Weed Technology

cambridge.org/wet

Influence of Broadcast Spray Nozzle on the Deposition, Absorption, and Efficacy of Dicamba plus Glyphosate on Four Glyphosate-Resistant Dicot Weed Species

Travis R. Legleiter[1], Bryan G. Young[2] and William G. Johnson[2]

[1]Graduate Student, Department of Botany and Plant Pathology, Purdue University, West Lafayette, IN, USA and [2]Professor, Department of Botany and Plant Pathology, Purdue University, West Lafayette, IN, USA

Weed Management-Major Crops

Cite this article: Legleiter TR, Young BG, Johnson WG (2018) Influence of Broadcast Spray Nozzle on the Deposition, Absorption, and Efficacy of Dicamba plus Glyphosate on Four Glyphosate-Resistant Dicot Weed Species. Weed Technol 32:174–181. doi: 10.1017/wet.2017.104

Received: 15 June 2017
Accepted: 9 October 2017

Nomenclature:
Dicamba; glyphosate; giant ragweed, *Ambrosia trifida* L. AMBTR; horseweed, *Conyza canadensis* (L.) Cronq. ERICA; Palmer amaranth, *Amaranthus palmeri* S. Wats. AMAPA; tall waterhemp, *Amaranthus tuberculatus* (Moq.) *Sauer* (= *A. rudis*) AMATU; soybean; *Glycine max* (L.) Merr.

Key words:
Droplet density; POST application; spray coverage

Author for correspondence:
T. R. Legleiter, P.O. Box 469, University of Kentucky Research and Education Center, Princeton, KY 42445. (E-mail: Travis.Legleiter@uky.edu)

Abstract

Dicamba-resistant soybean technology provides an additional site of action for POST control of herbicide-resistant broadleaf weeds in soybean but also raises concern of off-site movement and damage to sensitive crops in adjacent fields. Dicamba formulations approved for use on dicamba-resistant soybean require applicators to use nozzles producing large droplets to reduce the risk of spray-particle drift. The use of nozzles with relatively larger droplet spectra can reduce herbicide deposition on target weeds, especially if a filtering effect from the crop canopy occurs. Experiments were conducted to evaluate the influence of broadcast nozzle design on the deposition and efficacy of 280 g ha^{-1} glyphosate plus 140 g ha^{-1} dicamba applied POST to four herbicide-resistant weed species. The TTI11004 nozzle, the original nozzle labeled for dicamba applications on dicamba-resistant soybean, reduced deposition coverage and density on spray cards compared with the TT11004 and XR11004 nozzle. The AIXR11004 nozzle produces a very coarse droplet spectrum and did not reduce coverage on spray cards, though it did reduce deposition density. Herbicide solution deposition onto Palmer amaranth, tall waterhemp, giant ragweed, and horseweed ranged from 0.41 to 0.52, 0.55 to 0.87, 0.49 to 0.58, and 0.38 to 0.41 µl cm^{-2}, respectively. Nozzle design and droplet spectrum did not influence the deposition of herbicide solution onto the target weed, as all nozzles were equivalent for all species and site-years. Herbicide efficacy was not influenced by nozzle design, as weed control and plant height reduction were similar for all species. The results of this experiment show that the use of the TTI11004 nozzle for dicamba applications to dicamba-resistant soybean will provide acceptable herbicide deposition and efficacy when applied under the label requirements of weed height and carrier volume.

Introduction

Palmer amaranth, tall waterhemp, horseweed, and giant ragweed (Behrens et al. 2007; Johnson et al. 2010) are four dicot weeds that are ranked among the most troublesome weeds in the United States and the state of Indiana (Gibson et al. 2005; Van Wychen 2016). Palmer amaranth and tall waterhemp are problematic in row-cropping systems due to their rapid growth rates, prolific seed production, season-long emergence pattern, and a wide genetic diversity due to obligate outcrossing (Franssen et al. 2001; Schwartz et al. 2016; Sellers et al. 2003). Horseweed is problematic in soybean due to its high seed production, long-distance seed dispersal, and variable emergence pattern (Davis and Johnson 2008). Its competitiveness for light and ability to emerge in a wide range of environments make giant ragweed troublesome in soybean (Abul-Fatih and Bazzaz 1979; Baysinger and Sims 1991; Webster et al. 1994). In addition to the troublesome biology of these four dicot weeds, all four species have herbicide-resistant biotypes in multiple sites of action in many grain-producing states in the United States (Heap 2017). Resistance to glyphosate and acetolactate synthase inhibitors in all four weed species and resistance to protoporphyrinogen oxidase (PPO) inhibitors in waterhemp and Palmer amaranth have severely limited the POST herbicide options in soybean.

Growers in the state of Indiana have traditionally dealt with horseweed and giant ragweed as the predominant troublesome weeds in soybean. More recently, Palmer amaranth and tall waterhemp have become more widespread across the state of Indiana. Palmer amaranth has been confirmed in more than half of Indiana's counties, while 26 counties have confirmed glyphosate-resistant tall waterhemp, and 10 counties have confirmed PPO-resistant tall waterhemp (TRL and WGJ, personal observation). The introduction of dicamba-resistant soybean provides an additional tool for Indiana farmers and farmers across the United States to control these troublesome broadleaf weeds at planting and in season while providing an additional site of action to the soybean rotation.

While the commercialization of dicamba-resistant soybean will bring additional weed control options to farmers, there is concern that the introduction of this technology will increase the occurrence of off-site movement of dicamba onto susceptible vegetation (Johnson et al. 2012). The movement of dicamba from application sites is of special concern due to the low dosages that cause damage to susceptible dicot plants and the likely presence of economically important susceptible crops such as tomatoes (*Solanum lycopersicum* L.) and sensitive soybean in nearby locations during POST application timings (Chang and Vanden Born 1971). Tomatoes and sensitive soybean are susceptible to yield-reducing dicamba damage from a drift or volatility event (Kruger et al. 2012; Robinson et al. 2013). Concerns of widespread, economically damaging dicamba movement have recently increased, with multiple cases of off-site movement in the delta regions of Missouri, where unlabeled dicamba products were applied to dicamba-resistant soybean and cotton (Bradley 2016). The ultimate success of this new herbicide-resistant soybean technology will hinge largely on the success in minimizing off-site movement events.

