Off-target spray particle movement

Rodrigo Werle Bruno C Vieira Maxwel C. Oliveira
Guilherme Alves Greg Kruger

2021-08-04

Abstract

BACKGROUND:

1 Introduction

The widespread cases of glyphosate-resistant weeds throughout the US motivated farmers to adopt dicamba and 2,4-D tolerant crops.[1–5] As expected, the agricultural usage of dicamba and 2,4-D significantly increased in the US ("United States Department of Agriculture" 2020). Applications of dicamba and 2,4-D in new cropping areas during extended time in the growing season has led to increased opportunities for the off-target movement of these herbicides.[6,7] Spray drift is one of the main mechanisms of pesticide off-target movement and can be defined as the part of the pesticide application deflected away from the target area during or following applications.[8] Herbicide drift potential is influenced by application technique, environmental conditions, and surrounding vegetation.[9–13]

Dicamba and 2,4-D spray drift is a concern because these herbicides are very active on broadleaf vegetation, including soybean and cotton, causing distinctive crop injury and yield loss at very low dose exposures.[14] The adoption of best management practices during herbicide applications, including proper nozzle selection and the use of drift reducing adjuvants, are among the main strategies to manage spray droplet size and mitigate spray drift.[15–17] New dicamba and 2,4-D products are mostly applied using venturi nozzles with air-inclusion and pre-orifice components that increase spray droplet size and reduce spray drift potential.[18,19] Despite the advances in nozzle technology,[19] pesticide formulations and adjuvants,[17] spraying techniques,[20] strategies to mitigate spray drift,[11] and education and extension efforts,[4,21] dicamba and 2,4-D spray drift remains associated with crop injury complaints across the US. In addition to this, common practices to mitigate spray drift, such as the use of DRAs with venturi nozzles in combination with lower pressures and boom heights, could potentially compromise spray uniformity, deposition, and weed control[22] (Moraes et al. 2021).

The use of spray shields or hoods is another strategy to mitigate spray drift during pesticide applications.[22–26] These devices generally reduce spray drift potential by minimizing spray exposure to wind. Foster et al. (2018)[24] reported that a hooded sprayer reduced spray drift potential in approximately 50% regardless of the nozzles used compared to conventional applications. The use of spray hoods can potentially extend the available time for applications during windy conditions and allow the use of finer droplets with lower carrier volumes to optimize spray coverage and weed control.[22] Although the benefits of sprayer hoods have been studies and reported since the early fifties, the technique adoption has been relatively low among farmers and applicators.[13] With the increased usage of dicamba and 2,4-D and the spray drift incidents associated with both herbicides, crop protection professionals renewed their interest in spray hoods to further mitigate herbicide off-target movement during applications. Therefore, the objective of this study was to evaluate the effectiveness of spray hoods in reducing pesticide drift for spray solutions and nozzles typically used for new auxinic herbicide products.

2 Materials and Methods

2.1 Field study

Field experiments were conducted in three locations: North Platte, NE (geographic coordinates) on September 11-12/2021; Arlington, WI (geographic coordinates) on September 15-16/2021; and city, MO (geographic coordinates) on September 18-20/2021. Applications were made on bare ground, corn stubble (XX cm height) and ???? in NE, WI, and MO, respectively. The fields were flat and with no surrounding trees. Samples were processed and analyzed at the Pesticide Application Technology Laboratory of the University of Nebraska-Lincoln located in North Platte, Nebraska.

Three factors were evaluated: sprayer type, nozzle type, and spray solution. Each experimental treatment was replicated 10 times. Two sprayers (Manufacturer, city, state) were employed for this study, the only difference being the inclusion of a hood or no hood. These sprayers were 9.1 meters in width and each had a 1130 L polyethylene tank. Spray delivery was accomplished via a hydraulic pump driven by the accompanying tractor. Each sprayer was connected to its own tractor via the three-point hitch system. Nozzle spacing was 51 cm, and boom height was set at 90 cm above the ground level for both sprayers. The wind skirt on the hooded sprayer was set slightly above the soil surface or corn stubble. The height for each sprayer was maintained throughout the study via the sprayers' guide wheels and the tractors' hitch system. The hood was constructed of molded, polymer plastic that surrounded the nozzles (Manufacturer, city, state). The hood sections reached approximately 30.5 cm below the nozzle orifices, and a plastic curtain reached a further 10 cm below the plastic hood. Nozzles were properly attached to the boom in order to get no interference of hood and nozzle plume.

