drift.*

Keywords. *Drift-reducing technology, Surfactants, Wind tunnel.*

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Submitted for review in July 2019 as manuscript number NRES 13604; approved for publication as a Research Article by the Natural Resources & Environmental Systems of ASABE in May 2020.

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Weed management is a primary concern for agricultural producers. Weeds have caused an average annual yield loss in North American corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merrill] crops of 50% and 52%, respectively, equating to annual revenue losses of \$26.7 and \$17.2 billion dollars, respectively (Soltani et al., 2016, 2017). Herbicides are the most commonly-used weed management tool because they are cost-effective and provide timely weed control (Reddy, 2001). Over 91% of all corn, soybean, and cotton (*Gossypium hirsutum* L.) hectares received an herbicide application in 2016 and 2017 across the United States (USDA-NASS, 2017). In these applications, glyphosate and 2,4-D were among the top five most used active ingredients (Fernandez-Cornejo et al., 2014). In addition, broadleaf crops that are naturally sensitive to 2,4-D, such as soybeans, have been genetically modified to become tolerant to 2,4-D (Wright et al., 2010), which will increase its use in agriculture and may lead to damages on nearby sensitive crops due to off-target movement during the applications.

Although applications of glyphosate and 2,4-D are prevalent, the pesticide application process is complex (Ebert et al., 1999), and a multitude of factors must be accounted for to optimize each application (Kudsk, 2017). A 2016 survey from Missouri identified that more than 62% of applicators changed nozzles less than 50% of the time when switching herbicide products, and on average, only 45% of applicators inspected sprayer parts prior to each application (Bish and Bradley, 2017). As a result, unsuitable or inefficient applications may occur due to improper nozzle selection and other undetected issues (Klein and Kruger, 2011), which potentially leads to increased spray drift.

Spray drift is a critical concern for herbicide applications as previous research determined severe crop injury could occur up to 200 m downwind when synthetic auxin herbicides, such as 2,4-D, were applied (Byass and Lake, 1977). Additionally, previous research reported that crop injury can occur on exposed susceptible crops due to downwind drift from applications of glyphosate, 2,4-D, and dicamba herbicides (Johnson et al., 2006; Egan et al., 2014; Alves et al., 2017a; Kalsing et al., 2018). Drift may also contribute to the evolution of herbicide resistance as sublethal doses have been found to hasten the evolution process (Neve and Powles, 2005; Vieira et al., 2020a).

Multiple application factors, including droplet velocity and trajectory, boom height, distance to susceptible vegetation, air temperature and relative humidity, and wind speed influence spray drift have been previously used in drift prediction models (Miller and Hadfield, 1989; Hobson et al., 1993; Zhu et al., 1994; Smith et al., 2000). The largest focus for spray drift reduction practices has been placed on increasing spray droplet size evidenced by new herbicide labels registered by the U.S. Environmental Protection Agency requiring specific nozzle types, operating pressures, and tank-mixture combinations to be evaluated for their droplet size distributions prior to approval (Anonymous, 2017a, 2017b). This is because spray droplet size is one of the most manageable factors influencing pesticide applications and drastic reductions in downwind spray drift are possible when droplet size is increased (Alves et al., 2017b; Bueno et al., 2017; Vieira et al., 2018). Spray droplet size has been shown to be impacted by numerous factors including: adjuvants, pesticide formulations, interactions between spray solution chemistry and nozzle, nozzle orifice size, and application pressure (Butler Ellis et al., 1997; Butler Ellis and Tuck, 2000; Miller and Butler Ellis, 2000; Nuyttens et al., 2007a; Creech et al., 2015). Nozzle design or type influenced the emitted droplet size in both aerial and ground applications (Bouse, 1994; Nuyttens et al., 2007a) and was identified as the variable with the greatest influence over droplet size (Creech et al., 2015). Therefore, further research is needed to identify application parameters, specifically commonly-used nozzles and adjuvants, that can effectively increase droplet size and reduce drift potential of an application.

Because weather conditions cannot be controlled, it is very difficult to perform spray drift measurements in the field with a high degree of repeatability (Miller and Butler Ellis, 2000). Previous research indicates that the wind tunnel drift simulation method in controlled conditions reproduced near-field spray drift conditions (Vieira et al., 2018, 2019),

which makes the wind tunnel suited for studies where relative drift values are required (Derksen et al., 1999; Sidahmed et al., 2004).