Movement of herbicides by particle drift or volatilization is influenced by a number of factors, including meteorological conditions, herbicide formulations, sprayer setup, and droplet spectra size (Carlsen et al. 2006; Combellack 1982). While the meteorological conditions that affect herbicide movement cannot be controlled, the other factors can be controlled or manipulated by the applicator to mitigate off-site movement. Three EPA-approved dicamba products, Engenia™ (BASF Corporation, 26 Davis Drive, Research Triangle Park, NC 27709), Xtendimax™ (Monsanto, 800 N. Lindbergh Boulevard, St Louis, MO 63167), and FeXapan™ (DuPont Crop Protection, P.O. Box 80705 CRP 705/L1S11, Wilmington, DE19880-0705) are registered for application to dicamba-resistant soybean and contain label language that restricts applications to specific broadcast nozzle types, operating pressures, and orifice sizes to minimize the risk of off-site movement. The labels specifically restrict users to large-orifice nozzles that contain pre-orifice, air-induction, or turbulence chamber designs that produce extremely coarse to ultra-coarse droplet spectra and minimize the number of driftable fines. The use of nozzles that produce these larger droplet spectra will reduce horizontal movement of spray particles or drift due to their increased mass and reduced time in the state of fall when used in combination with the other labeled application parameters (Bode 1987).

Extremely coarse to ultra-coarse droplet spectra not only reduce off-site movement, but can also reduce herbicide spray coverage, which can reduce herbicide performance (Knoche 1994). While droplet size is largely influential on herbicide coverage and performance, the type of herbicide, target species, and interfering crop canopies must also be considered (Knoche 1994). Performance of contact herbicides is much more influenced by droplet size and coverage than systemic herbicides, such as dicamba and glyphosate, that can perform over a wider range of coverages and droplet sizes (Ramsdale and Messersmith 2001). The architecture of the target weed also influences the overall deposition of herbicide solution, because dicots with greater leaf areas are likely to receive greater coverage than monocot species that have a smaller leaf surface to capture droplets (Dorr et al. 2008). The interference of a crop canopy can also alter herbicide coverage, because droplets can be filtered and coverage reduced at lower levels in the canopy, where target weed(s) may exist (Bradley and Sweets 2008; Legleiter and Johnson 2016).

POST applications of dicamba in dicamba-resistant soybean are most likely to be targeted toward troublesome and herbicide-resistant broadleaf weeds such as Palmer amaranth, tall waterhemp, giant ragweed, and horseweed (Norsworthy et al. 2012). These applications are likely to occur with interference from a crop canopy if they following a PRE application or interference from other weeds in a total POST application system (Legleiter et al. 2009).

The objective of this experiment was to evaluate (1) the influence of droplet spectra produced by two traditional flat-fan nozzles and two drift-reduction air-induction nozzles on deposition of a POST glyphosate plus dicamba application on glyphosate-resistant Palmer amaranth, tall waterhemp, giant ragweed, and horseweed and (2) the resulting absorption of the herbicides into each weed species and any differences in efficacy on those species.

Materials and Methods

Field Sites

The experimental data set is represented by 2 site-years per weed species or 8 total site-years. Field experiments were conducted at locations with populations of glyphosate-resistant Palmer amaranth, tall waterhemp, horseweed, and giant ragweed during the 2015 and 2016 growing seasons. Locations of experiments can be found in Table 1. Vegetation was terminated before planting either with tillage or a paraquat treatment, with the exception of the Brookston 2016 site, which was planted into an existing stand of horseweed due to delays in planting and spray applications due to weather. A glyphosate-resistant soybean variety (Asgrow® 2933, Monsanto) was planted at all sites in 38-cm row spacing at rate of 312,000 to 370,000 seeds ha^{-1}. A PRE application of acetochlor at 840 g ai ha^{-1} (Warrant®, Monsanto) was applied to the Medaryville 2016 Palmer amaranth and Meigs 2016 tall waterhemp experiment sites to suppress high-density populations of each respective weed species and allow for soybean emergence and development before the POST application. Planting dates for each location can be found in Table 1.

Herbicide Application and Experimental Design

Plots were arranged in a randomized complete block design with six replications, and measured 3-m wide by 8-m long. An all-terrain vehicle with a 2-m side boom with four nozzles spaced on 50-cm centers was used to apply treatments. Treatments were applied using nozzle orifices rated for a 1.5 L min^{-1} output, pressurized at 276 kPa at a travel speed of 19 km h^{-1} in an effort to replicate commercial field applications. Total output of the spray application was 94 L ha^{-1}. Crop stage, weed height and density, and weather conditions at the time of application are listed in Table 1.

Four 110° broadcast flat-fan TeeJet® (TeeJet Technologies, 200 W. North Avenue, Glendale Heights, IL 60139) nozzles were selected for evaluation due to the following design attributes: the XR11004 represents a traditional, single-stage, flat-fan nozzle without any drift-reduction attributes; the TT11004 represents a two-stage plus turbulence chamber nozzle design; the AIXR11004 represents a two-stage air-induction nozzle design; and the TTI11004 represents a two-stage, air-induction, and turbulence chamber nozzle design. The AIXR11004 and TTI11004 nozzles would both represent drift-reduction technology nozzles,

Table 1. Planting date, date of herbicide application, and application parameters for the Palmer amaranth, tall waterhemp, giant ragweed, and horseweed site-years.[a]