Nozzle types were TTI11003 and AIXR11003 (Teejet Technologies, Wheaton, IL), and ULD12003 (Pentair, Minneapolis, MN). All nozzles have air inclusion features and the carrier volume was 140 L ha^-1 applied at 276 kPa operating pressure and 2.6 m s-1 application speed.

The spray solutions were prepared at the same day of applications and were water alone and water plus a drift-reducing adjuvant based on polyethylene glycol, choline chloride, and guar gum (IntactTM, Precision Laboratories, LLC, Waukegan, IL) at a rate of 0.5% v v-1. Additionally, a rhodamine fluorescent dye (Red Dye, Cole-Parmer, Vernon Hills, IL) was added to all solutions at a rate of 0.5% v v-1. The volumetric median diameter (VMD) of droplets and volume percentage of droplets finer than 200 µm (V200) were measured at the Pesticide Application Technology Laboratory using a Sympatec Helos-Vario K/R laser diffraction system (Sympatec Inc., Clausthal, Germany), setup with a R7 lens, with a dynamic size range of 9 to 1,800 µm. The distance from the nozzle tip to the laser was 0.3 m. The VMD and V200 for each combination spray solution versus nozzle type are listed in Table 1.

2.1.1 Application and field layout

Prior to the applications, 27 drift collection stations were placed downwind of the sprayed area in three transects (spaced by 7.6 m) and perpendicular to the spray line (Figure 1). For each transect, collectors were positioned at 1, 2, 3, 4, 8, 16, 31, 45, 60 m from the edge of the application zone. Additionally, three drift stations were placed 5 m upwind from the edge of the application zone and four petri dishes (150 mm diameter) were placed in-swath. All collectors were positioned 10 cm above the ground surface. Mylar cards (Grafix Plastics, Cleveland, OH) were used as drift collectors. Cards with dimensions of 10 x 10 cm were placed upwind and up to 31 m downwind, whereas cards with dimensions of 20 x 20 cm were placed at 45 and 60 m downwind.

Each replication was considered as one pass of the sprayer, equivalent to 828 m2 in total area (91 m length x 9.1 m wide). Before each pass, a new set of mylar cards and petri dishes were placed at the sampling points. Five minutes after the end of each application was performed, cards and petri dishes were collected and placed individually into pre-labeled plastic bags. All samples were carefully managed to avoid cross-contamination and stored into dark containers until further analysis in laboratory in order to prevent photodegradation of rhodamine dye. Samples were collected from the furthest to the nearest downwind distance. Different teams were designated to work at downwind, upwind, and in-swath zones, and gloves were changed between application passes.

The targeted wind velocity was between 3.6 to 6.7 m s-1 and ± 30° of being perpendicular to the driveline before applying a treatment. When necessary, the driveline and application zone was shifted to maintain the ± 30° wind direction target. Meteorological conditions (air temperature, and relative humidity, wind speed, wind direction) were collected at 2 m height and 1-min intervals using a HOBO RX3000 Weather Station (Onset Computer Co., Bourne, MA, USA) positioned upwind of the sprayed area. The wind speed and direction data were collected using 2D WindSonic anemometers (Gill Instruments, Lymington, UK). The meteorological data for each respective treatment is listed in Figure 2.

2.1.2 Dye quantification

Samples were taken to the laboratory for dye extraction and quantification using fluorometry technique. Distilled water was used as extraction solution added to each bag using a bottle top dispenser (LabSciences Inc., 60000-BTR, Reno, NV). Samples collected downwind were rinsed with 50 mL of distilled water, whereas samples collected upwind and in-swath were rinsed with 20 mL of distilled water. The samples were agitated for 15 s and then a 1.5 mL aliquot from each sample bag was drawn to fill a glass cuvette. The cuvette was placed in a rhodamine module inside a fluorometer (Trilogy 7200.000, Turner Designs, Sunnyvale, CA) using green light. Serial dilutions were performed upon each tank sample to generate calibration curves, which allowed the conversion of relative fluorescence unit into mg L-1 and further expressing data into ɳL cm-2.