The objectives of this research were: (1) to characterize the effects of nozzle type, adjuvant, and airspeed on downwind spray drift deposits from a tank-mixture of glyphosate (potassium salt) and 2,4-D amine in a low-speed wind tunnel; and (2) to identify the influence of nozzle type and adjuvant on the droplet size distribution from a tank-mixture of glyphosate plus 2,4-D amine.

MATERIALS AND METHODS

Experiments were conducted at the Pesticide Application Technology Laboratory (PAT Lab) at the West Central Research and Extension Center of the University of Nebraska-Lincoln in North Platte, Nebraska, in 2015. Treatments were performed in a low-speed wind tunnel with plexiglass walls and square working sections of 1.2 m wide, 1.2 m high, and 15 m long (Alves et al., 2017a). Applications were made at environmental conditions of 20°C ($\pm 2^\circ\text{C}$) air temperature and 60% ($\pm 5\%$) relative humidity. The wind tunnel facility has an air-conditioning system that controlled air temperature and relative humidity held stable throughout the testing period naturally. One study was conducted to measure the spray droplet size distribution of nozzle type and adjuvant combination treatments when tank-mixed with glyphosate and 2,4-D amine. Two additional, separate studies were conducted to evaluate the effects of nozzle type, adjuvant, and airspeed on downwind spray drift deposits from a tank-mixture application of glyphosate and 2,4-D amine.

DROPLET SIZE MEASUREMENTS

Droplet spectrum for each combination of five spray solutions ([herbicide solution (HS) alone and tank-mixed with either non-ionic surfactant (NIS), drift reduction agent (DRA), modified vegetable oil (MVO), or silicone surfactant (SIL)] and three flat-fan nozzle types [Extended Range (XR11002), Drift Guard (DG11002), and Air Induction Extended Range (AIXR11002) (Spraying Systems Co., Wheaton, Ill.)] was evaluated at 207 kPa. Herbicide solution was composed of the potassium salt of glyphosate (Roundup PowerMax[®], Monsanto Co., St Louis, Mo.) and 2,4-D amine (DMA 4 IVM[™], Dow AgroSciences LLC., Indianapolis, Ind.) at rates of 1260 and 450 g ae ha⁻¹, respectively. Four adjuvants (Wilbur-Ellis Co. LLC, Fresno, Calif.) were individually tank-mixed at maximum label rates with the glyphosate plus 2,4-D amine solution (table 1). An additional HS with no tank-mixed adjuvants was also tested. Solutions were prepared simulating an application at 94 L ha⁻¹.

Droplet spectrum was analyzed using a Sympatec HELOS-VARIO K/R laser diffraction droplet sizing system (Sympatec Inc., Clausthal, Germany) set up with an R7 lens with a dynamic size range of 18 to 3500 μm across 31 sizing bins. The distance from the nozzle tip to the laser was 0.3 m. This system is integrated into the wind tunnel and the airspeed was maintained at 6.7 m s⁻¹ during data acquisition (Fritz et al., 2014a; Butts et al., 2019a). Three replicated

Table 1. Adjuvants tank-mixed with glyphosate plus 2,4-D amine solutions.

Abbreviation ^[a]	Adjuvant Ingredient	Trade Name ^[b]	Rate
NIS	alkylphenol ethoxilate, butyl alcohol, dimethylpolysiloxane	R-11 [®]	% v v ⁻¹
DRA	modified vegetable oil, amine salts of organic acids, organic acids	Crosshair [®]	0.37
MVO	methyl soyate, nonylphenol ethoxilate blend	Superspread TM MSO	2.00
SIL	polyether, polymethylsiloxane, copolymer and polyether	Syl-Coat TM	0.37

^[a] NIS, non-ionic surfactant; DRA, drift reduction agent; MVO, modified vegetable oil; SIL, silicone surfactant.