Site-year	Weed species	Planting date	Treatment date	Soybean stage	Weed height	Weed density	Temperature	Relative humidity	Wind speed
				Trifoliate	cm	m^{-2}	C	%	km h^{-1}
MDV 2015	AMAPA	May 20	July 15	8	5–15	0.5–2	23	74	10
MDV 2016	AMAPA	May 19	June 16	3	5–10	3–4	24	67	5
MGS 2015	AMATA	May 14	June 28	5	10–15	20–50	22	64	0
MGS 2016	AMATA	May 7	June 17	4	8–10	10–15	29	44	6
WL2015	AMBTR	May 29	June 19	2	10–15	2–5	21	91	8
WL2016	AMBTR	April 25	June 3	3	10–15	1–5	25	56	0
MGS2015	ERICA	May 7	June 20	4	10–15	2–3	22	92	2
BRK2016	ERICA	May 20	June 11	1	8–30	50–70	29	58	8

[a] Abbreviations: BRK, Brookston, IN; MDV, Medaryville, IN; MGS, Meigs South Research Facility; WL, West Lafayette, IN; AMAPA, Palmer amaranth; AMATA, tall waterhemp; AMBTR, giant ragweed; ERICA, horseweed.

although only the TTI11004 is currently labeled for applications of the approved dicamba formulations.

The herbicide solution was 280 g ha^{-1} glyphosate (Roundup PowerMax®, Monsanto) plus 140 g ha^{-1} dicamba (Engenia™, BASF) and a nonionic surfactant (NIS) at 0.25% v/v. The lower than labeled rates of herbicide were used to maximize any differences in efficacy that might occur between application treatments. A visual pink foam marker dye (Vision Pink™, Garrco Products, P.O. Box 619, Converse, IN 46919-0619) and a fluorescent 1,3,6,8 pyrene tetra sulfonic acid (PTSA) dye (Spectra Trace SH-P, Spectra Colors, 25 Rizzolo Road, Kearny, NJ 07032) were also included in the spray mixture at 0.25% v/v and 600 µg ml^{-1}, respectively.

Data Collection and Analysis

Spray Solution Coverage and Deposition Density

Spray solution coverage and deposition density were evaluated using 5 cm by 7.6 cm cardstock coated with Kromekote that shows defined marking when contacted with spray solutions containing the Vision Pink™ foam marker dye. Five cards were placed parallel to the ground in each plot using metal holders just before each application. Cards were placed at the height of the target weeds and were arranged in a diagonal pattern between two soybean rows to capture droplets at all positions. Cards were allowed to dry after application and were then placed in plastic bags for storage until further analysis.

A duplex scanner (Image Center™ ADS-2000, Brother International, 200 Crossing Boulevard, Bridgewater, NJ 08807-0911) was used to convert the cards into 600 by 600 dpi, 24-bit color digital images. The pink droplet depositions were separated from the white background of the image using Assess 2.0 Image Analysis Software for Plant Disease Quantification, (American Phytopathological Society, 3340 Pilot Knob Road, St Paul, MN 55121). The Assess data output included the area of droplet depositions (mm^2) and droplet deposition counts from within the area of the card. Using the known size of the cards, the droplet deposition area was converted to percent coverage, and droplet deposition counts were converted to deposition density.

The five individual cards from each plot were treated as subsamples of the whole plot. Differences in percent coverage and deposition density were analyzed using ANOVA in SAS v. 9.4 PROC MIXED (SAS Institute, Cary, NC 27513) with replication as a random factor. Means separation occurred at alpha = 0.05 adjusted for Tukey honest significant difference (HSD). Means were pooled across site-years within a species when differences between site-years did not occur.

Herbicide Solution Deposition on Target Weeds

Herbicide deposition data were collected using a fluorescent tracer dye and methods developed based on Fritz et al. (2011). One plant of the target weed that represented the average weed height of the plot was harvested and washed with 200 ml of an NIS (Triton™ X-100, EMD Chemicals, 480 South Democrat Road, Gibbstown, NJ 08027) and water (1:1000) solution immediately following herbicide application. The representative target weed height for each site can be found in Table 1; crew members were instructed to collect 10- to 15-cm-tall weeds with minimal overhead interference at the Brookston 2016 site, which had a large variation in weed heights. Plants were washed in the solution using the following method: a syringe was used to pull wash solution from the clean vial before any introduction of plant material; the target plant was then cut at the soil surface while being grasped with a set of forceps and was then placed into and agitated in the wash solution for 30 s; and the plant was then rinsed with the solution from the syringe as it was removed from the wash vial. Washed plants were then placed in envelopes for transportation back to the campus laboratory for whole-plant leaf-area analysis using a leaf-area meter (LI-3100, LI-COR, 4647 Superior Street, Lincoln, NE 68504-5000). Between treatments, the forceps were washed with a 1:1 water and methanol solution to avoid cross contamination; if used properly, the syringes were only exposed to uncontaminated solution and were only replaced between treatments if a contamination event occurred.

Wash solutions were transported to the campus laboratory and quantified for raw fluorescence with a laboratory fluorimeter (Trilogy Laboratory Fluorometer, Turner Designs, 1995 N. 1st Street, San Jose, CA 95112) equipped with a PTSA-specific module. The PTSA concentration (µg ml^{-1}) in the wash solution, known volume of the wash solution (200 ml), known rate of PTSA in the spray-tank solution (600 µg ml^{-1}), and leaf area of the plant (cm^2) were all used to calculate the final values of wash solution deposited onto the target plant surface ($\mu l\ cm^{-2}$).

ANOVA of spray solution deposition onto target plants was conducted using SAS v. 9.4 PROC MIXED with means separation using Tukey HSD at alpha = 0.05. Herbicide solution deposition means within a species were pooled across site-years when differences between years were not significant.

Dicamba Concentration on Leaf Surface

Dicamba concentration on the leaf surface was taken immediately following herbicide application and at 2, 4, 6, and 24 h after herbicide application. One leaf from a target species plant was harvested from each replication at each timing. The leaf was selected from a plant of the target height as described in the previous section; the harvested leaf was at the node below the newest fully expanded leaf. The selected leaf was washed in 50 ml of 1:1 water and high-performance liquid chromatography–grade methanol solution. The wash procedure consisted of using a syringe to extract 10 ml of clean solution from the 50 ml vial before introducing any leaf material and then agitating the leaf in the remaining solution in the vial for 30 s. The leaf was then rinsed with the 10-ml solution from the syringe as it was pulled from the wash solution vial. Wash solutions were stored at room temperature in closed boxes until preparation and analysis. The leaf area and the biomass of the leaves were taken from the washed leaves in the lab following collection in the field. Leaf wash solutions were collected from all six replications, although only three replications were analyzed for dicamba concentration in the procedures described in the following paragraphs.