2.2 Greenhouse study

A completely randomized design

2.3 Statistical analyses

The statistical analyses were conducted with R statistical software version 4.1.0.[27] Data analyses were performed with Bayesian inference with “brms” package.[28] Bayesian inference uses Markov chain Monte Carlo algorithms for sampling a probability distribution;[28] and avoids singular fit from frequentist linear models when using complex random effects.

2.3.1 Field study

Solution, sprayer and nozzle factors were grouped as a single fixed effect (herein treatments) due to missing factor water in Missouri. Resulting in a combination of 12 treatments.

2.3.1.1 Spray solution deposition at upwind and inswath Data was fitted to a mixed model using *brm* function. Treatments were the fixed effects and blocks nested within location random effects. Model family was gaussian and prior distribution was set to student-t with mean 0.5, standard deviation 3 and 11 degrees of freedom. The posterior summaries (mean and highest posterior density) were estimated with *emmeans* function from the “emmeans” package. Treatment means were compared using Bayes Factor (BF).[29,30] In short, if BF > 1 there is evidence for H1 (difference between treatments); whereas, if H0 < 1 there is evidence for H0 (no difference between treatments). If BF = 1, there is no evidence. The level of evidence (anecdotal, moderate, strong, very strong, and extreme) varies as the BF value increases (evidence for H1) or decreases (evidence for H0).

2.3.1.2 Spray solution deposition at downwind Data was fitted to a Bayesian linear mixed model using *brm* function. Spray solution deposition and distance were log-transformed to meet linearity. A single model was fitted to each treatment. For each model, treatments and distance were the fixed effects and blocks nested within location random effects. Model family was gaussian and prior distribution was set to student-t with mean 0.5, standard deviation 3 and 11 degrees of freedom. For clarification, intercepts, slopes were back-transformed with *exponential* function. Moreover, the linear models fitted were used to predict the distance where no spray particle deposition was detected (0 ηL cm^{-2}) for each treatment, which was also back-transformed to m scale.

The area under the curve (AUC) was used to validate the linear models. The spray solution deposition across distances within an experimental unit were used to calculate the absolute AUC value. The AUC was performed with *audps* function from the "agricolae" package. The AUC is commonly used for plant disease progress[31,32] but has been used to calculate herbicide injury.[33] Data was fitted to a mixed model using *brm* function. Treatments were the fixed effects and blocks nested within location random effects. Model family was gaussian and prior distribution was set to student-t with mean 0.5, standard deviation 3 and 11 degrees of freedom. The posterior summaries and treatment means were estimated and compared using Bayes Factor (BF) as above-mentioned.

2.4 Greenouse study

The Dv(10,50,90), RS, and % drifable fines was fitted to a Bayesian linear mixed model using *brm* function. In the models, solution and nozzle were set as fixed effects. Model family was hurdle gamma and prior distribution was set to student-t with mean 0.5, standard deviation 1 and 2 degrees of freedom. For each response variable, two models were fitted: with and without interaction (solution and nozzle). A model comparison was made with **bayesfactor_models** from "bayestestR" package[34] to investigate interaction significance. For all response variables (Dvs, RS and % drifable fines), the best model was with interaction. The posterior summaries and treatment means were estimated and compared using Bayes Factor (BF) as above-mentioned.

3 Results

3.1 Spray solution deposition at inswath and upwind

In general, Open sprayer treatments resulted in a more variable spray particle deposition than Hood treatments (Figure 1). The inclusion of either DRA or Water strongly impacted spray particle deposition inswath for Open sprayer treatments, regardless nozzle type. The top and bottom three treatments contained either DRA or Water, respectively. For example, treatment DRA-Open-ULD resulted in the highest spray particle deposition (1318.5 ηL cm^{-2}, Figure 1). In contrast, 911.2 nL cm^{-2} was the lowest spray solution deposition, which was achieved with Water-Open-ULD treatment. Hood sprayer treatments resulted in a more uniform spray particle deposition. Furthermore, there were less than 0.29 ηL cm^{-2} spray deposition at upwind with strong evidence (BF < 0.25) of no difference between all pairwise treatment contrasts (data not shown).