^[b] Wilbur-Ellis Co. LLC, Fresno, Calif..

measurements were collected for each treatment. Spray parameters of interest were $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ (the droplet diameters for which 10%, 50%, and 90% of the total spray volume is contained in droplets of lesser diameter, respectively), relative span (RS), and volume percentage of droplets smaller than 100 μm (percent fines - V_{100}) (*ASABE Standards*, 2016). Relative span is a dimensionless parameter that indicates uniformity of droplet size distribution, calculated using equation 1, while V_{100} is an indicator of the potential risk of drift.

$$RS = \frac{(D_{v0.9} - D_{v0.1})}{D_{v0.5}} \quad (1)$$

where

RS = relative span (dimensionless)

$D_{v0.9}$ = volumetric diameter of droplets in which 90% of the total spray volume is contained in droplets of lesser diameter (μm)

$D_{v0.5}$ = volumetric diameter of droplets in which 50% of the total spray volume is contained in droplets of lesser diameter (μm)

$D_{v0.1}$ = volumetric diameter of droplets in which 10% of the total spray volume is contained in droplets of lesser diameter (μm).

Spray classifications were determined using the ASABE S572.1 standard (*ASABE Standards*, 2017) modified to adjust for real-world scenarios as it has been widely accepted that pesticide formulation affects droplet size (Miller and Butler Ellis, 2000; Creech et al., 2015). Reference nozzles were used to apply water alone and generate spray classification reference curves in accordance with S572.1 standard.

The droplet size from tested herbicide solution and research nozzle pairings was then evaluated and a spray classification generated to account for both the herbicide solution and nozzle effect on droplet size. These methods are common to adjust for differences among laboratory settings (Fritz et al., 2014b) and evaluate a multitude of herbicide formulation by nozzle interactions affecting spray classifications (Henry et al., 2016; Creech et al., 2018; Vieira et al., 2018; Butts et al., 2018, 2019b).

DOWNWIND SPRAY DEPOSITION

Adjuvant and Nozzle Type Study

A study to evaluate the interaction between adjuvant and nozzle type on downwind spray deposition in a low-speed wind tunnel was conducted in a completely randomized design with five replications in a $5 \times 3 \times 7$ split-split-plot arrangement with spatial units. Main plots consisted of the five spray solutions aforementioned (HS alone and tank-mixed with either NIS, DRA, MVO, or SIL). Subplots consisted of three flat-fan nozzle types (XR11002, DG11002, and AIXR11002). Sub-subplots consisted of seven downwind distances from the nozzle (2, 3, 4, 5, 6, 7, and 12 m). A diagram shows the experimental design for the first replicate (fig. 1). These nozzles were chosen because many burndown applications using older glyphosate plus 2,4-D formulations (2,4-D amine) are still made with DG and AIXR nozzles. The XR nozzle was used to represent the worst-case scenario.

The herbicides, adjuvants, and their respective rates were the same used in the Droplet Size Measurements Study. Solutions were prepared simulating an application at 94 L ha^{-1} . In addition, a 1,3,6,8-pyrenetetrasulfonic acid tetra sodium

Figure 1. Diagram of the experimental design. Abbreviations: HS, herbicide solution; NIS, non-ionic surfactant; DRA, drift reduction agent; MVO, modified vegetable oil; and SIL, silicone surfactant.

salt (PTSA) fluorescent tracer (Spectra Colors Corp., Kearny, N.J.) was added to the solutions at 600 mg L⁻¹ to be detected by fluorometry (Fritz et al., 2011; Hoffmann et al., 2014; Roten et al., 2014).

All applications were performed at 207 kPa pressure and in a 2.2 m s⁻¹ airspeed at the nozzle height measured using a portable anemometer (Nielsen-Kellerman Inc., Kestrel® 4000, Boothwyn, Pa.).

Airspeed and Nozzle Type Study

A study to evaluate the interaction between airspeed and nozzle type on downwind spray deposition in a low-speed wind tunnel was conducted in a completely randomized design with five replications in a 3 × 4 factorial scheme comprising the same three nozzle types described in the previous studies (XR, DG, and AIXR) and four airspeeds (0.9, 2.2, 3.6, and 4.9 m s⁻¹). The herbicide solution (tank-mixture of glyphosate and 2,4-D amine) and pressure (207 kPa) were the same as used in the previous studies. Spray drift deposition was collected only at 12 m downwind from the nozzle, which is the furthest distance from the nozzle capable in the wind tunnel.