Wash solutions were prepared for analytical analysis by taking a 1-ml aliquot of wash solution and adding 500 ng of d_3-dicamba (CDN Isotopes, Pointe-Claire, QC, Canada) as an internal standard. Samples were dried in a vacuum concentrator, then derivatized by adding 40 µl anhydrous pyridine and 60 µl MSTFA, and finally heated for 1 h at 60 C.

Levels of dicamba were determined using a gas chromatograph/mass spectrometer–mass spectrometer analysis. The gas chromatograph was a 1310 Thermo Trace using a Thermo TG-SQC column (15 m by 0.25 mm by 0.25 µm). A 1-µl injection volume was used with an inlet temperature of 250 C with a 10:1 inlet split ratio and column flow of 1.5 ml min^{-1}. The thermal gradient had an initial temperature of 120 C, held for 1 min, a 20 C min^{-1} increase until 320 C, then held for 3 min. The retention time for dicamba was 3.6 min.

Analytes were then quantified with a Thermos TSQ Evo 8000 triple-quadrupole mass spectrometer. Positive chemical ionization mode was used, with a methane flow rate of 1.0 ml min^{-1}. Quantitation was based on multiple reaction monitoring. A transition of 292 to 202 was used for dicamba and 295 to 204 for d_3-dicamba. A collision energy of 5 V was used for all transitions. Data were collected and analyzed with Thermo Chromeleon v. 7.2 SR4 software (Thermo Fisher Scientific, Waltham, MA). Responses for dicamba were normalized and quantitated against the internal standard.

Quantities of dicamba from the wash samples were then converted to nanograms of dicamba per square centimeter of leaf surface area using the previously measured leaf areas. A two-factor ANOVA was used to evaluate differences in nanograms of dicamba per square centimeter between nozzles and collection times. Analysis was conducted using SAS v. 9.4 PROC MIXED with means pooled across years for each species to increase the power of statistical analysis. Means separation was performed with Tukey HSD, $\alpha = 0.05$.

Herbicide Efficacy

Plots were evaluated for herbicide efficacy 21 d after application. A 0% to 100% visual evaluation was taken for control of the target weed species with 0% representing no control and 100% representing complete control. Height measurements were taken for three randomly selected plants per plot and for three plants within untreated strips in each replication block at the Palmer amaranth, tall waterhemp, and horseweed sites. Heights of giant ragweed were not taken due to the overall high efficacy of dicamba on the species and a lack of measurable plants. Height measurements of the three plants per plot were treated as subsamples of the whole plot and converted to percent height reduction using the weed heights in the untreated strips.

Differences in visual evaluations and percent height reduction were determined using ANOVA in SAS v. 9.4 PROC MIXED with means separation using Tukey HSD at alpha = 0.05. Replications were considered a random factor. Visual evaluation means for Palmer amaranth, giant ragweed, and horseweed were pooled across years due to a lack in differences between years. Visual evaluation means for tall waterhemp and plant height reduction means for all species were pooled across years to maximize statistical power due to similarities in means differences.

Droplet Spectrum Analysis

Spray droplet spectrum analysis was conducted on one randomly selected nozzle of the four used for each nozzle type in the field study in an effort to broaden the applicability of the data to droplet categories rather than just the four specific nozzles evaluated. Analysis was conducted using the discriminating spray tank mix from the field experiments (280 g ha^{-1} glyphosate plus 140 g ha^{-1} dicamba plus 0.25% v/v NIS) and the labeled rates of the products (1,120 g ha^{-1} glyphosate plus 560 g ha^{-1} dicamba plus 0.25% v/v NIS).

The Pesticide Application Technology Laboratory at the University of Nebraska–Lincoln West Central Research and Extension Center (UNL PAT) conducted spray droplet spectrum analysis. Before analysis, each nozzle tip was flow rated to determine that wear or damage had not occurred to the orifice during field experiment applications. The spray droplet spectrum was analyzed using laser diffraction with a Sympatec Helos Vario KR particle-size analyzer equipped with an R7 lens. Analysis was conducted within a low-speed wind tunnel with an air velocity of 24 km h^{-1} to aid in evacuation of spray droplets from the laser path after analysis. The spray plume of each nozzle was analyzed three times by traversing the entire plume vertically through the laser path. The Dv_{10}, Dv_{50}, and Dv_{90}, which represents the percentage (10, 50, and 90 respectively) of droplets within the spray volume that are at or below the reported diameter, were output from the analysis. Each nozzle and herbicide rate combination was classified into a droplet category based on the Dv_{10}, Dv_{50}, and Dv_{90} values using an established reference curve from the UNL PAT lab per ASABE S572.1.

Results and Discussion

Droplet Spectrum Analysis

The spray droplet sizes produced by the nozzle types were as expected, with a Dv_{50} of 234 to 276 µm occurring with the single-stage XR11004 nozzle and Dv_{50} values of 337 to 763 µm provided by the TT11004, AIXR11004, and TTI11004 two-stage nozzles (Table 2).