3.2 Spray solution deposition at downwind

Treatments with highest intercepts, which is the amount of spray particle deposition near the treated area, were Water-Open-AIXR (15.7 ηL cm^{-2}), followed by DRA-Open-AIXR (15.7 ηL cm^{-2}), and Water-Open-ULD (12.0 ηL cm^{-2}; Figure 2). In contrast, DRA-Hood-TTI, DRA-Hood-ULD and DRA-Hood-AIXR treatments resulted in the lowest intercepts (< 2.0 ηL cm^{-2}). In addition, there is evidence that treatments with Hood sprayer provided faster decay of spray particle deposition (slopes; Figure 2). The treatments with highest slope decay were Water-Hood-TTI (-0.50), DRA-Hood-TTI (-

0.48), DRA-Hood-ULD (-0.44), Water-Hood-AIXR (-0.43), Water-Hood-ULD (-0.43), and DRA-Hood-AIXR (-0.39).

The predicted distance where no spray particle deposition was detected varied upon treatments (Figure 3A). In general, Open sprayer treatments resulted in spray particle deposition at longest distances. For example, the distance of non-detectable spray particle deposition with Open sprayer treatments varied from 9.9 m (DRA-Open-TTI) to 54.9 m with DRA-Open-AIXR; whereas Hood sprayer treatments varied from 1.4 to 8.2 m with DRA-Hood-TTI and Water-Hood-AIXR, respectively.

Similar trend was observed in AUC. Treatments with Hood or Open sprayer strongly impacted on AUC values (Figure 3B). The highest AUC values were Water-Open-AIXR (87.4), followed by Water-Open-ULD (72.9) and DRA-Open-AIXR (72.6). In contrast, DRA-Hood-TTI (13.9), DRA-Hood-ULD (14.3) and Water-Open-AIXR (21.9) resulted in lowest AUC values. The impact of Open and Hood sprayer is demonstrated in treatments including AIXR nozzles. There is a high difference in AUC (50.7) between DRA-Open-AIXR vs DRA-Hood-AIXR (BF > 100). Moreover, addition of DRA did reduced AUC values when comparing within fixed factors, sprayer (Hood and Open) and nozzle (AIXR, TTI and ULD); however, addition of DRA were not statistically different for some contrasts, including DRA-Hood-TTI vs Water-Hood-TTI (BF = 0.91), DRA-Open-TTI vs Water-Open-TTI (BF = 0.55), and DRA-Open-AIXR vs Water-Open-AIXR (BF = 0.93).

3.3 Dv, Relative Span

4 Discussion

4.1 Droplet size

As expected, the TTI nozzle produced coarser spray classification compared to the ULD and the AIXR nozzles across all spray solutions tested. In a response surface modeling approach in which nozzles were tested at different operational setups, TTI nozzles had greater percentage of operational setups producing Ultra Coarse (90%) spray classification compared to ULD (2%) and AIXR (0%) nozzles.[35] Legleiter et al. (2018)[36] reported that glyphosate + 2,4-D (premixture formulation) applications using a TTI11004 nozzle produced coarser spray classification (Ultra Coarse) when compared to AIXR11004 (Very Coarse), TT11004 (Coarse), and XR11004 (Medium) nozzles. Alves et al. (2020)[37] reported that applications of different dicamba formulations using a TTI110015 nozzle had larger droplet size across all formulations when compared to applications using an AIXR110015 nozzle. Zaric (2020)[38] reported that the TTI11004 nozzle consistently produced coarser spray droplet size across multiple spray solutions when compared to the ULD12004 nozzle.