Application and Wind Tunnel Set Up

Prior to each application, collectors composed of colorless polymer monofilament line 2 mm in diameter of round shape (Oregon Products, Magnum Gatorline™, Portland, Ore.) and 1.0 m length were positioned at each distance, parallel to the tunnel floor and perpendicular to the air flow (fig. 2a). Applications were made using a one-nozzle spray boom. The flat fan tip discharge was oriented towards the tunnel floor and perpendicular to the air flow (fig. 2b). Nozzles and collectors were placed at 0.6 and 0.1 m above the

tunnel floor, respectively (figs. 2c, 2d). A 1.2 × 0.5 m rug with polyethylene blades 1 cm tall (GrassWorx LLC., St. Louis, Mo.) was positioned on the sprayed area to absorb droplets. Each replication consisted of a continuous 10-s application (±0.2 s), controlled by a digital auto shut-off timer switch (Intermatic Inc., EI 400C, Spring Grove, Ill.).

Once each application was performed, monofilament lines were collected and placed individually into pre-labeled plastic bags. In the laboratory, 40 mL of a 10% v v⁻¹ isopropyl alcohol solution was added to each plastic bag using a bottle top dispenser (LabSciences Inc., 60000-BTR, Reno, Nev.). Samples were then swirled and shaken to release fluorescent material. After the tracer was suspended in the solution, a 1.5 mL aliquot from each sample bag was drawn to fill a glass cuvette, which was placed in a PTSA module inside a fluorimeter (Turner Designs, Trilogy 7200.000, Sunnyvale, Calif.) using ultra-violet light to obtain fluorescent data. Tracer recovery from the collector was 96% and detection limit was 4 ng mL⁻¹. Relative fluorescence units (RFU) data was converted into ng of PTSA cm⁻² of collector using the calibration curve of the tracer. The total circumferential area of outside surface of collector was used as sampling area.

STATISTICAL ANALYSES

Droplet size data were subjected to analysis of variance (ANOVA) using Sisvar Statistical Software, version 5.6 (Ferreira, 2011). Comparisons were made using Scott Knott's multiple comparison test at $\alpha = 0.05$. For analysis of deposition in both studies, Kolmogorov-Smirnov and Levene's tests were applied to analyze normality of residuals

Figure 2. Drift collector (a), spray boom (b), nozzle types (c), and schematic drawing of the wind tunnel detailing the position of collectors and nozzle (d). Collectors placed from 2 to 12 m were used in the Adjuvant and Nozzle Type Study and only at 12 m were used in the Airspeed and Nozzle Type Study.

and homogeneity of variance, respectively, using SPSS Statistical Software, version 20 (SPSS Inc., Chicago, Ill.). Deposition data were transformed by square root (x) and then subjected to ANOVA at $\alpha = 0.05$. Back-transformed data are presented for clarity. When significant differences were observed between nozzle type and adjuvant, nozzles and adjuvants were compared to each other by Tukey's multiple comparison test, whereas regression analysis was performed for the distances and airspeeds, both at $\alpha = 0.05$. Regression models were made using SigmaPlot Software, version 14 (Systat Software Inc., Chicago, Ill.).

RESULTS AND DISCUSSION

DROPLET SIZE MEASUREMENTS

The addition of SIL in HS reduced the droplet diameter ($D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$) up to 20 μm , increased the V_{100} , and produced a more heterogeneous spectrum (greater RS) for all three nozzles compared to HS alone (table 2). The greatest potential risk of drift (largest V_{100} and smallest $D_{v0.1}$) for each nozzle type was produced using the SIL adjuvant compared to the other adjuvants and HS alone with 16.4%, 5.0%, and 2.5% for the XR, DG, and AIXR nozzles, respectively. The adjuvant NIS produced similar droplet spectrum compared to HS alone for the XR and DG nozzles. However, it reduced the $D_{v0.5}$ and increased the percent fines for the AIXR nozzle in comparison to HS alone, HS plus DRA, and HS plus MVO. The adjuvant DRA did not affect the $D_{v0.1}$ and V_{100} compared to the HS alone across nozzles; however, it increased the $D_{v0.5}$ for the DG nozzle, did not alter the $D_{v0.5}$ and decreased the $D_{v0.9}$ for the AIXR nozzle. The adjuvant MVO increased the $D_{v0.5}$ of droplets compared to the other adjuvants and HS alone across nozzles. The HS plus MVO sprayed using the AIXR nozzle produced the lowest V_{100}