Table 2. Dv_{10}, Dv_{50}, Dv_{90}, and spray classification category for each nozzle at a discriminating and full rate of glyphosate plus dicamba.[a]

Nozzle	Herbicide rate[b]	Dv_{10}	Dv_{50}	Dv_{90}	Spray classification category[c]
		———————— µm ————————			
XR11004	Discriminating	144	276	426	Medium
	Full	105	234	406	Fine
TT11004	Discriminating	162	337	556	Medium
	Full	159	356	628	Medium
AIXR11004	Discriminating	238	466	712	Very coarse
	Full	209	432	688	Very coarse
TTI11004	Discriminating	373	732	1,093	Ultra-coarse
	Full	380	763	1,164	Ultra-coarse

[a] Dv_{10}, Dv_{50}, and Dv_{90}: the percentage (10, 50, and 90 respectively) of droplets in the spray volume that are at or below the reported diameter.
[b] Discriminating rate: 280 g ha^{-1} glyphosate plus 140 g ha^{-1} dicamba; full rate: 1,120 g ha^{-1} glyphosate plus 560 g ha^{-1} dicamba.
[c] Spray classification categories assigned using reference curve generated at the University of Nebraska–Lincoln Pesticide Application Technology laboratory in accordance to ASABE S542.1.

The two air-induction nozzles, AIXR11004 and TTI11004, had Dv_{50} values of 432 to 763 µm; they also both had Dv_{10} values greater than 200 µm, indicating spray volume contained less than 10% driftable fines (Table 2). Despite the low percentage of driftable fines for both air-induction nozzles, only the TTI11004 nozzle with the greatest volume mean diameter is allowed for applications of the approved dicamba formulations. When comparing the Dv_{50} values between the herbicide rates, the XR11004 and AIXR11004 nozzles had a smaller Dv_{50} value at the full rate compared with the reduced rate. The smaller Dv_{50} at the full rate would be expected with the increased amount of glyphosate formulation and surfactant load which is known to decrease droplet size (Hilz and Vermeer 2013). Conversely, the two nozzles with turbulence chambers (TT11004 and TTI1104) produced smaller Dv_{50} values at the reduced rate, which may be an indication of an interaction of the turbulence chamber design.

The Dv_{10}, Dv_{50}, and Dv_{90} values of each nozzle and herbicide rate were plotted on an established standard curve and placed into droplet categories in accordance to ASABE S572.1. The TT11004 produced medium droplets at both herbicide rates, the AIXR11004 produced a very coarse droplet spectrum for both rates, and the TTI11004 produced the largest droplet spectrum of ultra-coarse for both herbicide rates (Table 2). The XR11004 nozzle was the only nozzle to differ in droplet spectrum categories between the two herbicide rates, with the full rate producing a fine spectrum and the reduced rate producing a medium droplet spectrum. The two reduced-drift nozzles of interest (AIXR11004 and TTI11004) provided similar droplet categories between rates, despite differences in Dv_{50} values between rates, allowing for evaluation of the data in the following sections without regard to the rate. The two non–air induction nozzles (TT11004 and XR11004) will be considered as medium droplet–producing nozzles, as this is the category that both fell within at the discriminating rate.

Spray Solution Coverage and Deposition Density

Spray solution coverage was reduced by the TTI11004 nozzle (10.7% to 20.1%) compared with the AIXR11004 (11.1% to 24.6 %), TT11004 (16.1% to 25.9 %), and XR11004 (16.6% to 26.6%) nozzles in the tall waterhemp, horseweed, and giant ragweed experiments (Table 3). The TTI11004 nozzle also reduced spray solution coverage compared with the XR11004 and TT11004 nozzles in the Palmer amaranth experiments and was similar to the AIXR11004 (Table 3). The other drift-reduction nozzle, AIXR11004, was similar to the two smaller droplet–producing nozzles in all experiments, with the exception of the 2015 Palmer amaranth site. The decrease in spray coverage with the ultra-coarse droplet produced by the TTI11004 nozzle was

Table 3. Glyphosate plus dicamba solution coverage on spray cards placed at the height of Palmer amaranth, tall waterhemp, giant ragweed, and horseweed at a POST application.

	AMAPA[a]		AMATA[a]			
Broadcast nozzle	2015	2016	2015	2016	AMBTR[a,b]	ERICA[a,b]
	———————— % coverage[c] ————————					
XR11004	16.6 A	26.6 A	21.4 A	24.5 A	25.0 A	21.3 A
TT11004	16.1 AB	25.9 A	21.8 A	23.2 A	23.9 A	22.0 A
AIXR11004	11.1 BC	24.6 AB	22.7 A	23.0 A	22.6 A	20.7 A
TTI11004	10.7 C	20.1 B	14.6 B	15.9 B	18.7 B	17.5 B

[a] Abbreviations: AMAPA, Palmer amaranth; AMATA, tall waterhemp; AMBTR, giant ragweed; ERICA, horseweed
[b] Means pooled across site-years.
[c] Means within a column followed by a different letter are significantly different. Tukey HSD at $\alpha = 0.05$.

Table 4. Glyphosate plus dicamba deposition counts per square centimeter on spray cards placed at the height of Palmer amaranth, tall waterhemp, giant ragweed, and horseweed at a POST application.

Broadcast nozzle	AMAPA[a] 2015	AMAPA[a] 2016	AMATA[a,b]	AMBTR[a,b]	ERICA[a,b]
	———————— Droplet no. cm^{-2c}	————————			
XR11004	41 A	52 A	53 A	50 A	42 A
TT11004	33 A	46 A	46 B	42 B	39 A
AIXR11004	19 B	28 B	31 C	26 C	25 B
TTI11004	9 C	15 C	13 D	14 D	13 C

[a] Abbreviations: AMAPA, Palmer amaranth; AMATA, tall waterhemp; AMBTR, giant ragweed; ERICA, horseweed.
[b] Means pooled across site-years.
[c] Means within a column followed by a different letter are significantly different. Tukey HSD at $\alpha = 0.05$.

Table 5. Deposition of glyphosate plus dicamba spray solution on target plants of Palmer amaranth, tall waterhemp, giant ragweed, and horseweed.

Broadcast nozzle	AMAPA[a,b]	AMATA[a] 2015	AMATA[a] 2016	AMBTR[a,b]	ERICA[a,b]
	———————— $\mu l\ cm^{-2}$	————————			
XR11004	0.41	0.57	0.86	0.52	0.38
TT11004	0.46	0.59	0.87	0.49	0.41
AIXR11004	0.45	0.62	0.85	0.51	0.39
TTI11004	0.52	0.55	0.78	0.58	0.39
P	0.6864	0.8245	0.7066	0.4634	0.9328

[a] Abbreviations: AMAPA, Palmer amaranth; AMAT, tall waterhemp; AMBTR, giant ragweed; ERICA, horseweed.
[b] Means pooled across site-years.

expected, as previous work has also shown a decrease in coverage with increasing droplet size (Knoche 1994).