Creech et al. (2015)[18] reported that nozzle design had major effects on spray droplet size, whereas spray solution influenced droplet spectrum to a less extent. The addition of DRA increased spray droplet size across all nozzles tested herein. Samples et al. (2021)[39] reported that the addition of DRAs (polymer and guargum) increased the spray droplet size of herbicide spray mixtures containing combinations of glyphosate, glufosinate, acetochlor, *S*-metolachlor, dicamba, fomesafen, and/or 2,4-D applied with an AIXR11005 nozzle. Zaric (2020)[38] reported that the addition of DRAs consistently increased spray droplet size for dicamba applications using TTI1104 and ULD12004 spray nozzles. These findings highlight the specific instructions regarding nozzle selection for the new dicamba products ("Engenia Product Label" 2021, "Xtendimax Product Label" 2021), in which nozzles producing Ultra Coarse spray classifications are approved for applications. Label instructions for new 2,4-D formulations are more flexible in terms of nozzle selection, where Coarse, Very Coarse, and Extremely Coarse spray classifications are allowed ("Enlist Duo Product Label" 2021, "Enlist One Product Label" 2021). New dicamba and 2,4-D product labels also include specific DRAs to be used, especially when products are tank mixed with other pesticides.

4.2 Spray solution deposition in-swath

For conventional applications (open) without DRA, the TTI nozzle had greater in-swath spray deposition volume on petri dishes compared to the ULD and AIXR nozzles. It has been previously reported that applications with Ultra Coarse spray had greater in-swath deposition volume on petri dishes compared to finer spray classifications.[40] Finer sprays have a greater percentage of spray volume comprised of small droplets that are more susceptible to spray drift.[19] These small droplets have more aerodynamic drag and lose their initial momentum rapidly, therefore having their trajectory highly influenced by the wind compared to coarser droplets.[41] It is important to highlight that greater spray deposition volume collected on petri dishes does not mean greater spray coverage, as coarser sprays result in reduced spray coverage when compared to finer spray classifications.[36,41]

For conventional applications (open), the addition of DRA consistently increased in-swath spray deposition volume (petri dishes) compared to applications without DRA. Samples et al. (2021)[39] reported that the addition of DRAs (polymer and guargum) to several herbicide tank mixtures had inconsistent deposition results on soybean and cotton when compared to herbicide applications without adjuvants. Authors reported that while the addition of polymer and guargam based adjuvants increased cotton spray deposition for glyphosate + dicamba + *S*-Metolachlor spray mixture, the same adjuvants had no effect or decreased cotton spray deposition when mixed to glyphosate + 2,4-D. Moraes et al. (2021) (Moraes et al. 2021) reported that the addition of DRAs could have a negative effect on spray uniformity, especially with nozzles producing coarser spray classifications at lower spray pressures.

Results reported herein indicate an inconsistent effect of hooded sprayers on in-swath spray deposition. For applications with DRA, the conventional sprayer (open) had greater in-swath deposition compared to hooded applications. On the other hand, for applications without DRA, the hooded sprayer had greater in-swath deposition compared to the conventional sprayer. Wolf et al. (1993)[22] observed that solid spray shields generally decreased in-swath deposition uniformity. Authors noted that spray solution dripping from sprayer shield walls could increase the in-swath deposition variability during applications. Wolf et al (1993)[22] and Moraes et al. (2021) observations could explain the lower spray deposition obtained for hooded applications with the addition of the DRA, although this hypothesis needs to be further investigated.

4.3 Spray solution deposition at downwind

For conventional (open) applications without DRA, the TTI nozzle had less drift potential compared to AIXR and ULD nozzles, as expected. Alves et al. (2020)[37] reported similar results in a wind tunnel study, where applications of different dicamba formulations using a TTI nozzle had less spray drift compared to applications using an AIXR nozzle. Authors reported that soybean plants were still showing 50% biomass reduction from 9.9 to 13.4 m downwind the nozzle for applications with the AIXR nozzle, whereas this distance range was reduced to 6.4 to 7.2 m for applications using the TTI nozzle. In another wind tunnel study, Alves et al. (2017)[42] reported that dicamba applications with a TTI nozzle had 0.6% spray drift at 12 m downwind the nozzle, whereas applications with XR, TT, and AIXR nozzles had 13.5, 6.6, and 3.2% drift, respectively. As previously reported,[17,43] the addition of DRA reduced spray drift across all nozzles tested herein.