(0.50%). For XR and DG nozzles, MVO also reduced the V_{100} compared to the HS alone. The XR nozzle produced the finest droplets, followed by the DG and AIXR nozzles, respectively. These results suggest, regardless of nozzle type, that the use of MVO would be recommended for increasing the droplet size and reducing the percent fines, thereby reducing the drift potential of the application. However, to further reduce the drift potential of glyphosate plus 2,4-D amine, it is advisable to use a combination of an AIXR nozzle (coarse spray classification) and an MVO adjuvant. The adjuvants did not change the spray classification of the droplets according to ASABE S572.1 (*ASABE Standards*, 2017). According to the nozzle manufacturer, the XR11002, DG11002, and AIXR11002 nozzles produce Fine, Medium, and Very Coarse spray classification, respectively, using water at 207 kPa pressure and 25°C temperature. Thus, the herbicides and adjuvants changed the spray classification from Very Coarse to Coarse in comparison to water alone when sprayed through AIXR nozzle.

These outcomes corroborate results that also discouraged the use of XR nozzles in high-wind environmental conditions due to increased drift potential (Johnson et al., 2006). Mota and Antuniassi (2013) also observed that solutions with vegetable and mineral oils provided coarser droplets compared to those produced using silicone adjuvants when sprayed through an air inclusion nozzle (Hypro® Guardian Air 11003). Opposite to results observed in this study, previous research showed the droplet volume diameter was increased by using drift-control adjuvants (polymer- and fatty acid-based) sprayed using an air inclusion nozzle (Teejet® AI11004) (Mota and Antuniassi, 2013). This highlights the importance of research such as this to evaluate the interaction between nozzle types and adjuvants on droplet size distribution and drift potential as conflicting results have been observed.

Table 2. Droplet spectrum from glyphosate plus 2,4-D amine solution tank-mixed with adjuvants sprayed through three nozzle types.^[a]

Solution ^[b]	$D_{v0.1}$ ^[c]	$D_{v0.5}$	$D_{v0.9}$	V_{100}	RS	Spray Classification ^[d]
	XR 11002					
	----- μm -----			%		
HS	85 h	192 j	339 f	14.91 j	1.32 i	Fine
HS + NIS	85 h	193 j	341 f	14.84 j	1.33 i	Fine
HS + DRA	85 h	194 j	342 f	14.67 j	1.32 i	Fine
HS + MVO	116 g	220 i	344 f	6.12 i	1.03 c	Fine
HS + SIL	80 i	186 k	334 f	16.39 k	1.36 j	Fine
	DG 11002					
	----- μm -----			%		
HS	136 e	295 g	488 d	4.26 g	1.19 g	Medium
HS + NIS	137 e	296 g	489 d	3.92 f	1.19 g	Medium
HS + DRA	137 e	300 f	495 d	4.12 g	1.19 g	Medium
HS + MVO	166 d	321 e	487 d	1.66 b	0.99 b	Medium
HS + SIL	129 f	285 h	479 e	5.03 h	1.23 h	Medium
	AIXR 11002					
	----- μm -----			%		
HS	178 b	386 b	604 a	2.01 c	1.10 e	Coarse
HS + NIS	174 c	382 c	595 b	2.25 d	1.10 e	Coarse
HS + DRA	179 b	385 b	594 b	1.99 c	1.08 d	Coarse
HS + MVO	215 a	404 a	590 b	0.50 a	0.93 a	Coarse
HS + SIL	168 d	369 d	584 c	2.48 e	1.12 f	Coarse

^[a] Averages followed by the same letter in the column do not differ using Scott Knott's test at $\alpha = 0.05$.

^[b] Abbreviations: HS, herbicide solution; NIS, non-ionic surfactant; DRA, drift reduction agent; MVO, modified vegetable oil; SIL, silicone surfactant.

^[c] $D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$: droplet diameter for which 10%, 50%, and 90% of the total spray volume is contained in droplets of equal or lesser size, respectively; V_{100} : volume percentage of droplets finer than 100 μm ; RS: Relative span.