Deposition density was the greatest with the two non–drift reduction nozzles and ranged from 33 to 53 deposits cm^{-2} across all sites (Table 4). The drift-reduction AIXR11004 nozzle produced 19 to 31 deposits cm^{-2}, which was lower than the two non–drift reduction nozzles, but greater than the TTI11004 nozzle (9 to 15 deposits cm^{-2}) (Table 4). The decrease in deposition density with an increase in droplet size would be expected with a set carrier volume and may be a concern if approaching a minimum threshold for deposition.

The use of spray cards gives an effective estimate of solution coverage of a surface as well as density of depositions onto a surface. The data collected by the cards in this study across multiple species were as expected in comparison to previous work (Knoche 1994). However, due to differences in target plant leaf surface angles and composition, investigating the actual deposition onto our target weed leaf surfaces is warranted.

Herbicide Solution Deposition on Weed Species

Means of herbicide solution deposition onto Palmer amaranth, giant ragweed, and horseweed were pooled across years, while tall waterhemp means were separated. Deposition of herbicide solution on Palmer amaranth was 0.41 to 0.52 $\mu l\ cm^{-2}$, giant ragweed deposition was 0.49 to 0.58 $\mu l\ cm^{-2}$, and horseweed deposition was 0.38 to 0.41 $\mu l\ cm^{-2}$ (Table 5). Herbicide solution deposition onto tall waterhemp was 0.55 to 0.62 $\mu l\ cm^{-2}$ in 2015 and 0.78 to 0.87 $\mu l\ cm^{-2}$ in 2016. Differences between tall waterhemp site-years likely occurred due to differences in weed density, because the density was higher in 2015 than in 2016 (Table 1), and a depleted soybean canopy in 2016. The lower level of soybean canopy and lower densities of tall waterhemp plants in 2016 likely reduced the amount of droplet filtering and thus increased overall herbicide solution deposition onto the target plants. The lowest solution deposition occurred on horseweed, which can be attributed to the vertical architecture of smaller leaves stacked along the bolting stem on horseweed that are less exposed to a broadcast application than the other three weed species, which have more horizontally spread leaf architectures.

The theoretical maximum herbicide solution deposition on the leaf surfaces would be 0.935 $\mu l\ cm^{-2}$, which is simply a conversion of the field application rate (0.94 $l\ ha^{-1}$) to microliters per square centimeter. In comparison to a theoretical maximum deposition, the depositions in these studies were 41% to 93% of that value. A reduction in the deposition compared with the theoretical maximum would be expected, because the application was not made to a flat surface in a vacuum, but in the field, with environmental conditions that effect deposition and highly variable deposit surfaces of multiple plant species that occur at varying angles and heights.

There were no differences in herbicide solution deposition between nozzle types within each species, despite differences in site-years and variability among weed species. The two air-induction nozzles (AIXR11004 and TTI11004) both provided equivalent herbicide solution deposition on the four target species compared with the two traditional medium droplet–producing nozzles.

The deposition of herbicide solution from a broadcast application onto these four broadleaf weeds was not affected by the nozzle design or droplet spectrum, but rather was more likely affected by filtering from the soybean canopy and other weeds, and the overall weed leaf architecture.

Dicamba Concentration on Leaf Surface

The level of dicamba on the leaf surface was influenced by time after application ($P < 0.0001$); the influence of nozzle and the interaction of nozzle and time after application was insignificant for all four weed species (Figure 1). Dicamba levels on the leaf surface were greatest at the 0-h time for all four weed species and ranged from 707 to 1,083 ng dicamba cm^{-2} leaf surface area (Table 6). These concentrations of dicamba are 50% to 77% of the field application target of 1,400 ng cm^{-2} or 140 g ha^{-1}. The recovery efficiency of dicamba from the leaf surface following application was similar to the recovery efficiency of the fluorescent dye. Dicamba levels on the leaf surface were reduced by 2 h after application and continued to drop until 24 h after application for all four weed species (Table 6).

Dicamba concentration analysis from the surface of the leaf following herbicide application revealed that likely maximum absorption of the herbicide occurs 2 h after application for waterhemp, giant ragweed, and horseweed and at 4 h for