Hooded applications substantially reduced spray drift potential across all treatment scenarios. For instance, hooded applications using the AIXR nozzle without DRA had similar drift potential compared to conventional applications using the TTI nozzle with DRA despite the major droplet size differences between these treatments. These results indicate that the adoption of spray hoods combined with proper nozzle selection and the addition of DRAs to the spray solution can substantially reduce spray drift potential during pesticide applications. Foster et al. (2018)[24] reported that the advent of spray hood considerably reduced spray drift for glyphosate applications using Fine, Medium, Very Coarse, and Ultra Coarse spray qualities. In a wind tunnel study, Ozkan et al. (1997)[25] reported that several spray shields were effective in reducing spray drift, where a double-foil shield reduced spray drift in 59% compared to applications without shields. In laboratory tests, Smith et al. (1982) reported that a spray shield could reduce spray drift up to 70%, although field studies indicated an inconsistent performance where spray shields either increased or decreased spray drift during tests.

The results reported in this study highlight the importance of adopting best management practices during pesticide applications to mitigate spray off-target movement to the surrounding environment. Hooded applications with AIXR and ULD nozzles resulted in satisfactory spray drift reduction despite the finer droplet spectrum compared to the TTI nozzle. This could have implications for weed control as applications with Ultra Coarse droplet spectrum have reduced spray coverage compared to finer spray classifications. Legleiter et al. (2018)[36] reported that glyphosate + 2,4-D applications with Ultra Coarse (TTI11004) spray had reduced spray coverage on artificial targets (cards) compared to Medium (XR11004), Coarse (TT11004), and Very Coarse (AIXR11004) sprays. However, authors reported that spray droplet spectrum did not influence 2,4-D absorption in Palmer amaranth (*Amaranthus palmeri*), waterhemp (*Amaranthus tuberculatus*), giant ragweed (*Ambrosia trifida*), and horseweed (*Erigeron canadensis*). Increasing the application carrier volume is one strategy to overcome the reduced coverage from applications using coarser sprays. Butts et al. (2018)[44] reported that dicamba applications with Ultra Coarse spray resulted in optimal weed control for applications at 187 L ha-1, whereas Extremely Coarse spray resulted optimal weed control for glufosinate applications. However, applications with increased spray carrier volume are less efficient due to additional time and water requirements during the operation.[22] Hooded applications using AIXR and ULD nozzles can provide increased spray coverage compared to TTI nozzles while having low drift potential, which allows for applications at reduced carrier volumes.

Because of the substantial drift reduction, applications with hooded sprayers could also reduce product buffer zone requirements. New dicamba formulations provide incentives to the use of qualified hooded sprayers by decreasing the required downwind buffer from 73 m to 33 m (“Engenia Product Label” 2021, “Xtendimax Product Label”

2021). Although the benefits associated with hooded sprayers, the technology has not been well accepted by farmers. Nordby and Skuterud (1974)[13] mentioned that farmers could see spray hoods as cumbersome and expensive devices that do not allow applicators to check nozzles during applications. Considering the widespread adoption of dicamba and 2,4-D tolerant crops and the increase in these herbicide usage, hooded sprayers could be a very effective technique to mitigate spray drift during pesticide applications.

5 Conclusion

6 Acknowledgments

7 Conflict of Interest Declaration

8 Tables (each table complete with title and footnotes)

9 Figure Legends

References

1 Behrens MR, Mutlu N, Chakraborty S, Dumitru R, Jiang WZ, LaVallee BJ, *et al.*, Dicamba Resistance: Enlarging and Preserving Biotechnology-Based Weed Management Strategies, *Science* **316**:1185–1188, American Association for the Advancement of Science (2007).

2 Heap I and Duke SO, Overview of glyphosate-resistant weeds worldwide, *Pest Management Science* **74**:1040–1049 (2018).

3 Sammons RD and Gaines TA, Glyphosate resistance: State of knowledge, *Pest Management Science* **70**:1367–1377 (2014).

4 Werle R, Oliveira MC, Jhala AJ, Proctor CA, Rees J, and Klein R, Survey of Nebraska Farmers' Adoption of Dicamba-Resistant Soybean Technology and Dicamba Off-Target Movement, *Weed Technol* **32**:754–761 (2018).

5 Wright TR, Shan G, Walsh TA, Lira JM, Cui C, Song P, *et al.*, Robust crop resistance to broadleaf and grass herbicides provided by aryloxyalkanoate dioxygenase transgenes, *Proceedings of the National Academy of Sciences* **107**:20240–20245 (2010).