^[d] Droplet spray classification according to ASABE S572.1 (*ASABE Standards*, 2017), obtained with each solution.

ADJUVANT AND NOZZLE TYPE DRIFT STUDY

A three-way interaction between solution, nozzle and distance was not significant at $\alpha = 0.05$ for deposition data. Therefore, results were based on the interactions of solution versus nozzle ($p < 0.0171$), solution versus distance ($p < 0.0001$), and nozzle versus distance ($p < 0.0001$). The MVO adjuvant tank-mixed with glyphosate plus 2,4-D amine solution reduced the spray deposition compared to the other adjuvants and HS alone for all three nozzles corroborating the droplet size distribution results (table 3). Conversely, NIS adjuvant increased the drift when compared with HS alone for all three nozzles. The AIXR nozzle generated the lowest spray deposition across solutions, from 105 to 172 ng cm^{-2} , whereas the highest values were produced through the XR nozzle, from 292 to 429 ng cm^{-2} . These results can be associated to the droplet size data, in which the MVO adjuvant and air inclusion nozzle produced coarser droplets and lower percent fines compared to the other solutions and nozzles.

The HS plus MVO produced the lowest spray deposition across distances when nozzles were pooled (table 4). Compared to HS alone, it reduced the deposition by 18% at 2 m and 36% at 12 m. At the furthest distance from the nozzle (12 m), HS plus NIS generated greater deposition compared to the HS alone. Although the SIL reduced the $D_{v0.5}$ of the droplet spectrum, the HS with this adjuvant produced similar spray deposition at 12 m compared with HS alone. Complementing these results, spray deposition decreased as downwind distance from nozzle increased following four-parameter exponential functions with R-squared values over 99% (fig. 3).

As results presented in this study suggest, finer droplets and higher V_{100} (obtained using SIL) did not lead to a greater spray deposition at 12 m when compared to HS alone and pooled across nozzle types. By pooling the droplet size data across nozzle types, the $D_{v0.1}$ and V_{100} of the HS plus SIL solution were 125 μm and 7.97%, respectively, whereas for the HS alone they were 133 μm and 7.06%, respectively. The differences of 8 μm for $D_{v0.1}$ and 0.91 percentage point for V_{100} between these two solutions were not great enough to produce difference on spray deposition at 12 m downwind. Each group of adjuvants has unique characteristics indicating that their use should depend on the specific purpose of each application (Oliveira et al., 2013). Although spray drift can be estimated based on droplet size distribution (Wang and Rautmann, 2009; EPA, 2017), a more appropriate recommendation regarding spray drift should be based on actual

Table 4. Tracer deposition from glyphosate plus 2,4-D amine applications tank-mixed with adjuvants.^[a]

Distance (m)	Solution ^[b]				
	HS	HS + NIS	HS + DRA	HS + MVO	HS + SIL
	----- ng cm^{-2} -----				
2	631 b	802 d	671 b	514 a	727 c
3	396 b	448 d	396 b	307 a	426 bc
4	259 b	260 b	254 b	197 a	276 b
5	159 b	195 c	177 bc	121 a	185 bc
6	116 b	135 c	125 bc	87 a	127 bc
7	81 b	98 c	97 bc	63 a	96 bc
12	25 b	35 c	34 bc	16 a	26 b

^[a] Averages followed by the same letter in the row do not differ using Tukey's test at $\alpha = 0.05$. Data combined across nozzle types.

^[b] HS, herbicide solution; NIS, non-ionic surfactant; DRA, drift reduction agent; MVO, modified vegetable oil; SIL, silicone surfactant.

drift measurements from fields, test benches or wind tunnel studies, especially for ground applications.

The XR nozzle produced the highest spray deposition across distances when solutions were pooled, ranging from 957 ng cm^{-2} at 2 m to 52 ng cm^{-2} at 12 m (fig. 4). Conversely, the AIXR nozzle produced the lowest spray deposition, ranging from 428 ng cm^{-2} at 2 m to 12 ng cm^{-2} at 12 m as can be seen by Tukey's mean separation. At 12 m, the DG nozzle increased the spray deposition in 5 ng cm^{-2} in comparison to the AIXR nozzle. This can be explained as the AIXR nozzle produced the coarsest droplets ($D_{v0.5} = 367 \mu\text{m}$), lowest V_{100} (2%), and had a more homogeneous droplet size spectrum (lower RS). For all three nozzles, deposition decreased exponentially as the distance increased. A study conducted on a test bench showed that non-air inclusion nozzles had greater drift potential than air inclusion nozzles (Gil et al., 2014). Furthermore, nozzle type and size, pressure, and boom height affect drift, and air inclusion nozzles had the greatest reduction of drift potential, followed by pre-orifice nozzles and standard flat-fan nozzles, respectively, similar to results observed in the present research (Nuytens et al., 2007b).