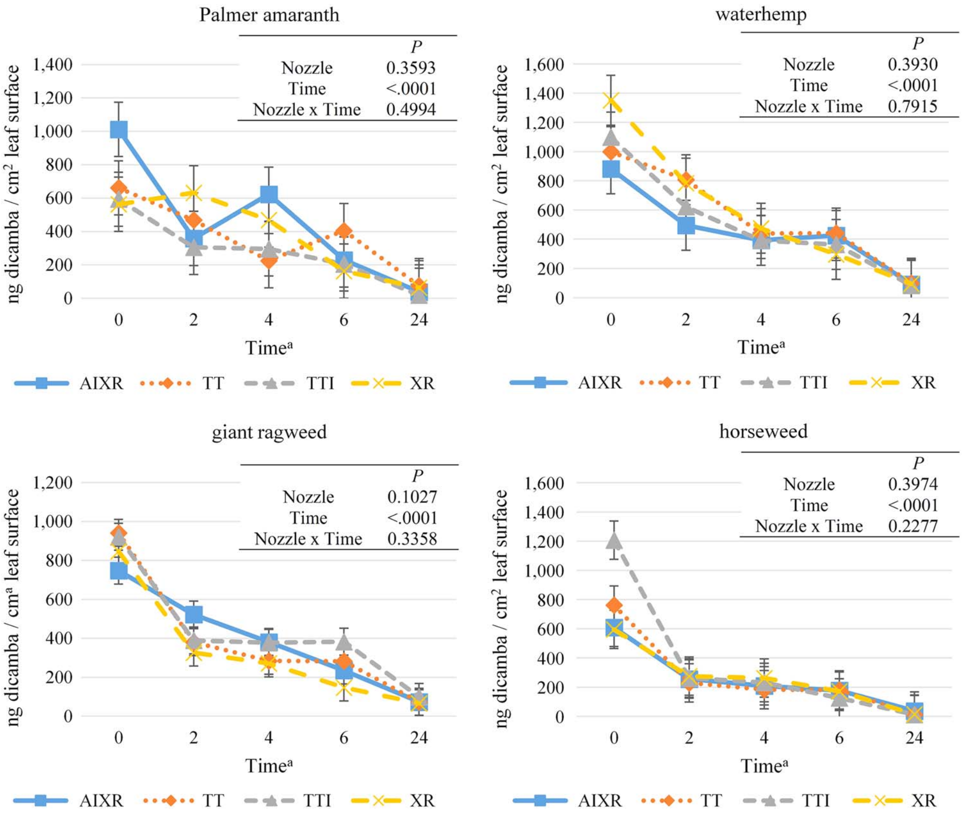

Figure 1. Concentration of dicamba on the leaf surface of Palmer amaranth, waterhemp, giant ragweed, and horseweed leaves over a 24-h period after herbicide application as influenced by broadcast spray nozzle design. Abbreviations: XR, XR11004 nozzle; TT, TT11004 nozzle; TTI, TTI11004 nozzle; AIXR, AIXR11004 nozzle (TeeJet Technologies, 200 W. North Avenue, Glendale Heights, IL 60139); Time = hours after application.

Palmer amaranth, with significant decreases on the leaf surfaces occurring at these times (Table 6). The droplet spectrum size of the nozzle used to make the application did not influence the absorption of dicamba in Palmer amaranth, waterhemp, giant ragweed, and horseweed, because the concentrations on the leaf surfaces were similar between all four nozzles at 0, 2, 4, 6, and 24 h after application (Figure 1). Results from the methods used in this study indicate that the use of drift-reduction nozzles that produce very coarse and ultra-coarse droplet spectra did not influence the absorption of dicamba in four glyphosate-resistant dicot species.

Table 6. Concentration of dicamba on the leaf surface of Palmer amaranth, waterhemp, giant ragweed, and horseweed leaves over a 24-h period following herbicide application.

Time	AMAPA[a]	AMATA[a]	AMBTR[a]	ERICA[a]
h after application	——— ng dicamba cm^{-2} leaf surface[b] ———			
0	707 A	1083 A	864 A	793 A
2	441 AB	678 B	405 B	256 B
4	403 B	425 BC	329 BC	222 BC
6	251 BC	382 C	262 C	165 BC
24	49 C	92 D	78 D	19 C

[a] Abbreviations: AMAPA, Palmer amaranth; AMATA, tall waterhemp; AMBTR, giant ragweed; ERICA, horseweed.

[b] Means within a column followed by a different letter are significantly different. Tukey HSD at α = 0.05.

Herbicide Efficacy

Control and height reduction means were pooled across site-years for each species due to similarities in mean differences. Visual control evaluations were 16% to 17%, 22% to 24%, 37% to 40%, and 77% to 85% for Palmer amaranth, tall waterhemp, horseweed, and giant ragweed, respectively (Table 7). Height reduction was 69% to 72%, 64% to 67%, and 63% to 69% for Palmer amaranth, tall waterhemp, and horseweed, respectively (Table 8). Height reduction was not taken for giant ragweed due to the high levels of efficacy and lack of measurable plants.

Table 7. Control of Palmer amaranth, tall waterhemp, giant ragweed, and horseweed 21 d after treatment with glyphosate (280 g ha^{-1}) plus dicamba (140 g ha^{-1}) as influenced by broadcast nozzle.

Broadcast nozzle	AMAPA[a]	AMATA[a]	AMBTR[a]	ERICA[a]
	———— %[b] ————			
XR11004	16 A	22 A	77 A	37 A
TT11004	17 A	23 A	77 A	37 A
AIXR11004	17 A	24 A	85 A	40 A
TTI11004	16 A	24 A	83 A	38 A

[a] Abbreviations: AMAPA, Palmer amaranth; AMATA, tall waterhemp; AMBTR, giant ragweed; ERICA, horseweed.

[b] Means within a column followed by a different letter are significantly different. Tukey HSD at α = 0.05.

Table 8. Percent height reduction of Palmer amaranth, tall waterhemp, and horseweed 21 d after treatment with glyphosate (280 g ha^{-1}) plus dicamba (140 g ha^{-1}) as influenced by broadcast nozzle.

Broadcast nozzle	AMAPA[a]	AMATA[a]	ERICA[a]
	——————— %[b] ———————		
XR11004	68 A	64 A	63 A
TT11004	69 A	67 A	66 A
AIXR11004	72 A	64 A	69 A
TTI11004	71 A	66 A	68 A

[a] Abbreviations: AMAPA, Palmer amaranth; AMATA, tall waterhemp; ERICA, horseweed.
[b] Means within a column followed by a different letter are significantly different. Tukey HSD at $\alpha = 0.05$.

There were no differences in control and height reduction as influenced by the nozzle design for any of the weed species (Tables 7 and 8). This was similar to the data on herbicide spray deposition, in that nozzle designs and droplet spectra did not have an influence on deposition of the herbicide solution or the resulting efficacy.

In conclusion, the results from the 2 site-years and four weed species indicate that the use of drift-reduction nozzles that produce very coarse to ultra-coarse droplets did not influence the deposition, absorption, or efficacy of a POST application of glyphosate plus dicamba, despite reductions in coverage on spray cards. It should be noted that in the majority of site-years, applications were applied to low-density weed populations and relatively small plants (5 to 15 cm), whereas commercial applications may occur on larger plants and higher densities. The four broadleaf weeds evaluated are likely to be the targets of POST applications of dicamba in dicamba-resistant soybean hectares. The success of dicamba-resistant soybean systems will hinge on the ability to keep dicamba applications on-site and from drifting onto sensitive non-target crops. The use of the approved DRT nozzles for POST applications will allow for lower drift-risk applications while achieving acceptable efficacy when applied in the appropriate conditions of smaller weeds and lower-density populations.