6 Soltani N, Oliveira MC, Alves GS, Werle R, Norsworthy JK, Sprague CL, *et al.*, Off-target movement assessment of dicamba in North America, *Weed Technol* **34**:318–330 (2020).

7 Werle R, Mobli A, Striegel S, Arneson N, DeWerff R, Brown A, *et al.*, Large Scale Evaluation of 2,4-D Choline Off-target Movement and Injury in 2,4-D-susceptible Soybean, *Weed Technology*:1–22, Cambridge University Press (2021).

8 Matthews G, Pesticide Application Methods, John Wiley & Sons (2008).

9 Al Heidary M, Douzals JP, Sinfort C, and Vallet A, Influence of spray characteristics on potential spray drift of field crop sprayers: A literature review, *Crop Protection* **63**:120–130 (2014).

10 Arvidsson T, Bergström L, and Kreuger J, Spray drift as influenced by meteorological and technical factors, *Pest Management Science* **67**:586–598 (2011).

11 Felsot AS, Unsworth JB, Linders JBHJ, Roberts G, Rautman D, Harris C, *et al.*, Agrochemical spray drift; assessment and mitigation—A review*, *Journal of Environmental Science and Health, Part B* **46**:1–23, Taylor & Francis (2010).

12 Hewitt AJ, Spray drift: Impact of requirements to protect the environment, *Crop Protection* **19**:623–627 (2000).

13 Nordby A and Skuterud R, The effects of boom height, working pressure and wind speed on spray drift, *Weed Research* **14**:385–395 (1974).

14 Egan JF, Barlow KM, and Mortensen DA, A Meta-Analysis on the Effects of 2,4-D and Dicamba Drift on Soybean and Cotton, *Weed Science* **62**:193–206, Cambridge University Press (2014).

15 Etheridge RE, Womac AR, and Mueller TC, Characterization of the Spray Droplet Spectra and Patterns of Four Venturi-Type Drift Reduction Nozzles, *Weed Technology* **13**:765–770, Cambridge University Press (1999).

16 Hewitt AJ, Spray optimization through application and liquid physical property variables–I, *Environmentalist* **28**:25–30 (2008).

17 Hilz E and Vermeer AWP, Spray drift review: The extent to which a formulation can contribute to spray drift reduction, *Crop Protection* **44**:75–83 (2013).

18 Creech CF, Henry RS, Fritz BK, and Kruger GR, Influence of Herbicide Active Ingredient, Nozzle Type, Orifice Size, Spray Pressure, and Carrier Volume Rate on Spray Droplet Size Characteristics, *Weed Technology* **29**:298–310, Cambridge University Press (2015).

19 Dorr GJ, Hewitt AJ, Adkins SW, Hanan J, Zhang H, and Noller B, A comparison of initial spray characteristics produced by agricultural nozzles, *Crop Protection* **53**:109–117 (2013).

20 Butts TR, Butts LE, Luck JD, Fritz BK, Hoffmann WC, and Kruger GR, Droplet size and nozzle tip pressure from a pulse-width modulation sprayer, *Biosystems Engineering* **178**:52–69 (2019).

21 Butts TR, Barber LT, Norsworthy JK, and Davis J, Survey of ground and aerial herbicide application practices in Arkansas agronomic crops, *Weed Technology* **35**:1–11, Cambridge University Press (2021).

22 Wolf TM, Grover R, Wallace K, Shewchuk SR, and Maybank J, Effect of protective shields on drift and deposition characteristics of field sprayers, *Can J Plant Sci* **73**:1261–1273, NRC Research Press (1993).

23 Burnside OC, A Shielded, Tractor-Mounted Sprayer for Research Plots, *Weed Science* **16**:386–388, Cambridge University Press (1968).

24 Foster HC, Sperry BP, Reynolds DB, Kruger GR, and Claussen S, Reducing Herbicide Particle Drift: Effect of Hooded Sprayer and Spray Quality, *Weed Technology* **32**:714–721, Cambridge University Press (2018).

25 Ozkan H, Miralles A, Sinfort C, Zhu H, and Fox R, Shields to Reduce Spray Drift, *Journal of Agricultural Engineering Research* **67**:311–322 (1997).