AIRSPED AND NOZZLE TYPE DRIFT STUDY

Downwind spray deposition was affected by a significant airspeed and nozzle type interaction ($p < 0.0001$). Deposition at 12 m downwind from the XR nozzle was greater than deposition generated from the DG and AIXR nozzles across airspeeds (fig. 5). The DG and AIXR nozzles generated similar deposit measurements at 0.9 and 4.9 m s^{-1} , respectively, although the AIXR produced on average a $D_{v0.5}$ 80 μm

Table 3. Tracer deposition from glyphosate plus 2,4-D amine applications tank-mixed with adjuvants sprayed through three nozzle types.^{[a] [b]}

Nozzle	Solution ^[c]				
	HS	HS + NIS	HS + DRA	HS + MVO	HS + SIL
	----- ng cm^{-2} -----				
XR 11002	363 bC	429 cC	405 bcC	292 aC	427 cC
DG 11002	217 bB	245 bB	209 bB	163 aB	232 dB
AIXR 11002	135 bA	172 cA	138 bcA	105 aA	139 bcA

^[a] Averages followed by the same letter, lower case in the row and upper case in the column, do not differ using Tukey's test at $\alpha = 0.05$. Data combined across distances.

^[b] Original data: $F_{\text{Levene}} = 6.291^{**}$; $K-S = 0.152^{**}$. Transformed data: $F_{\text{Levene}} = 1.462^{ns}$; $K-S = 0.102^{**}$. $F_{\text{sol} \times \text{noz} \times \text{dist}} = 0.9^{ns}$; $F_{\text{sol} \times \text{noz}} = 2.3^{**}$; $F_{\text{sol} \times \text{dist}} = 8.1^{**}$; $F_{\text{noz} \times \text{dist}} = 89.9^{**}$; F_{Levene} and Kolmogorov-Smirnov's (K-S) test values of the F statistics. Data transformed by square root (x). $F_{\text{sol} \times \text{noz} \times \text{dist}}$, $F_{\text{sol} \times \text{noz}}$, $F_{\text{sol} \times \text{dist}}$, $F_{\text{noz} \times \text{dist}}$. Calculated F-value for interaction between solution, nozzle, and distance; solution and nozzle; solution and distance; and nozzle and distance, respectively. ** Significant at $\alpha = 0.01$; ns Non-significant.

^[c] Abbreviations: HS, herbicide solution; NIS, non-ionic surfactant; DRA, drift reduction agent; MVO, modified vegetable oil; SIL, silicone surfactant.

Figure 3. Tracer deposition curves from glyphosate plus 2,4-D amine applications tank-mixed with adjuvants. Data combined across nozzle types. Abbreviations: HS, herbicide solution; NIS, non-ionic surfactant; DRA, drift reduction agent; MVO, modified vegetable oil; SIL, silicone surfactant. Fc, Calculated F-value; *, Significant at $\alpha = 0.05$.

coarser and had 2.8% less fines (V_{100}) than the DG nozzle. This illustrates that more factors play a role in spray drift other than droplet size alone. Future research should investigate how droplet velocity, surface tension, and viscosity may affect drift beyond droplet size to more accurately predict drift potential of glyphosate and 2,4-D amine solutions. Droplet size may be a primary factor influencing spray drift; however, Vieira et al. (2020b) reported that droplet velocity and their interactions with droplet size may affect drift potential of pesticide applications. The AIXR nozzle produced the lowest spray depositions at 2.2 and 3.6 m s^{-1} airspeeds (87 and 25 ng cm^{-2} , respectively). This indicates that this nozzle is a reliable option in applications of broad spectrum or non-selective herbicides, such as glyphosate and 2,4-D

amine, to reduce the potential risk of drift. Since glyphosate and 2,4-D are systemic herbicides, coarser droplets do not necessarily decrease their efficacies (Meyer et al., 2015; Creech et al., 2016), although efficacy is influenced by the interaction between tank-mixture, nozzle, and weed species (Meyer et al., 2015; Butts et al., 2019b). As a result, across treatments evaluated within this research, applications of glyphosate and 2,4-D amine should be made when wind speeds are minimal using an AIXR nozzle and the MVO adjuvant. These application parameters generate a Coarse droplet size, reduce drift potential, and would result in no expected loss in weed control using glyphosate and 2,4-D amine.