Acknowledgments. The authors would like to acknowledge Greg Kruger, Ryan Henry, and Annah Geyer of the UNL PAT lab in North Platte, NE, for the use of their low-speed wind tunnel and laser-diffraction system and assistance in analyzing the spray droplet spectra of the broadcast nozzles used in this study.

References

Abul-Fatih HA, Bazzaz FA (1979) The biology of *Ambrosia trifida* L. II. Germination, emergence, growth and survival. New Phytol 83:817–827

Baysinger JA, Sims BD (1991) Giant ragweed (*Ambrosia trifida*) interference in soybeans (*Glycine max*). Weed Sci 39:358–362

Behrens MR, Mutlu N, Chakraborty S, Dumitru R, Jiang WZ, Lavallee BJ, Herman PL, Clemente TE, Weeks DP (2007) Dicamba resistance: enlarging and preserving biotechnology-based weed management strategies. Science 316:1185–1188

Bode L (1987) Spray application technology. Pages 85–110 *in* McWorter G, Gebhardt MR, eds. Methods of Applying Herbicides. WSSA Monograph 4. Champaign, IL: WSSA

Bradley K (2016). A season to remember: our experiences with off-target movement of dicamba in Missouri. Page 75 *in* Proceedings of the 2016 North Central Weed Science Society Annual Meeting. Des Moines, IA: North Central Weed Science Society

Bradley KW, Sweets LE (2008) Influence of glyphosate and fungicide coapplications on weed control, spray penetration, soybean response, and yield in glyphosate-resistant soybean. Agron J 100:1360

Carlsen SK, Spliid NH, Svensmark B (2006) Drift of 10 herbicides after tractor spray application. 2. Primary drift (droplet drift). Chemosphere 64:778–786

Chang FY, Vanden Born WH (1971) Dicamba uptake, translocation, metabolism, and selectivity. Weed Sci 19:113–117

Combellack JH (1982) Loss of herbicides from ground sprayers. Weed Res 22:193–204

Davis VM, Johnson WG (2008) Glyphosate-resistant horseweed (*Conyza Canadensis*) emergence, survival, and fecundity in no-till soybean. Weed Sci 56:231–236

Dorr G, Hanan J, Adkins S, Hewitt A, O'Donnell C, Noller B (2008) Spray deposition on plant surfaces: a modelling approach. Funct Plant Biol 35:988–996

Franssen AS, Skinner DZ, Al-khatib K, Horak MJ, Peter A, Kulakow PA (2001) Interspecific hybridization and gene flow of ALS resistance in *Amaranthus* species. Weed Sci 49:598–606

Fritz B, Hoffmann W, Jank P (2011) A fluorescent tracer method for evaluating spray transport and fate of field and laboratory spray applications. J ASTM Int 8:1–9

Gibson KD, Johnson WG, Hillger DE (2005) Farmer perceptions of problematic corn and soybean weeds in Indiana. Weed Technol 19:1065–1070

Heap I (2017). International Survey of Herbicide Resistant Weeds. http://www.weedscience.org. Accessed: January 1, 2017

Hilz E, Vermeer AP (2013) Spray drift review: the extent to which a formulation can contribute to spray drift reduction. Crop Prot 44: 75–83

Johnson B, Whitford F, Weller SC, Legleiter T (2012) 2,4-D and Dicamba-Tolerant Crops—Some Factors to Consider. West Lafayette, IN: Purdue Extension ID-453-W

Johnson B, Young B, Matthews J, Marquardt P, Slack C, Bradley K, York A, Culpepper S, Hager A, Al-Khatib K, Steckel L, Moechnig M, Loux M, Bernards M, Smeda R (2010). Weed control in dicamba-resistant soybeans. Online. Crop Manag 9:10.1094/CM-2010-0920-01 RS

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

Kruger GR, Johnson WG, Doohan DJ, Weller SC (2012) Dose Response of glyphosate and dicamba on tomato (*Lycopersicon esculentum*) injury. Weed Technol 26:256–260

Legleiter TR, Bradley KW, Massey RE (2009) Glyphosate-resistant waterhemp (*Amaranthus rudis*) control and economic returns with herbicide programs in soybean. Weed Technol 23:54–61

Legleiter TR, Johnson WG (2016) Herbicide coverage in narrow row soybean as influenced by spray nozzle design and carrier volume. Crop Prot 83:1–8

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 60:31–62

Ramsdale BK, Messersmith CG (2001) Drift-reducing nozzle effects on herbicide performance. Weed Technol 15:453–460

Robinson AP, Simpson DM, Johnson WG (2013) Response of glyphosate-tolerant soybean yield components to dicamba exposure. Weed Sci 61: 526–536

Schwartz LM, Norsworthy JK, Young BG, Bradley KW, Kruger GR, Davis VM, Steckel LE, Walsh MJ (2016) Tall waterhemp (*Amaranthus tuberculatus*) and Palmer amaranth (*Amaranthus palmeri*) seed production and retention at soybean maturity. Weed Technol 30:284–290

Sellers BA, Smeda RJ, Johnson WG, Ellersieck MR (2003) Comparative growth of six *Amaranthus* species in Missouri. Weed Sci 51:329–333

Webster TM, Loux MM, Regnier EE, Harrison SK (1994) Giant ragweed (*Ambrosia trifida*) canopy architecture and interference studies in soybean (*Glycine max*). Weed Technol 8:559–564

Van Wychen L (2016). WSSA survey ranks Palmer amaranth as the most troublesome weed in the U.S., galium as the most troublesome in Canada (press release). http://wssa.net/2016/04/wssa-survey-ranks-palmer-amaranth-as-the-most-troublesome-weed-in-the-u-s-galium-as-the-most-troublesome-in-canada. Accessed: May 15, 2017