26 D. B. Smith, F. D. Harris, and B. J. Butler, Shielded Sprayer Boom to Reduce Drift, *Transactions of the ASAE* **25**:1136–1140 (1982).

27 R: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, Vienna, Austria (2021).

28 Bürkner P-C, **Brms** : An *R* Package for Bayesian Multilevel Models Using *Stan*, *J Stat Soft* **80** (2017).

29 Lee MD and Wagenmakers E-J, Bayesian Cognitive Modeling: A Practical Course, Cambridge University Press (2014).

30 Kass RE and Raftery AE, Bayes Factors, *Journal of the American Statistical Association* **90**:773–795, [American Statistical Association, Taylor & Francis, Ltd.] (1995).

31 Meena PD, Chattopadhyay C, Meena SS, and Kumar A, Area under disease progress curve and apparent infection rate of Alternaria blight disease of Indian mustard (Brassica juncea) at different plant age, *Archives of Phytopathology and Plant Protection* **44**:684–693, Taylor & Francis (2011).

32 Simko I and Piepho H-P, The Area Under the Disease Progress Stairs: Calculation, Advantage, and Application, *Phytopathology®* **102**:381–389, Scientific Societies (2011).

33 Striegel S, Oliveira MC, Arneson N, Conley SP, Stoltenberg DE, and Werle R, Spray solution pH and soybean injury as influenced by synthetic auxin formulation and spray additives, *Weed Technol* **35**:113–127 (2021).

34 Makowski D, Ben-Shachar M, and Lüdecke D, bayestestR: Describing Effects and their Uncertainty, Existence and Significance within the Bayesian Framework, *JOSS* **4**:1541 (2019).

35 Fritz B, Hoffman W, and Anderson J, Response Surface Method for Evaluation of the Performance of Agricultural Application Spray Nozzles, *Pesticide Formulation and Delivery Systems: 35th Volume, Pesticide Formulations, Adjuvants, and Spray Characterization in 2014*, ASTM International (2016).

36 Legleiter TR, Young BG, and Johnson WG, Glyphosate plus 2,4-D Deposition, Absorption, and Efficacy on Glyphosate-Resistant Weed Species as Influenced by Broadcast Spray Nozzle, *Weed Technology* **32**:141–149, Cambridge University Press (2018).

37 Alves GS, Vieira BC, Ynfante RS, Santana TM, Moraes JG, Golus JA, *et al.*, Tank contamination and simulated drift effects of dicamba-containing formulations on soybean cultivars, *Agrosystems, Geosciences & Environment* **3**:e20065 (2020).

38 Zaric M, Effects of Tank Contamination and Impact of Drift-Reducing Agents on Weed Control in Response to Dicamba Applications, *Theses, Dissertations, and Student Research in Agronomy and Horticulture* (2020).

39 Samples CA, Butts TR, Vieira BC, Irby JT, Reynolds DB, Catchot A, *et al.*, Effect of Deposition Aids Tank-Mixed with Herbicides on Cotton and Soybean Canopy Deposition and Spray Droplet Parameters, *Agronomy* **11**:278, Multidisciplinary Digital Publishing Institute (2021).

40 Vieira BC, Butts TR, Rodrigues AO, Golus JA, Schroeder K, and Kruger GR, Spray particle drift mitigation using field corn (Zea mays L.) As a drift barrier, *Pest Management Science* **74**:2038–2046 (2018).

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

42 Alves GS, Kruger GR, Cunha JPAR da, Santana DG de, Pinto LAT, Guimarães F, *et al.*, Dicamba Spray Drift as Influenced by Wind Speed and Nozzle Type, *Weed Technology* **31**:724–731, Cambridge University Press (2017).

43 Johnson AK, Roeth FW, Martin AR, and Klein RN, Glyphosate Spray Drift Management with Drift-Reducing Nozzles and Adjuvants, *Weed Technology* **20**:893–897, Cambridge University Press (2006).

44 Butts TR, Samples CA, Franca LX, Dodds DM, Reynolds DB, Adams JW, *et al.*, Spray droplet size and carrier volume effect on dicamba and glufosinate efficacy, *Pest Management Science* **74**:2020–2029 (2018).