Figure 4. Tracer deposition curves from glyphosate plus 2,4-D amine applications using three nozzle types. Data combined across solutions. Drift values with the same letters between nozzle types within each distance do not differ using Tukey's test at $\alpha = 0.05$. Abbreviations: Fc, Calculated F-value; *, Significant at $\alpha = 0.05$.

Figure 5. Airspeed effect on tracer deposition at 12 m downwind in glyphosate plus 2,4-D amine applications using three nozzle types. Drift values with the same letter within airspeed do not differ using Tukey's test at $\alpha = 0.05$. Abbreviations: Fc, Calculated F-value; *, Significant at $\alpha = 0.05$.

The spray deposition produced through all three nozzles increased non-linearly as the airspeed increased. However, as droplet size decreased (AIXR > DG > XR), the regression of spray deposition had a tendency to become more linear across increasing airspeeds. The function for the XR nozzle had the lowest coefficient of curvature (0.1248). This highlights the complexity of predicting spray drift in real-world field scenarios as the slopes of the models change respective to airspeed and nozzle type interactions. Additionally, as there are many other factors that influence spray drift (Dorr et al., 2013), more research must be conducted on the numerous interactions occurring, like those highlighted in the present research, to effectively predict spray drift.

A study evaluating dicamba spray drift found similar results in terms of modeling drift for the XR and AIXR nozzles (Alves et al., 2017b). Conversely, the authors found that dicamba spray drift increased more linearly when applications were made through an AIXR nozzle compared to an XR nozzle. These results suggest that drift across airspeeds do not solely depend on nozzle type but also on spray solution. More research is needed to fully understand these complex processes before accurate and precise drift estimates can be successfully made with current application technologies.

CONCLUSION

The AIXR 11002 nozzle produced the coarsest droplets, the lowest percentage of droplets prone to drift (V_{100}), the most homogeneous droplet spectrum (lower RS), and consequently, lowest spray deposition on drift collectors compared to all other treatments evaluated in this research. In applications of the potassium salt of glyphosate (1620 g ae ha⁻¹) plus 2,4-D amine (450 g ae ha⁻¹), the addition of a MVO adjuvant at 2% v v⁻¹ increased the droplet size, reduced the drift potential, and produced a more homogeneous droplet

spectrum in comparison to the other spray solutions. Conversely, the use of a SIL surfactant reduced the droplet size and increased the potential risk of drift, not only for the AIXR, but also for the DG and XR nozzles. Results suggest that MVO may be used to reduce downwind deposition of glyphosate and 2,4-D amine, whereas SIL, NIS, and DRA adjuvants were unsuccessful at reducing downwind deposition of glyphosate and 2,4-D amine regardless of nozzle type. Spray drift and herbicide efficacy field trials using glyphosate plus 2,4-D amine need to be conducted in order to make a more precise recommendations, especially with the AIXR nozzle and MVO adjuvant.

Spray deposition decreased exponentially as downwind distance increased across herbicide solutions, and increased non-linearly as airspeed increased across nozzle types. Applications of glyphosate and 2,4-D amine during higher airspeeds (5 m s⁻¹) should be avoided even when using low-drift nozzles. Results suggest that pesticide applications at recommended airspeeds combined with nozzle selection should be considered more important factors than adjuvant in order to mitigate spray drift.

ACKNOWLEDGEMENTS

The authors would like to thank the Coordination for the Improvement of Higher Education Personnel (CAPES-Brazil) for financial support of the first two authors and the research group of the PAT Lab for its assistance, especially the research assistants of 2015 (Luis Tobias, Frederico Guimarães, and Milos Zaric). No conflicts of interest have been declared.

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